The REgolith X-ray Imaging Spectrometer Flight Model: Structural Design, Analysis, and Testing

by

David Brad Carte

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

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Author .... Signature redacted
Department of Aeronautics and Astronautics
~~May 21~~, 2015

Certified by .... Signature redacted
Rebecca A. Masterson
Research Engineer
Thesis Supervisor

Certified by .... Signature redacted ..
David W. Miller
Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by .... Signature redacted .
Paulo C. Lozano
Chairman, Department Committee on Graduate Theses

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Abstract

Engineers of space flight programs face unique technical challenges created by the space environment in which these systems operate. High costs and increasing complexity of space programs create a greater demand for mission reliability. This demand further drives up development costs and project time lines. The result is that few missions are flown and few organization are able to participate in space program development.

Project budget and schedule overruns are in part a result of a risk-averse culture and the desire the create fail-proof systems. Resource constrained programs will have difficulty developing successful space systems if they attempt to fully address every risk. Rather, by taking a risk-tolerant posture, resource-constrained programs can more efficiently allocate resources to the most important areas of a system's development. By focusing effort and resources on high-risk areas, successful space programs can still be developed with lower budgets and smaller schedules than has traditionally been done.

Recent attempts to lower the time and budgets necessary to develop space systems have focused on developing smaller, less complex, and more numerous space system to replace traditionally larger, more expensive systems. The benefits of small space systems range from distributing risk across multiple systems and thereby lowering the cost of failure, to providing smaller organizations and universities the capabilities to develop their own space systems. Though these programs are cheaper, many organizations of small space systems are faced with limited resources that must be intelligently allocated to develop successful space programs.

This thesis presents the structural design, analysis, and testing of the REgolith X-ray Imaging Spectrometer (REXIS), a student-led instrument on board the National Aeronautics and Space Administration (NASA) Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer (OSIRIS-REx) asteroid sample return mission. As part a student experiment, the REXIS team must develop its system under tight resource constraints. The limited funding, personnel, equipment, and facilities available to the REXIS team all have important implications on how design, analysis, and testing decisions are made on REXIS. This thesis provides a discussion of key areas of the REXIS structural development and lessons learned from a structural engineering point of view.

Chapter 1 opens the discussion by talking about the motivation behind this thesis. It provides background information to the REXIS instrument and the context for the rest of the instrument discussion. The REXIS flight structural design and how this design facilitates the accomplishment of REXIS goals is presented in Chapter 2. Next, the analysis and testing of the Radiation Cover, one of REXIS's most critical elements, is described in Chapter 3. The key efforts taken on the REXIS structural development is discussed in Chapter 4. This particular section, through the discussion of the chronological development of the REXIS flight structural design, will highlight important areas of where efforts was focused on REXIS within the project constraints. Lastly, Chapter 5 provides lessons learned from a structural engineering point of view from the experiences on REXIS. Although the discussion focuses on the REXIS structural development, the examples and discussions described are relevant to other programs. This thesis is meant to provide insight into the REXIS development from which engineers of future small space programs can learn.

Thesis Supervisor: Rebecca A. Masterson
Title: Research Engineer

Thesis Supervisor: David W. Miller
Title: Professor of Aeronautics and Astronautics

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Chapter 1

Introduction

Developing successful space flight systems is challenging, expensive, time-intensive, and requires expert knowledge of space systems engineering. To provide insight and guidance into the engineering of small space systems, this thesis will examine the design, analysis, and testing of the REgolith X-ray Imaging Spectrometer (REXIS) from a structural engineering point of view. REXIS is a student instrument on board NASA's Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer (OSIRIS-REx) mission. As a space project, the REXIS team must contend with a number of challenges inherent to space systems engineering. In addition to these traditional challenges, the REXIS project, as a student instrument, faces the obstacles that come with limited resources. Throughout this thesis, the term *resources* is meant to describe funding, equipment, facilities, personnel, and other similar elements at a team's disposal to facilitate the project development. This thesis will use the structural development and testing of critical aspects of REXIS to illustrate how the project addresses the significant challenges of creating a space flight instrument under restricted resources.

Over the many years, space systems have revolutionized life for everyone through benefits realized through applications in global positioning, worldwide communication, information broadcasting, and many others. Numerous benefits remain to be discovered through the continuation of space system engineering. REXIS aids in this process both by the science it provides, and by training and exposing the future aerospace engineers to real-world space flight system development. While space exploration offers many advantages, the growing cost and time lines for space missions hinders humanity's ability to efficiently explore space. Many factors contribute to the typical cost and schedule overrun of space projects. When systems are costly and difficult to develop, success is highly dependent on how intelligently a team can utilize its available resources.

This chapter begins with a discussion on the background and motivation for this thesis. Next, it provides both the OSIRIS-REx and REXIS mission overviews and discusses the development philosophy and context under which REXIS is built. Lastly, this chapter explains the contributions this thesis aims to provide to the space industry community.

1.1 Background and Motivation

Both technical and nontechnical factors contribute to increasing budgets and longer development times among many space programs. One study performed at Aerospace of 40 National Aeronautics and Space Administration (NASA) robotic missions from 1992 to 2007 identifies an average cost growth of 27% and schedule growth of 22% over the initial allocated budget and schedule [1]. This result is typical among all space missions as they face many of the same challenges and factors causing budget and schedule overruns. Figure 1-1 shows the results of this study.

From an examination of these missions, one observes that space programs consistently run longer and use more resources than planned. These project overruns have negative impacts on strategic planning for the future. Organizations like NASA must be able to conduct their missions consistently, within predicted and specified budgets. By consistently failing to meet predicted and allocated resource budgets, aerospace organizations will face projects being cut and will not perform as many missions as planned. To the public, this inability to effectively and accurately plan reflects poorly on aerospace organization and decreases public desire and incentive to invest in aerospace missions. The budget and schedule overruns shown in Figure

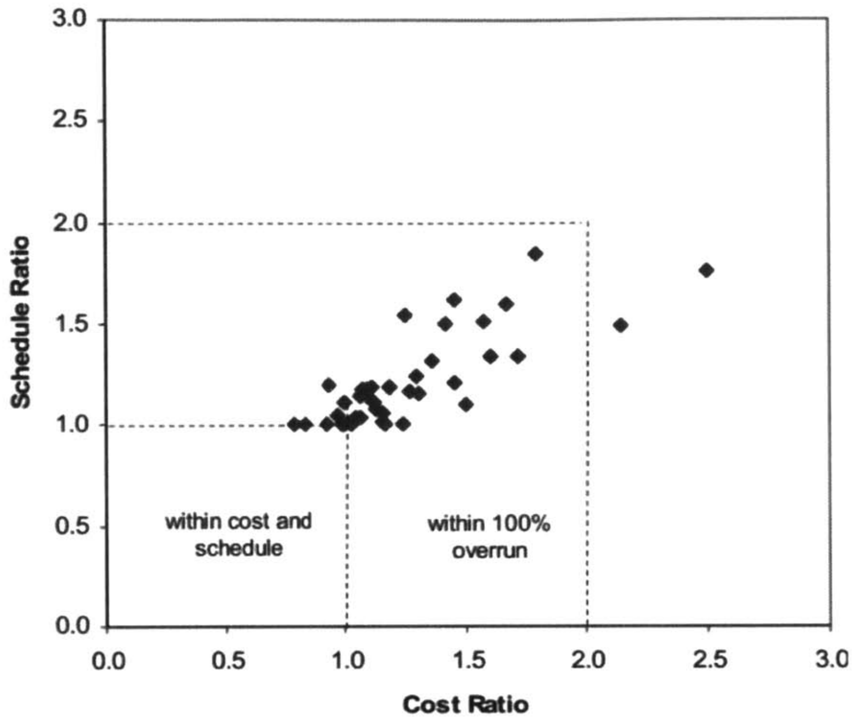


Figure 1-1: A plot of the ratio of actual cost to initial cost estimate and actual schedule to initial schedule estimate for selected NASA missions between 1992 and 2007. The average cost overrun is 27% and the average schedule overrun is 22% [1]

1-1 are due to a number of technical and non-technical factors. Some include underestimation of the challenges of space programs and the resources needed to address these, while non-technical factors such as a risk-averse culture drives up cost and development time as well.

From a technical perspective, key reasons contributing to the high cost and long budgets of space missions relate to the fundamental nature of operating in space. Engineering for a space environment necessitates considering factors not typically encountered on projects within Earth's atmosphere. As an example, the REXIS instrument faces a number of technical challenges as a multi-year asteroid sample return mission. The instrument must comply with strict contamination requirements to not harm the asteroid sample. Sensitive REXIS detectors require protection from radiation and very low operating temperatures to function correctly. These low thermal requirements conflict with the need to keep other components warm and within operational temperature limits. A low power budget limits the ability for REXIS to actively control the temperature of REXIS, leading to the need for a reliable passive thermal system. Minimal power also restricts the components available for use on REXIS. In addition to these, there are a number of other challenges such as the high stresses of launch cost of launch which put limits on the REXIS design and available budget[8] [9] [10]. Complications are encountered not only during operation, but also during development because simulating a realistic operational scenario is difficult. Replicating the launch, thermal, and other environments of space, while possible, is difficult and requires complex facilities and equipment. As systems get larger, it becomes increasingly more difficult and expensive to construct test setups that can accommodate these systems.

The need for high-performing, reliable systems is another major cause of project cost and schedule overruns. Once launched, space systems cannot be easily retrieved or accessed for maintenance and inspection. Often, projects must function for years or even decades without failures. These needs contribute to expensive, high-quality, and high-reliability parts incorporated into the design as well as a significant amount of analysis and testing in as close of a flight-like environment as possible. Risk aversion is prominent and typical as organizations attempt to avoid system failures. Because teams invest so much into their systems, the demand for reliability increases; therefore, teams spend even more time designing, analyzing, and testing, causing projects to take longer and be more expensive. This phenomena is described as the Space Spiral. The ever-increasing cost of space missions leads to longer schedules and a fewer number of missions. These factors lead to a demand for greater reliability, which, in turn, leads to even high cost, longer schedules and fewer missions [10].

Space programs must also contend with nontechnical factors such as governmental regulations and industry cultural issues that lead to cost and schedule overruns [10]. For example, Department of Defense (DoD) project timeliness typically span over multiple years, though congressional budgets are approved annually. The result is programs are continually re-evaluated and are forced to re-justify themselves to be approved for funding, adding both cost and delays; delays in turn lead to even higher costs [11]. Cumbersome bureaucracy has made streamlined space program development nearly impossible.

The issues discussed, in addition to many others, continue to push projects to be higher cost with longer development times. Several approaches, including risk and resources management can be used to decrease the cost of space missions.

1.2 REXIS Project Overview

REXIS is a small space system that must contend with the many challenges previously discussed, in addition to other mission-specific challenges. In order to help provide insight to future developers of space programs regarding effective resource allocation, this thesis examines the development of the REXIS flight model structure. With a limited budget, the REXIS team must intelligently select how it uses its resources to create a successful space instrument. This thesis allows the reader to experience the thought process and decisions made regarding how resources were allocated towards the REXIS structural development. The information provided throughout this thesis is meant to use REXIS as an example of how one team attempts to navigate the challenges of space engineering and the many factors and pressures that lead to high costs and long schedules of space programs. This section provides an overview of both OSIRIS-REx and REXIS. The discussion focuses on a high-level look at mission goals. Greater details of the REXIS instrument requirements and design are provided in Chapter 2.

1.2.1 OSIRIS-REx Overview

OSIRIS-REx is a NASA New Frontiers mission scheduled to launch in 2016. This mission will thoroughly characterize near-Earth asteroid Bennu in order to help shed light on how the planets formed and how life began. Ultimately, OSIRIS-REx will travel to the asteroid, Bennu, and return a pristine sample of the asteroid regolith to Earth for scientific study.

The target Bennu was selected as it is the most accessible carbonaceous asteroid and is representative of the type of object that may have brought prebiotic seeds of life and volatiles to Earth. Knowledge of this asteroid will give scientists a better understanding of planet formation and the origins of life. The OSIRIS-REx five mission goals are as follows [12]:

1. Return a pristine sample of carbonaceous asteroid regolith to study the nature, history, and distribution of its mineral and organic material.

2. Map the global properties of a primitive carbonaceous asteroid to provide context for the returned samples.

3. Document the in-site texture, morphology, geochemistry, and spectral properties of the regolith down to the sub-centimeter.

4. Measure the Yarkovsky effect on a potentially hazardous asteroid and constrain the asteroid properties that contribute to this effect.

5. Characterize the integrated global properties of a primitive carbonaceous asteroid to allow for direct comparison with ground based telescopic data of the entire asteroid population.

OSIRIS-REx utilizes five remote sensing instruments that aid in the completion of each of these scientific goals. The names of these remote sensing instruments flying on OSIRIS-REx are provided as well as references for further information:

1. OSIRIS-REx Laser Altimeter (OLA) [13]

2. OSIRIS-REx CAMera Suite (OCAMS) [14]

3. OSIRIS-REx Thermal Emission Spectrometer (OTES) [15]

4. OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) [16]

5. REgolith X-ray Imaging Spectrometer (REXIS) [3]

1.2.2 REXIS Instrument Overview

REXIS is a student-collaboration experiment on OSIRIS-REx. The primary goal of REXIS is to educate science and engineering students through participation in the development of space flight hardware. The project engineering team consists of Massachusetts Institute of Technology (MIT) graduate and undergraduate students and the staff at the MIT Space Systems Laboratory (SSL). REXIS is a collaborative effort between MIT's SSL, the MIT Earth, Atmospheric, and Planetary Sciences (EAPS) department, the Harvard College Observatory, MIT Lincoln Laboratory, and Aurora Flight Sciences, with support from NASA Goddard Space Flight Center (GSFC).

The two science objectives of REXIS are to classify Bennu among the known meteorite groups and map the surface elemental distribution and global element abundance of the asteroid regolith. Measurements of the elemental abundance ratios of Fe/Si, Mg/Si and S/Si enables REXIS to constrain Bennu to a single meteorite type. The Mg/Si and S/Si measurements allow classification within the carbonaceous chondrite class of asteroid of which Bennu is believed to belong. The second science objective is accomplished through the use of coded-aperture imaging to construct high-resolution images of the asteroid surface. A shadowgraph is collected on the detector plane at four-second intervals as OSIRIS-REx orbits around Bennu and as Bennu rotates on its own axis. These shadowgraphs are deconvolved in order to produce a sky image, producing a map of Bennu by co-adding each sky image [17].

This instrument will classify Bennu among the meteorite groups and map the surface elemental distribution through observation of fluorescent X-rays from Bennu in the 0.5-7 keV soft X-ray band [3]. REXIS observes X-rays using an array of charge coupled devices (CCDs) which are contained within the REXIS structure. A deployable Radiation Cover sits on top of the instrument. This Radiation Cover protects the detectors from damaging radiation during the multi-year cruise but must deploy upon arrival to Bennu in order for REXIS to gather science data.

The REXIS payload consists of two assemblies, the spectrometer and the Solar X-ray Monitor (SXM) (see Figure 1-2), that work together to accomplish the REXIS science goals. The spectrometer is the primary sensor of the REXIS payload and is responsible for observing and measuring the X-ray florescence from Bennu. While the spectrometer observes Bennu, the SXM simultaneously observes the X-ray emittance from the sun. Measurements from the SXM provides calibration and reference context for the spectrometer's measurements of Bennu. This thesis focuses on the spectrometer and will not discuss the SXM; the term *REXIS* is used interchangeably with the term *spectrometer* throughout this thesis.

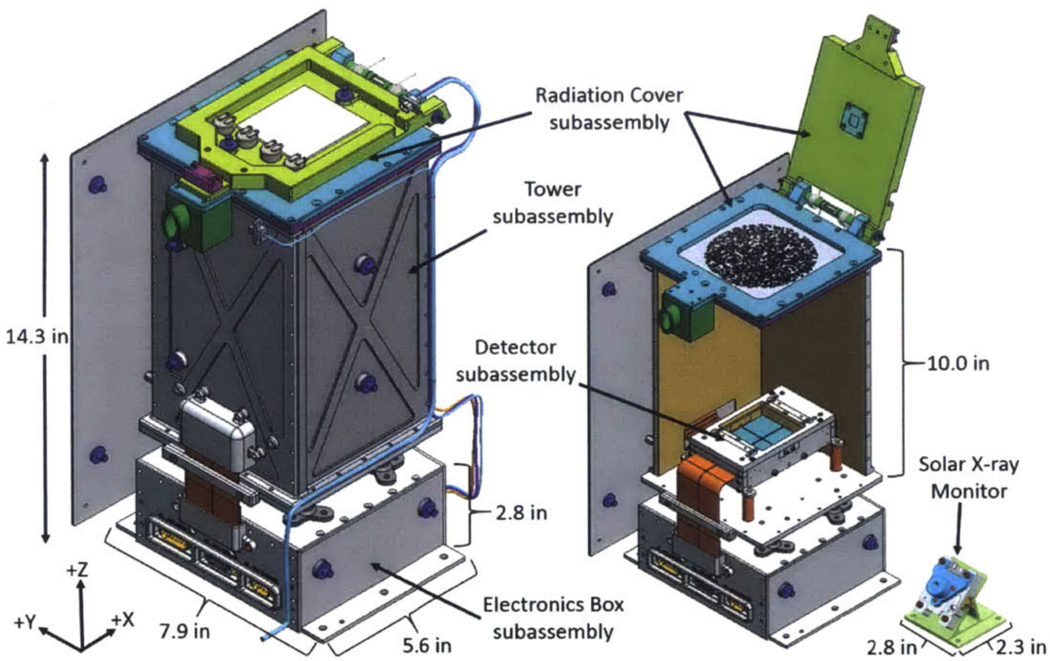


Figure 1-2: The REXIS spectrometer in the closed and open configuration along with the SXM. The open configuration on the right has the Radiation Cover deployed and two of the Tower Panels removed to provide viewing of the internal detectors

Figure 1-2 shows the closed configuration of REXIS as well as an internal view with the deployed Radiation Cover. The CCD detectors internal to REXIS measure the X-ray fluorescence from Bennu. In order to protect these CCDs from radiation damage during the multi-year cruise to the asteroid, a deployable Radiation Cover is closed from launch until the arrival to the asteroid at which point it will be opened. The CCDs are thermally isolated, with two sets of low thermal conductivity standoffs, from the warm Electronics Box that houses the avionics stack. These boards power and control all of REXIS operations. Connected to the detector package is a space-facing

Radiator to achieve very low temperatures that are necessary for CCD performance. Detailed discussion of the REXIS design is provided in Chapter 2.

1.3 REXIS Development Philosophy and Risk Posture

REXIS is classified as a NASA Class D payload. Rated from A through D, Class D payloads are typically characterized by higher risk and lower cost in comparison to their higher-rated counterparts [18]. High risk in this context refers to projects that take more chances, have less redundancy, and expend fewer resources into solving every issue. Class D systems are permitted to be higher risk as the consequence of failure is relatively low. As such, achievement of OSIRIS-REx Level 1 requirements is independent of REXIS success, although successful the measurements taken by REXIS will complement the science data gathered by the other instruments on OSIRIS-REx. With a risk-tolerant posture, REXIS is developed under a philosophy that attempts to effectively manage the risk associated with flying the instrument.

The REXIS team aims to develop a successful space system by including the intelligent management of acceptable risk throughout the instrument development. To accomplish this goal, REXIS attempts to allocate resources to address the most critical issues and areas on REXIS while accepting less-pressing risks. Because risk is a function of both the likelihood of failure and the consequence of failure, a risk with a high likelihood of failure may not necessarily be an issue if the consequence of such failure is marginal. The REXIS team evaluates which risks pose the largest threats to the mission and address these while understanding that many risks must be accepted. A risk matrix used to evaluate how critical a risk is based on likelihood and consequence is shown in Figure 1-3. Risks in the red zone require the most attention while those in the green are more acceptable for the mission.

When developing space projects, teams have different types of resources that can be used. These general categories of expendable resources are money, time, system

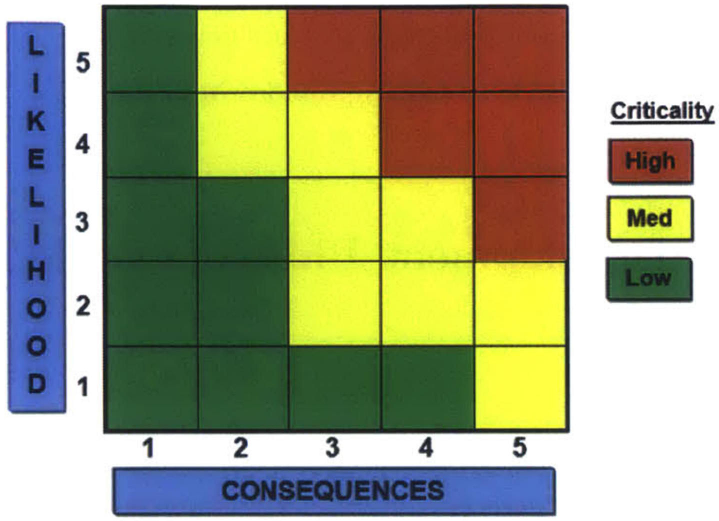


Figure 1-3: Risk matrix used on REXIS to determine the criticality of a risk. The criticality is both a function of the likelihood of the risk occurrence and the severity of the consequence if such a risk were to occur. [2]

performance, and risk. When it comes to making trades between these different areas, it is often more acceptable to spend more money and time to address system issues and ensure thorough development. It is less appealing to sacrifice system performance or take larger risks, largely due to the need for high reliability discussed in Section 1.1. Particularly important to this thesis is the approach of accepting risk as a substitute for spending more money and time, or degrading system performance.

The discussion on risk is dividing into two sections. The first aspect of risk examines how risky a project is to the developers in the sense that the project is an investment. The second type of risk examines the technical risk in which one is concerned with technical failures. These two types of risk are discussed in Sections 1.3.1 and 1.3.2, and provide the background in which REXIS is developed with regards to its risk philosophy.

1.3.1 Risk Management of Space Systems

Space mission budgets and schedules can be reduced by taking a more risk-tolerant posture and reducing the emphasis on infallible system reliability. This approach to risk is described by the use of small space systems. In this thesis the term *small* *space system* represents a state of mind, referring to less complex systems constructed under limited resources, and it often, but not necessarily, includes space systems of physically small size. Conversely, *large space systems* is meant to describe complex missions with large teams, and big budgets. Small space systems include instrument payloads or standalone small satellites (SmallSats). While the OSIRIS-REx mission does not fall under the small space system category, the REXIS payload, being built with a small budget and engineering team of graduate students, certainly does. As REXIS is included in this classification of small space systems, this particular section provides an overview of the benefits of these types of space systems. Consider Figure 1-4, which shows the cost of Galileo and the comparable cost of 11 NASA small satellites. A variety of missions can be performed with the same cost necessary to create one large one. The small missions in this study include missions of smaller size, cost, capabilities, and mission scope.

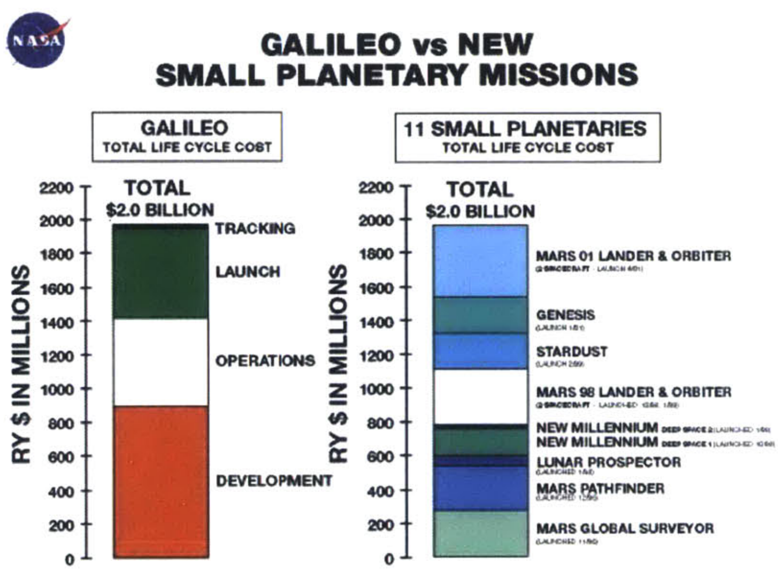


Figure 1-4: Comparison of Galileo cost with 11 small NASA planetary missions [2]

More projects for lower costs allows for the diversification of science goals. Studies have even shown that NASA low-cost space programs are on par with, if not more effective than, larger systems in terms of science received per dollar spent [19]. Small missions are also cost-effective ways to rapidly test newly developed technologies before implementation on a larger system. In this way, small space programs serve as building blocks to validate the application of new technologies [20].

Investing in multiple low-cost systems means that failures are acceptable because there are a number of other programs still in operation [9]; the failure of one satellite or instrument is independent of others and does not jeopardize other programs. In fact, failures of one program can provide valuable lessons learned that can be used to achieve greater success on other projects. Conversely, a failure of a major multi-decade, multi-billion dollar program is catastrophic [2]. As mentioned earlier in Section 1.2.2, a REXIS failure does not impair the OSIRIS-REx mission or other instruments. This fact enables REXIS to accept more risks, knowing that the success of other systems is independent of REXIS success.

When dealing with large systems, the need for higher reliability leads to larger costs and schedules following the Space Spiral cycle discussed in Section 1.1. It is important that organizations are willing to take risks with their projects as doing so leads to technological advancement. An important aid to taking risk is minimizing the cost of the project; the lower the cost, the lower the potential loss on investment. By using smaller and cheaper systems, a smaller focuses on reliability is needed because a failure is less consequential. Less reliability translates to quicker development, and hence more missions, which further reduces the risk of particular mission failure. In this way, the Space Spiral can be reversed.

In addition to these advantages, lower costs and smaller time lines of small space systems allow space project participation from universities and small businesses. By providing students, the future generation of aerospace engineers, hands on experience developing space flight systems, the space industry will benefit as a whole as these students enter the industry more prepared [21] [22]. Furthermore, university programs are typically working on the cutting edge of technological research. Therefore, enabling their access to space allows for greater technology implementation and development.

1.3.2 Managing Technical Risk in Small Space Systems

Space systems must face a number of technical challenges, and program teams address these challenges by creating designs that are robust against different threats. With few resources, the REXIS team must distribute its resources in the most effective manner such that the most severe threats are addressed and less important ones are accepted. Some REXIS examples include the risk that the structure will fail during a vibration test, the risk that a Radiation Cover will not open in space, or the risk that the CCDs will not be within their operating temperature range. The team must decide how resources are divided to address risks according to their criticality.

Small organizations developing small space systems face several programmatic challenges that hinder their abilities to fully address technical risks. NASA recognizes the benefit of low-cost Class D missions (see Risk Classification for NASA Payloads [18]). However, the risk-adverse culture and approach to building NASA risk Class A, B, and C systems is often applied to low-cost Class D missions [23]. These burdens make it difficult for low-budget programs to effectively manage their projects. Lengthy and frequent reviews and requirements consume funds and time, causing project resources to stretch thin. With already minimal resources available, further reducing available budget and time increases the chances of system failure. Small programs have a hard time surviving in a risk-adverse industry where strict regulations are imposed on programs not fully equipped to handle them [24].

With all the challenges, both technical and nontechnical, that small space programs encounter, teams must efficiently allocate resources in accordance with risk mitigation. In an attempt to reverse the Space Spiral, projects should not follow the path of attempting to completely and fully address all system risks. Rather, effort and resources must be intelligently spent on areas where risk is highest. Referring to the risk matrix shown in Figure 1-3, a project may need to fly a large number of green and even several yellow risks in order to allocate enough resources to address all of the red risks. This fact is especially true for projects being constructed with limited resources.

An important point to make is that attempting to substantially address all risks is counterproductive and will in fact *increase* overall mission risk. By spending time, money, and effort on areas that are not of major concern, a team inherently reduces resources that can be used areas more critical for mission success. Effective resource allocation to address important risks within a risk-tolerant posture is necessary for overall mission health. Space system project teams must learn to balance their resources such that overall system risk, rather than component or subsystem risk, is minimized. In this way, small teams can increase their chances of developing small space systems under tight resource constraints.

1.4 Contribution of this Thesis

This thesis aims to provide guidance addressing how structural engineers of small space systems with limited resources should manage these resources and their effort throughout the development of their system. Because Class D systems are often held to the rigorous standards of higher class missions but lack the appropriate resources, a greater percentage of their resources are spent accommodating reviews and documentation processes rather than investing in technical performance of the system. While it is of course beneficial for Class D missions to be scrutinized appropriately in proportion to the cost and risk of the mission, until this is the case, engineers must be able to manage their resources as efficiently as possible.

When held to a higher and more rigorous standard than what is warranted giving the scope of a mission, project resources are stretched thin. The result is that these programs cannot sufficiently address technical issues while also attempting to comply with regulations that governing organizations demand. Without any guidance on how engineers should focus their resources, low budgets programs are likely to continue being over budget and schedule and see higher instances of failure.

To provide this guidance, this thesis will use REXIS to discuss how the instrument team focuses resources and effort. Discussion will focus on important factors structural engineers should consider throughout the system's development regarding the balancing of resources. In particular, this thesis discusses how decisions made during the system's development can greatly affect the cost and schedule necessary to comply with strict NASA regulations. Examples used from the author's experience illustrate how one decision verses another can help utilize resources more effectively while still meeting mission requirements and standards.

This thesis will document important aspect of the REXIS development from the point of view of the REXIS structural engineer. Chapter 2 presents the REXIS structural design which serves as the basis for the rest of the REXIS discussion throughout the thesis. The analysis and testing efforts of the REXIS Radiation Cover are covered in Chapter 3. Some of the major development steps through the design, analysis, and testing of the REXIS structure to arrive at the flight model structural design are discussed in Chapter 4. Lastly, lessons learned from structural engineering experiences on REXIS are presented in Chapter 5 and highlight important areas to be considered especially when operating under tight resource constraints. While drawing on specific examples encountered on REXIS, these lessons are meant to be applicable to similarly resource-constrained space programs. This thesis will discuss some major considerations that can be used on various projects to use limited resources more efficiently. The information provided in this thesis is meant to facilitate the more efficient and successful development of comparable small space systems. Through technical discussion and lessons learned, it is intended that readers will be better prepared to more effectively handle the various challenges and obstacles sure to be encountered during the development of their space systems.

Chapter 2

REXIS Project Overview

This chapter focuses on the REXIS structural design. It begins by discussing the major mission requirements and how these requirements drive the structural design. Next the discussion focuses on the specifics of the design and is divided by instrument subsystem. Examples and discussions in later chapters commonly refer to specific components and aspects of the structural design that are explained this chapter.

2.1 REXIS Requirements

The REXIS mission is governed by internal REXIS-driven science requirements and external requirements and constraints imposed by OSIRIS-REx. Internal requirements dictate what must be met in order for REXIS to successfully gather and process asteroid measurements data. OSIRIS-REx requirements ensure REXIS will do no harm to the spacecraft or other instruments on board, as well as mechanically and electrically interface with the spacecraft which is necessary to function correctly.

Recall from Section 1.2.2 that REXIS uses a set of detectors to measure X-rays from the asteroid surface. Additionally, a Radiation Cover protects these detectors during mission cruise and opens prior to the collection of data. These two elements are fundamental to the success of the REXIS mission. As such, the two REXIS science requirements, out of many, that most drive the structural design are:

1. The REXIS detector array shall be passively cooled to less than -60 °C during

operation [3].

2. The REXIS detector array shall tolerate a total non-ionizing dose of $1.9 \times 10^8 MeV/g$ before Detailed Survey.

These overarching measurement requirements are necessary for the successful operation of REXIS and flow down to more specific internal engineering requirements that facilitate the successful detector operation. Note that "Detailed Survey" describes the point in the missions where REXIS begins measuring X-rays from Bennu. For an understanding of the REXIS requirements hierarchy, the two measurement requirements listed above are Level 3 requirements which drive the structural Level 4 requirements (See Figure 2-1).

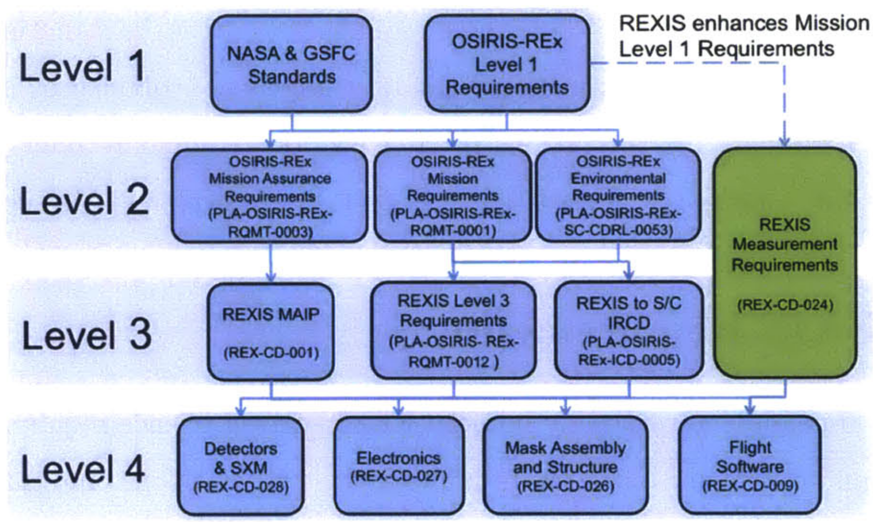


Figure 2-1: The REXIS requirements tree. Note that Level 3 science requirements drive the structural Level 4 engineering requirements

The -60 °C detector temperature requirement is fundamental for achieving sufficient detector performance. Without meeting this requirement, the REXIS detectors will not achieve the necessary spectral resolution [3]. This requirement influences the thermal system that is coupled with the instrument structure. The second requirement specifying the total non-ionizing dose the CCDs can tolerate dictates the need for a protective cover against radiation. REXIS uses a deployable Radiation Cover to protect the CCDs during the cruise to Bennu. This requirement drives the structural design because unless the Cover can deploy and open, the detectors will have no view of the asteroid and REXIS will not be able to complete its mission. A failure of the Radiation Cover to open will cause the REXIS mission to fail as well. The Level 3 measurement requirements therefore drive Level 4 structural requirements. For example, a derivative requirement on the CCD protection and Radiation Cover functionality is that the deployment system hardware must remain above -20 °C at all times. Details on the REXIS detectors and Radiation Cover design are discussed later in this chapter.

At the spacecraft level, REXIS follows a "do no harm" philosophy as part of the OSIRIS-REx mission. Under this risk posture, REXIS follows a number of requirements that ensure that its operations do not pose a risk to the other instrument or spacecraft missions. The major driving structural requirements imposed on REXIS from OSIRIS-REx are the following:

1. REXIS shall comply with the requirements for a Class D payload specified in NPR 8705.4, Appendix B [23].
2. REXIS shall comply with allocated a "not to exceed" (NTE) mass budget of 7.5 kg.
3. REXIS shall be compatible with the natural and induced environments specified in the OSIRIS-REx Environmental Requirements Document (ERD).
4. REXIS shall follow the OSIRIS-REx Contamination Control Plan (CCP).

By designating REXIS as a Class D instrument, OSIRIS-REx ensures that a REXIS failure will not impact the spacecraft or other instruments. In this sense, REXIS has flexibility to accept risks as its performance will not impact the rest of OSIRIS-REx; no other system depends on the successful operation of REXIS. The REXIS mass budget and additional volume requirements naturally limit the size of the instrument. In compliance with the ERD, REXIS must, among many things, maintain positive structural margins of safety (MS) against structural loads due to the launch and thermal environment of the mission. Finally, as an asteroid sample return mission, the OSIRIS-REx CCP designates requirements to ensure the sample is not compromised. The CCP specifies particular levels of cleanliness for REXIS, dictates particular processes such as instrument bakeouts that must be performed to remove particulates due to outgassing, and bans the use of certain materials from coming into contact with the instrument. Although a Class D instrument, REXIS must closely adhere to these contamination requirements in order to ensure the safety and integrity of the asteroid sample.

Particularly challenging is that OSIRIS-REx will launch in September 2016 and cruise to Bennu for over two years, meaning REXIS will not open its Radiation Cover until several years after launch. Because the REXIS detectors must be kept below -60 °C, other areas, in particular the Radiation Cover, will also be at cold temperatures during the cruise to Bennu. This long-duration cold storage of the Radiation Cover creates large uncertainties regarding its ability to open effectively upon arrival to Bennu.

Furthermore, REXIS must be sure that it does not risk the integrity of the asteroid sample. This requirement puts large restrictions on REXIS's development process and in-flight operations, in particular, the Radiation Cover deployment. The REXIS team must ensure that this opening does not emit particulates or contaminates that will jeopardize the integrity of the asteroid sample. Detailed discussion on the Radiation Cover and the efforts placed on testing and verifying its design takes place in Chapter 3.

The REXIS engineering team must meet not only these challenging technical and mission requirements, but must do so on a limited budget. As a student instrument, the REXIS team must develop and construct this system with few resources, including funding, equipment, facilities, and personnel. To develop a fully functional instrument under the given requirements, all resources must be used with maximum efficiency. This need is addressed largely through the division between analysis and testing, striking a balance between the two in order to achieve the largest return on the effort invested.

2.2 REXIS Design Overview

This section discusses the REXIS instrument hardware in the context of how it contributes to the system's performance. The fully assembled REXIS instruments are shown in Figure 2-2. The left shows the REXIS spectrometer with the Radiation Cover in the closed position. The view on the right shows REXIS with the Radiation Cover deployed and with some of the spectrometer walls removed so that the inside detectors can be seen. The SXM, not discussed in this thesis, is shown in the bottom right.

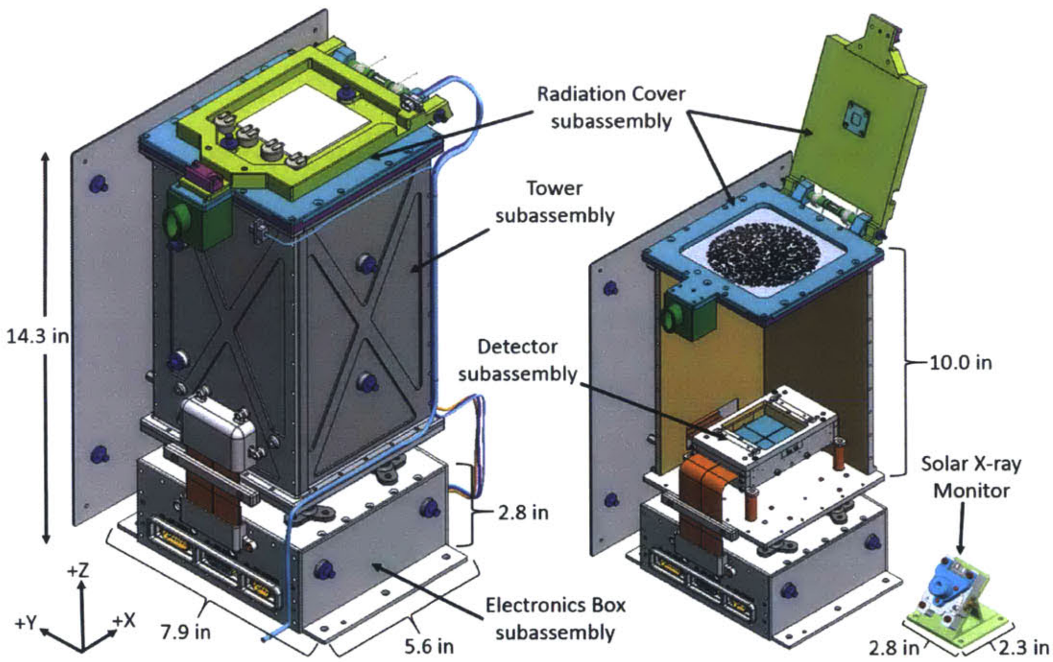


Figure 2-2: The REXIS spectrometer in the close and open configuration along with the SXM. The open configuration on the right has the Radiation Cover deployed and two of the Tower Panels removed to provide viewing of the internal detectors

The discussion of this section is broken into instrument subassemblies. Each section focuses on one of the subassemblies and the contributions it offers to the overall system performance. This discussion begins with the detector subassembly. The detectors are protected inside the REXIS structure and measure the fluorescent X-rays from Bennu. Next, the Electronics Box subassembly contains the electronics necessary to power and control all REXIS operations. The Tower subassembly protects the detectors, contains the Radiator, and supports the last subassembly, the Radiation Cover subassembly. The Radiation Cover subassembly sits on top of the Tower and protects the detectors from radiation until arrival to Bennu at which point the Radiation Cover will deploy and open. Finally, the thermal multi-layer insulation (MLI) design is presented as it is an important aspect of the spectrometer thermal design. The remainder of this section discusses these subassemblies in detail.

2.2.1 Detector Subassembly

The Detector Assembly Mount (DAM), shown in Figure 2-3, is the primary sensor for REXIS science measurements. Housed inside the DAM is a 2x2 array of MIT Lincoln Laboratory CCID-41 charge coupled devices (CCDs). The CCDs used by REXIS have heritage on the Suzaku XIS and Chandra ACIS-S detectors [25]. Each CCD consists of a 1024 by 1024 imaging pixel array accompanied by a non-imaging framestore [26]. The core of the Detector Assembly Mount (DAM) is this array of CCDs as they are the X-ray measuring components of the DAM.

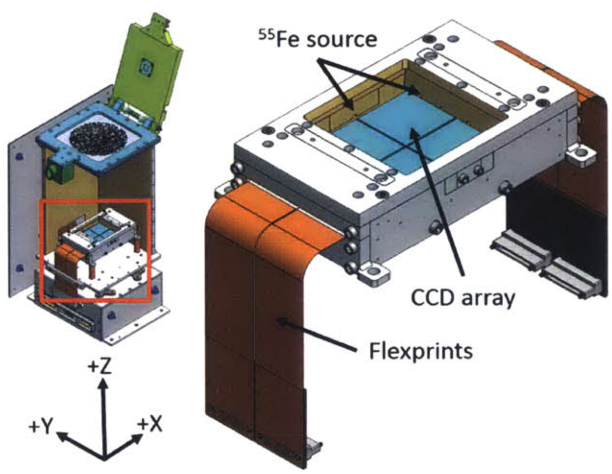


Figure 2-3: DAM subassembly

The remaining structure of the DAM is meant to align, calibrate, and protect the detector array. Tight mechanical tolerances and special features of the DAM structure tightly align the CCDs with respect to one another and align internal ^{55}Fe sources with the CCDs. These tight tolerances ensure proper pixel illumination from the ^{55}Fe sources. Power and data flow to and from each CCD via Flexprint cables to the instrument electronics.

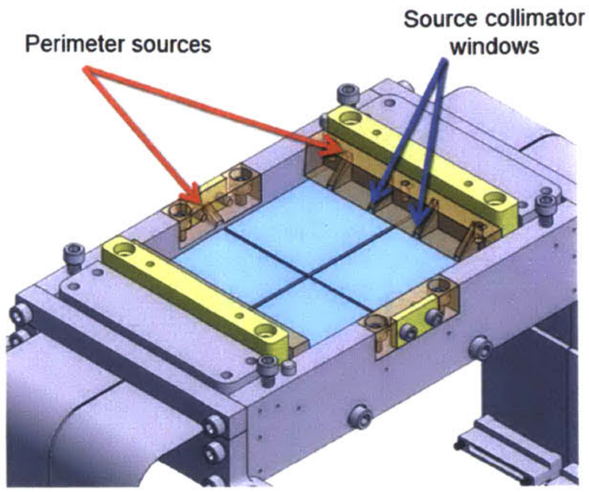


Figure 2-4: Location of calibration sources within the DAM [3]

Prior to gathering science data from Bennu, the REXIS CCDs will undergo an in-flight calibration using ^{55}Fe calibration sources internal to the instrument. Within the DAM are four separate pieces which hold these ^{55}Fe sources, a fifth source is present on the underside of the Radiation Cover (See section 2.2.4). The DAM calibration components are shown in Figure 2-4. These sources, facing the CCDs, are collimated to illuminate the boundaries between nodes of each CCD. With this scheme, each CCD node receives photons of a known energy enabling the measurement of the gain and spectral resolution of the detectors [26].

2.2.2 Electronics Box Subassembly and Thermal Isolation Layers

The joining subassembly to the DAM is the Electronics Box (EBox), that includes the Thermal Isolation Layers. The EBox can be seen in Figure 2-5 with the Front Panel removed to show the internal avionics stack. The EBox houses the avionics stack of three printed circuit boards (PCBs) which power and control REXIS operations. This stack is composed of the Main Electronics Board (MEB), the Interface Board, and Video Board. The MEB controls the operation of REXIS, processes the raw CCD images, and communicates with the spacecraft. The Interface and Video Boards together are known as the Detector Electronics (DE). These boards work together to convert and transfer raw CCD data to the MEB for processing.

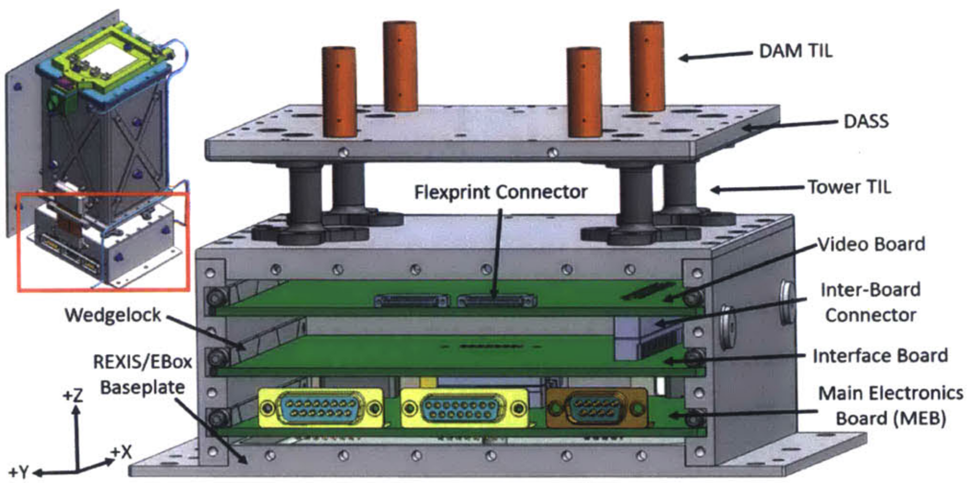


Figure 2-5: Electronics Box subassembly

The EBox provides the structural support between the boards and helps maintain a benign thermal environment for the electronics. The portion of the EBox subassembly that houses the electronics boards is constructed of six separate panels that form the box. The electronics boards are each 5.5" x 6" and connect to one another through inter-board connectors, forming the avionics stack. The avionics board stack is designed to slide in and out of the EBox with access from the Front and Rear Panels that can be removed with minimal effort even after the assembly of the entire spectrometer.

As can be seen, each PCB interfaces with the sides of the EBox with wedgelocks on either end of the -Y and +Y sides of the boards. The boards slide into and rest within slots built into the EBox Side Panels. When tightened, the wedgelocks expand and secure the boards in place with friction. The wedgelocks provide a stiff structural connection and good thermal conductivity from the boards to the walls. This avenue for heat dissipation is important to prevent the board components from exceeding their temperature limits during operation. The simplified removal of the board stack after assembly is an important feature in the event that electronics issues are experienced after integration and need to be identified and resolved. Additionally, walls of the EBox structure are at least 1/8" thick to provide the electronics shielding against radiation that could cause upsets or latchups [3].

The spacecraft wiring harnesses connect to the MEB through the EBox Front Panel while the REXIS SXM harness connects to the MEB through the EBox Rear Panel. The DAM Flexprints, through which power and data flow to the CCDs, connect to the Video Board through slots in the Front and Rear EBox Panels. Mechanically, REXIS mounts to the spacecraft through the EBox Baseplate which also serves as the base for the entire spectrometer.

A passive thermal system is used to cool the detectors below this requirement. Discussed in Section 2.1, the detectors must be kept below a temperature requirement of -60 °C to achieve the desired spectral resolution from the CCDs. The DAM is thermally separated from the warm EBox using two separate Thermal Isolation Layers (TILs) of standoffs. These TILs and separation between the DAM and EBox are shown in Figure 2-6. The Tower TIL separates rests on top of the EBox top and supports the entire upper portion of the instrument. The DAM TIL is the second layer and support just the DAM. Combined, both of these layers have a low thermal conductivity that prevents heat from conductively transferring to the CCDs from the warm EBox and help maintain a 120 °C temperature difference between the top of the EBox and the detectors [27].

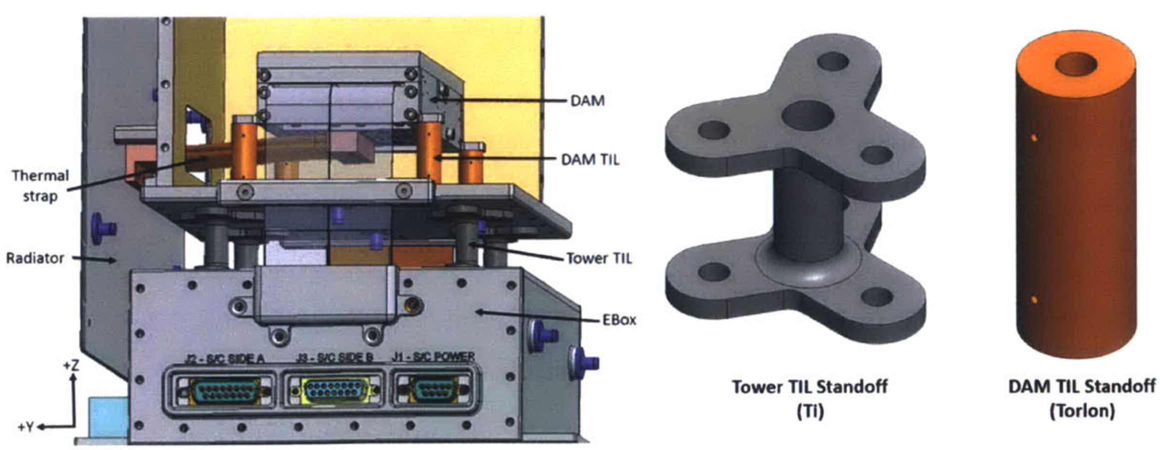


Figure 2-6: Thermal control elements allowing the DAM to maintain cold temperature requirements

The first layer, called the Tower TIL separates the top of the EBox and the

Detector Assembly Support Structure (DASS). As these standoffs support the main portion of the REXIS structure, Titanium (Ti) is the selected material due to its high strength and relatively low thermal conductivity. The Tower TIL includes four of these standoffs at each corner of the EBox Top Plate. Each standoff uses a tri-flange design to resist motion in multiple axes. A hollow center and thin cylindrical walls minimize the thermal conductivity across the standoff. The Tower TIL supports roughly 8.3 lb, about 68% of the REXIS mass.

Known as the DAM TIL, the second TIL layer consists of four Torlon standoffs which separate the DAM from the DASS. Each DAM TIL standoff is a cylinder of solid Torlon which is tapped to accept a fastener on either end. Although the Torlon standoffs are not nearly as strong as the Tower TIL, they only support the DAM, which is 0.95 lb, about 8% of the total REXIS mass. These standoffs sacrifice strength to make up for significantly lower thermal conductivity, which is essential as these standoffs interface directly with the DAM.

2.2.3 Tower Subassembly

The Tower subassembly includes the main walls or Tower Panels of the spectrometer, the Radiator, the Thermal Strap, and the Flexprint Shield hardware. The Tower surrounds the detectors while the Radiator and Thermal Strap are essential elements of the passive thermal system design. Additional Flexprint hardware covers and protects exposed areas of the Flexprints.

The Tower Panels are 1/16" thick aluminum (Al) 6061 plates with reinforced portions of 1/8" thick regions around the perimeter and in an "X" shape through the center of each Panel. The main purposes of the Tower Panels are to contain the detectors inside, protect them against radiation damage during the spacecraft cruise to Bennu, support the Coded Aperture Mask used during science observation, and provide the necessary focal length between the detector plane and the Mask. This subassembly is shown in Figure 2-7.

As the CCDs have a field of view of the Tower side walls, these Panels, along with some of the DAM components, are coated in 160 microinches of gold to attenuate the

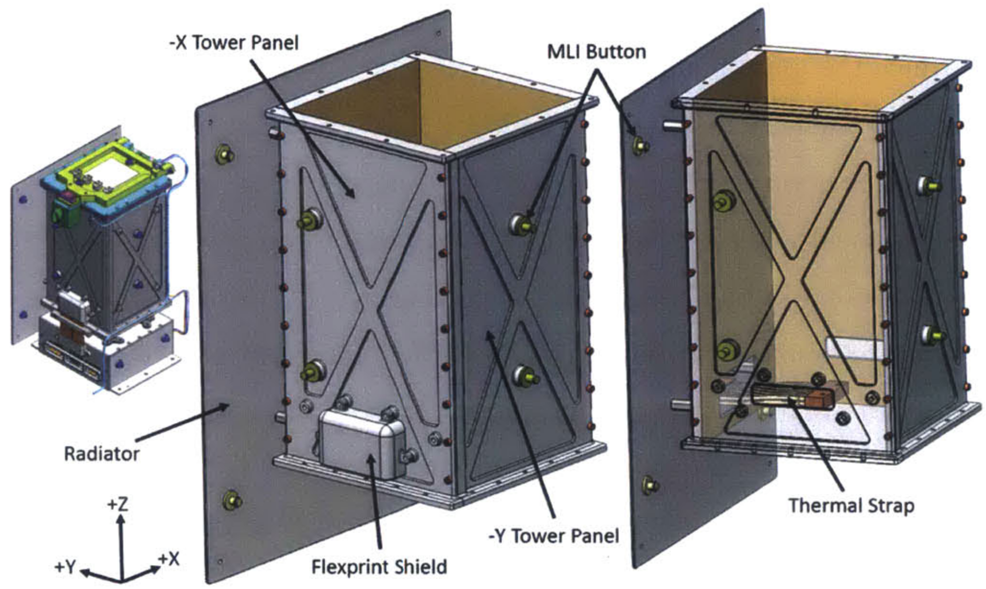


Figure 2-7: The Tower subassembly with a transparent view of the -X Tower Panel to show the internal thermal strap

X-ray fluorescence of the Al Panels. This attenuation is needed as the Al fluoresces strongly in the energy range of interest, thereby interfering with the measurements of interest. Each Tower Panel fastens to the adjacent Panels and also to the perimeter of the DASS. To allow the DAM to connect to the EBox, the +X and -X Tower Panels each contain a slot through which the DAM Flexprints exit. Flexprint Shields cover these slots and surround the majority of the Flexprints, providing protection against damage that may occur during on-ground assembly and handling.

As part of the passive thermal system, a flexible Thermal Strap facilitates the transfer of heat from the CCDs to the Radiator. Shown previously in Figure 2-6, the Thermal Strap attaches to the underside of the DAM Array Base and conductively couples the DAM to the Radiator. The +Y Panel contains a slot through which the Thermal Strap passes to connect the DAM to the Radiator. The REXIS Thermal Strap is 99% copper and is constructed out of flexible copper braids with copper end pieces which interface with the Radiator and DAM. Flexibility within the strap is meant to absorb deformations caused from vibration and thermal distortion during the mission, thereby reducing stresses on both the DAM and Radiator. This stress reduction is an important aspect of the Thermal Strap as any failure within the strap interfaces can greatly reduce the high thermal conductivity between the DAM and Radiator which the strap nominally offers.

The REXIS Radiator is a 9.8" x 12.6" flat 1/16" thick Al plate that faces deep space. Due to the nonlinear component of heat transfer due to radiation and nonexistent convective heat transfer, the Radiator is essential for maintaining CCD temperatures below the -60 °C requirement. The space-facing side of the Radiator is coated in Z93C55 white paint. This paint gives the Radiator a low absorptivity and high emissivity which minimize the amount of energy absorbed by REXIS while maximizing the amount rejected to space. The Radiator is mounted to the +Y Tower Panel by five stainless steel standoffs. The thermal conductivity of the Radiator standoffs is desirably low to prevent excessive cooling of the Tower Panels. The reason for this desire is the Radiation Cover subsystem, which attaches to the top of the Tower Panels, must stay warm to facilitate successful functioning of the Radiation Cover deployment system. See Stout and Masterson for more information on the REXIS thermal system [27].

2.2.4 Radiation Cover Subassembly

The REXIS Radiation Cover subassembly sits atop the Tower Panels and consists of the Mask Frame, Coded Aperture Mask (CAM), Radiation Cover and supporting thermal and deployment hardware. Note that the terms Radiation Cover Subassembly, refers all these pieces together, whereas "Radiation Cover" refers to the deployable panel. REXIS utilizes this one-time deployable Radiation Cover to protect the CCDs from radiation damage during the cruise to Bennu. Positioned on top of the instrument, the Cover is closed from launch in 2016 until observation in 2019, at which point the cover is 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 [28]. Use of the Radiation Cover limits damage so that the REXIS detectors can meet measurement objectives through its primary mission phase. The Radiation Cover is deployed using an TiNi Aerospace FD04 Frangibolt actuator that is discussed later. The Radiation Cover in the open position is shown in Figure 2-8 while Figure 2-9 shows the Radiation Cover subassembly in the closed position.

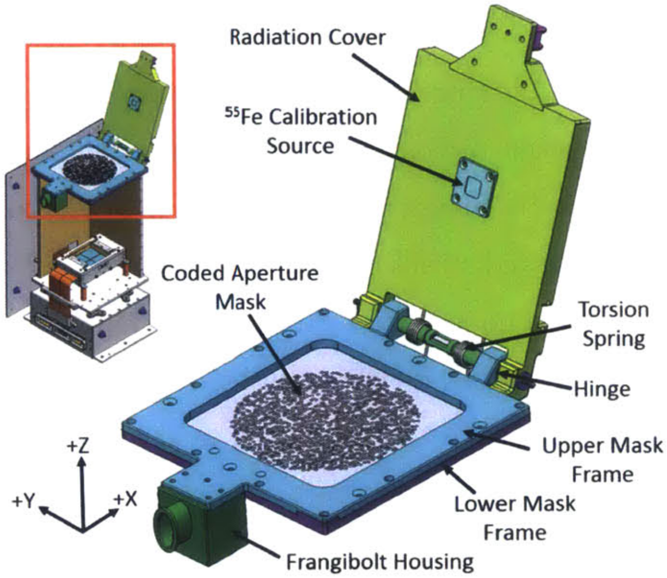


Figure 2-8: Deployed view of the Radiation Cover

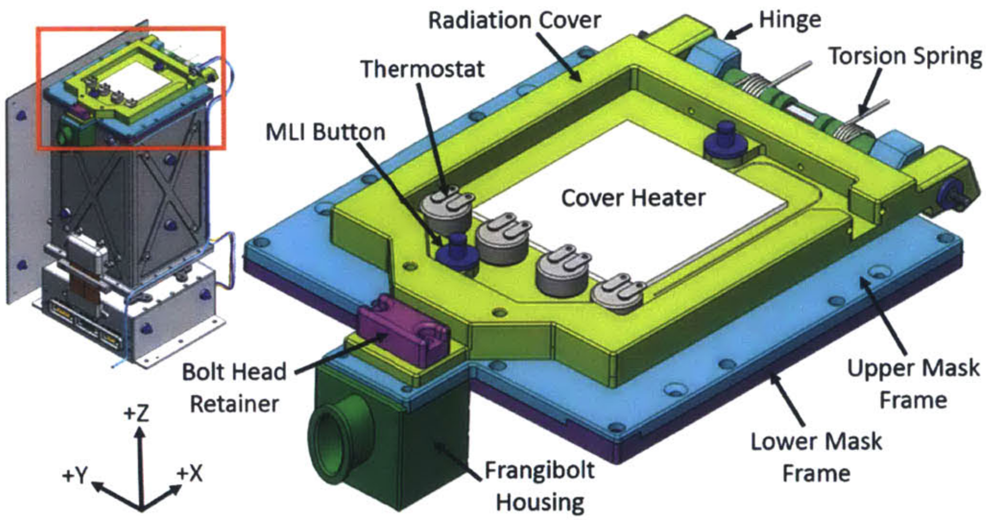


Figure 2-9: Radiation Cover subassembly

The deployable Radiation Cover covers the top of the CAM. While in the stowed position (Figure 2-9), there is no direct line of sight for radiation to impinge on the CCDs. Contained on the underside of the Radiation Cover is the fifth ^{55}Fe source which is used by the CCDs during internal calibration. This source works in cooperation with the internal sources present on the DAM (Reference Figure 2-4).

Made of Al 6061, the Radiation Cover is 0.157" thick at its minimum to provide sufficient radiation protection to the CCDs. The Cover rotates about a custom spring hinge with a 3/16" diameter stainless steel shaft and two torsion springs. The shaft rotates within Vespel SP-3 bushings. Vespel bushings provide a low friction contact surface to aid in the rotation of Radiation Cover and shaft during the Cover deployment. The dissimilarity in materials between the Al CAM Frame and Radiation Cover, the Vespel bushings, and steel shaft minimize the risk of cold welding between the components which would impede the opening of the Radiation Cover. Additional shaft sleeves 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 center sleeve is cut to expose a flattened portion of the shaft. This flattened feature is used for gripping during assembly so locknuts can be installed on either end of the shaft. The hinge, along with all the elements of which it is composed, is shown in Figure 2-10.

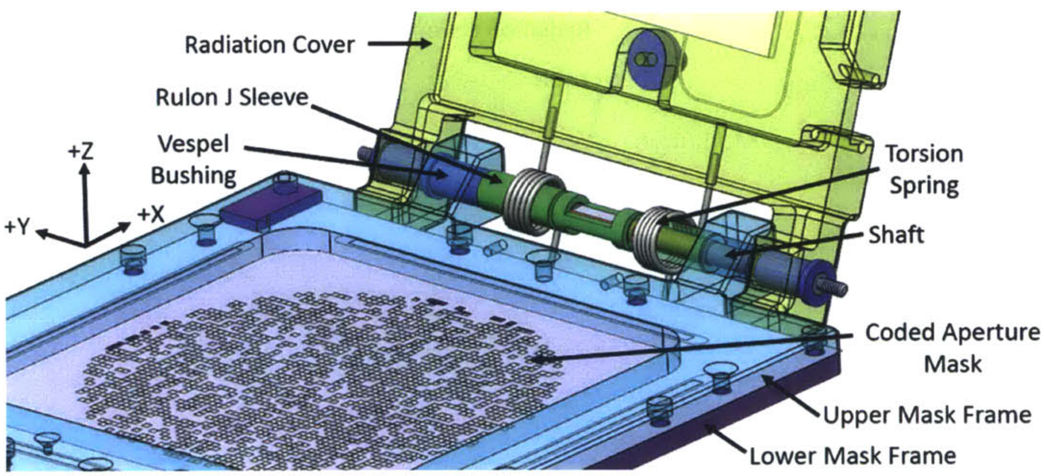


Figure 2-10: Hinge of the Radiation Cover subassembly. Some components are made transparent to facilitate viewing of the internal elements of the hinge

The Radiation Cover is joined to the Mask Frame at a hinge using the Radiation Cover shaft. The Mask Frame is composed of an upper and lower section which clamp the CAM in between the two. A series of ridges and grooves in the Upper and Lower Mask Frames tension the CAM and reduce single-point stress locations which can deform the minute pixel connections. Alignment features in the Mask

Frame components ensure that the CAM is aligned with respect to the CCDs when assembled. The underside of the Lower Mask Frame is also coated in 160 microinches of gold due to being in the field of view of the CCDs.

The Radiation Cover is recessed from the Upper Mask Frame by .015". The only portion that touches the Mask Frame when stowed is a localized region near the Frangibolt. The purpose of this recession is to minimize the contact area between the Radiation Cover and Mask Frame to reduce the risk of cold welding that could occur while the Radiation Cover is stowed closed for multiple years. Furthermore, this contact region around the Frangibolt is coated in Teflon-impregnated anodize to further reduce the risk of surface cold welding. The lack of contact area between the perimeter of the Radiation Cover and the Mask Frame also increases the Radiation Cover Heater efficiency. Without the conductive path from the Radiation Cover perimeter, less heat is lost to the Mask Frame. Rather, this heat is focused towards the Frangibolt and the associated deployment system hardware. The Radiation Cover deployment system refers to all elements that play a part in the opening of the Radiation Cover. This designation includes the Frangibolt stackup, the hinge components, the temperature control elements of the Radiation Cover, the wiring harnesses, and Radiation Cover hardware.

The Radiation Cover is stowed closed and deployed by use of an FD04 Frangibolt actuator and custom notched titanium (Ti) bolt produced by TiNi Aerospace. The FD04 Frangibolt actuator consists of a Copper-Aluminum-Nickel shape memory alloy (SMA) cylinder and provides 550 lbs of force to fracture the fastener in tension during actuation. 9VDC applied to the actuator internal heater heats the shape memory alloy, causing it to expand and fracture the custom Ti bolt. Once the Ti bolt is fractured, the door is released and held open by the hinge torsion springs. This model actuator is selected due to its lower power requirements and larger stroke in comparison to other FC model Frangibolts, making it less sensitive to installation preload [28]. Although Frangibolts have been in use since 1994 [29], the FD04 is a newly developed miniaturized model of the standard FC model Frangibolts and only has flight heritage on the DICE CubeSat in 2011 [30]. REXIS is the first instrument to employ the FD04 in interplanetary use; for this reason, a large testing effort is taken to verify its performance in REXIS's operating environment.

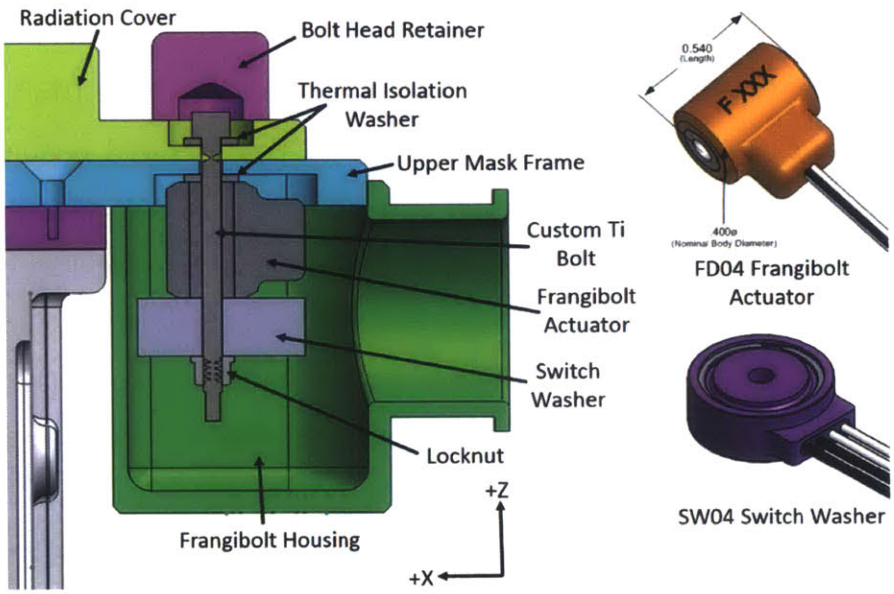


Figure 2-11: Cross-section view inside the Frangibolt Housing to show the components used in the Frangibolt stackup

The components of the Frangibolt stackup shown in Figure 2-11 include the custom Ti bolt, two Ti Thermal Isolation Washers, the TiNi Frangibolt actuator, the TiNi Switch Washer, and a locknut to hold everything in place. This cross-section view of the Frangibolt Housing shows the orientation of the components in the Frangibolt stackup. The Ti bolt runs through concentric holes in both the Radiation Cover and Upper Mask Frame, joining the pieces together. The Ti washers underneath the bolt head and between the actuator and the Upper Mask Frame thermally isolate the stackup from the rest of the structure. This isolation ensures that the Frangibolt is able to reach its actuation temperature when power is applied. The Switch Washer in the stackup is a compressed switch that signals the actuation of the Frangibolt. Finally, a locknut holds all components of the stackup in place and is torqued to establish the desired installation preload on the Ti bolt. The Frangibolt stackup is contained within the Bolt Head Retainer and the Frangibolt Housing. The Bolt Head Retainer attaches to the Radiation Cover and traps the Ti bolt head and one Thermal Isolation Washer. The Frangibolt Housing attaches to the underside of the

Upper Mask Frame and traps all other components once the Frangibolt actuates and the Ti bolt fractures. Along with containing the stackup components, the Frangibolt Housing is meant to capture any contamination or particulates that may be generated on account of the Frangibolt actuation.

The primary method of defense against contaminant generation is the TiNi Switch Washer. Once the Frangibolt actuates, the thermal path to the rest of the REXIS structure is cut and continual power application to the Frangibolt will quickly overheat the actuator, causing it to burn and release contaminants. The Switch Washer, as part of the stackup, is a closed circuit while under preload. When the bolt fractures and the bolt preload is released, the Switch Washer state changes to an open circuit. The MEB monitors the Switch Washer state throughout the firing sequence of the Frangibolt, cutting power to the actuator when the opening of the Switch Washer is detected.

In the event of a Switch Washer failure, a backup Frangibolt Timer will cause the MEB to cut applied power after the Timer length is exceeded. As the needed duration of power to heat the Frangibolt to the actuation temperature is largely dependent on the system temperature, the Timer length is a parameter than can be changed in flight and will be established based off real-time temperature measurements. This temperature measurement is provided by a platinum resistance thermometer (PRT) on the Frangibolt Housing.

As the components on the Radiation Cover will get extremely cold and be stowed at these temperatures for over two years during cruise, a heater on the Radiation Cover keeps the Frangibolt assembly and hinge components above their survival cold temperatures and project requirements of -20 °C. This project requirement flows down from the need to have a successful Radiation Cover deployment. The value of -20 °C is 30 °C above the vendor-specified operational temperature limit and is selected to keep the unit as warm as possible to minimize the risk that it fails during the long cruise. Mechanical thermostats monitor the Radiation Cover temperature to keep the deployment system components above their temperature limits. These thermal components are placed in the center region of the Radiation Cover (reference Figure

2-9). The surface of this recessed area has no coatings, but rather is bare aluminum to better facilitate the epoxy adhesion of the components. MLI covers the Radiation Cover and helps keeps the Radiation Cover components above their temperature requirements during flight. The MLI blanket mechanically attaches to two MLI buttons and is also adhered to the thick rim of the Radiation Cover with double-sided transfer adhesive tape.

Deployment of the Cover exposes the CAM and provides the CCDs a view of the asteroid. The CAM of the Radiation Cover subassembly defines the spectrometer field of view and casts an X-ray shadow on the CCDs during asteroid observation which is used to form images during ground data processing. The CAM is a 0.004" thick stainless steel sheet which contains a 3.87" diameter circular pattern of 0.060" square pixels. The CAM pixel pattern is random with an open fraction of 50%. On the external asteroid-facing side of the CAM, a layer of SiOx is vapor deposited to minimize the temperature variations induced by sunlight during the few phases of the mission when sunlight falls directly on the CAM. The CAM's thin and delicate nature make it suspect to thermal deformations. Direct sunlight on the CAM can rapidly heat it and cause deformations and structural failures between the pixel junctions, degrading science performance. Minimization of temperature gradients across the CAM is important to reduce pixel deformation which will degrade science performance. Gold is deposited on the underside of the CAM to attenuate the X-ray fluorescence of the stainless steel and avoid interference with data collection from the asteroid, as is done with the Tower Panels and DAM components. The Radiation Cover is designed to deploy to an opening angle of 110 degrees with respect to its starting position. This angle is enough to move the Radiation Cover out of the field of view of the detectors.

2.2.5 Multi-Layer Insulation

In order to reduce radiative heat loss from REXIS, nearly the entire instrument is covered in MLI blankets. The MLI is necessary to maintain REXIS desired system temperatures. The REXIS spectrometer uses eight different MLI blankets to completely cover and insulate the instrument. These blankets are mechanically secured to the structure using MLI buttons and snap rings which hold the blankets to the buttons. REXIS implements internally and externally threaded MLI buttons constructed of G10. Internally threaded MLI buttons allow a fastener to screw into the button, whereas the externally threaded MLI button contain a threaded extension of the button which screws into a mating threaded hole. Additional two-sided transfer adhesive and Kapton tape are used to perform custom connections between MLI blankets.

These blankets are installed simultaneously with the instrument assembly. The reason is that certain steps in the assembly eliminate access to areas where blankets are needed. Therefore, these blankets are installed on the assembly prior to moving on with the instrument assembly. Once complete, MLI blankets cover the entire EBox including the EBox top and underside of the DASS, the Tower Panels, the instrument-facing side of the Radiator, and the top of the Radiation Cover. The MLI installation is discussed later in Section 4.4.5 and shown in Figure 4-20.

2.3 Structural Engineering Background

This section discusses major topics and elements of structural engineering that pertain to the design, analysis, and testing of the REXIS structure as well as similar systems. These topics provide background to much of the work performed on REXIS that are discussed in later sections. While all topics presented here were not necessarily encountered on REXIS or discussed in detail throughout the thesis, this section is meant to provide readers with an understanding of some of the major considerations that must be taken as a structural engineer in the development of small space systems. These topics are provided as they are important areas of structural engineering of space systems. Sources are provided for additional and detailed research into the topics discussed.

This sections first covers aspects related to the design and analysis of space structures. Information includes fundamentals of structural engineering such as sources of major mechanical loading, different loading cases to consider, and design factors such as stress concentrations. The section then covers information regarding the use of mechanisms in space factors to consider. The next focus is placed on the testing of space structures to include different types of tests, the purpose of performing different types of tests, and some specific examples of testing lessons learned from industry.

2.3.1 Design and Analysis of Space System Structures

Space System Structural Engineering Fundamentals

Structural engineering encompasses a wide array of responsibilities from designing system requirements and specifications to the final flight system testing. Within this process is an iterative nature of progressively more detailed and refined designing, analyzing, and testing. Wijker, in *Spacecraft Structures*, provides a good starting point of the various factors to consider when designing, analyzing, and testing spacecraft structures. Information ranges from fundamental stress equitations, such as axial stress, bending stress, shear stress, and torsional stress, which were useful for much of the REXIS structural stress calculations, to test considerations, to less obvious but important characteristic of structural engineering such as the need and method for calculated venting holes to avoid over-pressurization of boxes [31].

As the backbone of spacecraft systems, the structure is necessary to support the rest of the system and ensure it survives the trip to space. The bounding loads for structures typically come from the launch environment. Therefore, the loads created from launch will often dominate the analysis and testing of a structure. Combustion of the launch vehicle engines and the resulting thrust creates vibration, shock, and acoustic loads that all systems much withstand [31]. Particular attention is given to the launch loads and a number of resources are available to provide a detailed discussion of loading sources and their effects on mechanical systems [32] [31].

Important loads during launch are steady-state accelerations, sinusoidal vibrations, random vibrations, acoustic loads, shock loads, and pressure variations. Maximum steady-state accelerations occur at the end of a propulsion phase of a rocket stage. The acceleration increases because the mass of the launch vehicle decreases while the thrust remains the same. Low-frequency sinusoidal vibrations, from 5-100 Hz, occur as a result of engine build-up of thrust and combustion which excite the low-frequency domain. Random vibration loads, in the 20-2000 Hz domain, are generated as a combination of moving mechanical parts such as turbopumps and structural elements interacting with acoustic pressure. The noise of the launch vehicle engines generate acoustic loads in the broad frequency spectrum from 20-10000 Hz and most severely affect membranes and panels. Events such as engine ignition and stage separation create shock loads in space structures. Shock loads are short duration and can be examined using a Shock Response Spectrum (SRS). An SRS is a plot that shows the responses of a number of single degree of freedom systems to an excitation, and provides an estimate of the response of an actual system and its components to a given transient input. Lastly, the launch phase creates pressure differentials within spacecraft volumes; sufficient venting of air must be available to prevent damaging the structure or components on account of these pressure differences [32] [31] [8].

It is important to understand how the forces generated by these different loading scenarios will affect a space structure. The most common method for calculating these forces and stresses is through a finite element model and analysis. As these models can sometimes provide inaccurate stress predictions as a result of errors of how the model was created, it can be useful to use these models to generate expected forces at interfaces and use engineering stress equations to determine stresses. Because the ability to calculate structural stress by hand using engineering stress equation is often needed, an understanding of structural characteristics is required so that one considers the various failure modes possible. An example highlighting the need for this knowledge is the difference in behavior of a column in tension verses compression. In tension, the maximum sustainable load of a member is dependent only on the properties of the material selected. However, this same member in compression can be subjected to a buckling failure and therefore must be analyzed against its critical stress which is dependent on the member's length, cross section, as well as material properties [33]. The various loading cases one must consider varies depending on the particular structural type or feature analyzed. As an example, analysis of columns must examine various loading cases to include axial, compressive, buckling, torsion, and shear loading. Different loading cases also apply to different types of structural elements such as columns, plates, or joints. As such, an understanding of how structures behave under loading is important to correctly and accurately predict a structure's performance when loaded. Structural engineering mechanics references can provide the fundamental equations and knowledge necessary to perform much of the structural analysis for major structural elements [34] [35].

Along with beams, plates, and other structural features of a design, the structural joint design must be carefully analyzed to ensure failures do not occur at these interfaces. Interfaces can be both permanent, such as welding, and non-permanent using a bolted design. Permanent welded joints have the advantage of created lightweight and maximum stiffness joints, but make demounting impractical and make lightly damped structures with maximum transmissibility which can cause damage to the system during vibration. Bolted joints make assembly and disassembly easy with a wide variety of types from which to choose, but can add significant weight to the system and require an accurate installation preload to obtain maximum performance. REXIS uses strictly bolted joints and uses the analysis of these bolts to ensure that mechanical interfaces do not fail. An important example is the analysis of the REXIS baseplate bolted joints that mount the spectrometer to the spacecraft deck. Further detail on joint analysis and design can be found in additional sources [33] [36].

Along with the more static loading cases, fatigue loading is of particular concern due to the vibration and cyclic loading that occurs during launch. Fatigue is the occurrence where structures crack or break due to repetitive alternating loads. Furthermore, the stresses that cause fatigue damage can be much less than the strength of the material. For this reason, fatigue can be very dangerous as system can be perceived to have sufficient structural margins but are susceptible to fatigue. These cyclic loads create local stresses that cause cracks to form and propagate through a structure until it eventually fails. We often define failure of a structure as yielding or permanent plastic deformation. Cyclic loading can form cracks in material defects at the microscopic level. These fatigue stresses cause localized areas at high stress areas of the crack time to have irreversible plastic deformations. Cyclic loading makes the material continually yield and fail, causing cracks to grow [37]. An s-N Fatigue curve can be used to predict the life of a structure at a particular stress level. The Palmgren-Miner rule allows the life prediction at cumulative stress levels. This rule is useful as multiple stress levels occur during launch, and the number of cycles can also be predicted for launch or test [31].

Typically, analyzing structural elements based on basic structural stress equations alone is not sufficient. Real-world structures often have features such as grooves, holes, fillets, or notches that create localized areas of concentrated high stress. For this reason, one must consider the presence of stress concentration factors when designing structures. A stress concentration factor can be considered to be the maximum peak stress in a body as compared to the nominal stress without the presence of stress concentrations. This factor allows one to scale a nominal predicted stress to the maximum predicted stress at localized high-stress regions on account of stress concentration features. Taking stress concentrations into consideration is imperative during design to create structures that do not have excessively high stress concentration factors and during analysis to correctly predict the maximum stresses. It is important to note that the associated stress concentration factor varies depending on the particular shape of the analyzed element and stress concentration feature. A comprehensive discussion of stress concentration factors and their values based on different structural shapes is given in *Peterson's Stress Concentration Factors* [38].

Because weight is such a considerable limiting factor for space systems, engineers desire achieving the greatest return on their materials used. Often, this structural trade translates into achieving highest strength for the lowest weight. But sometimes other factors are desired such as materials with particular electrical or thermal properties. Osgood provides a discussion and summary of structural types and materials through the use of a structural index. This structural index, is used to find the most efficient combination of cross-sectional shape and material such that one can achieve the highest strength structure with the lowest weight. Included are lists of material strength to density ratios and material performance in the vacuum, radiation, and thermal environment of space [33]. These characteristics are important for factors such as radiation shielding and creating an effective thermal system.

Space System Mechanisms

Many space structures are responsible for more than just supporting and strengthening a system so that it survives launch and other induced loading. Often structures contain movable components in order to deploy solar arrays, doors, and other aspects of a system that are stowed at launch. Mechanisms add additional challenges to space structures as they introduce complexity and the number of ways the system can fail.

Space systems that employ mechanisms face many challenges in the space environment. Mechanisms can vary from a simple single-use, spring-loaded device to a complex device requiring motors, gears, lubricants, electrical wiring, feedback control, heaters, and other features. The difficulty with mechanisms is that the space environment creates many challenges not experienced on earth. Furthermore, once launched, fixing a mechanisms becomes nearly out of the question unless under extreme circumstances. For this reason, mechanisms must be made exceptionally reliable. As with most space components, mechanisms must be lightweight to reduce overall system cost. This need often competes with reliability because it prevents the use of redundancy in the mechanism.

Sarafin provides a valuable discussion on the mechanisms development process. He takes the reader through the evolution of the mechanisms starting in the conceptual design phase where one identifies the preliminary requirements and creates a reasonable mechanisms concept to address each set of requirements. Iterations of analysis and testing help engineers evaluate which concept can best address the requirements to develop a more detailed and final mechanisms design. Eventually, qualification tests should be performed with integrated flight unit testing to validate the design. Also included is a discussion on various mechanisms components and commentary on how they are used. Helpful lists are provided for those trying to explore different options and particularly relevant to REXIS is a summary of commonly used feedback devices. Some of the devices listed are magnetic pickups, limit switches, and potentiometers [39].

Feedback devices in general are essential in order to understand how a mechanism has performed. In some cases, feedback is necessary as an input into some form of control or further steps. In situations where a mechanism only deploys something such as a solar array, feedback can tell the operators whether the deployment was successful. It is difficult to decipher if a system is operating effectively or has failed without feedback. This feedback can help one determine what has gone wrong so they can begin to address the problem and learn from mistakes for the future.

Other challenges of mechanism use in space can arise from a difficult thermal environment, risks of cold welding, problems with lubricants, and ensuring sufficient system reliability such that these mechanisms don't get "stuck" in a failed state that is not fixable without physical access. With each new added part in the mechanism, the design becomes more complex, increasing the opportunities for failures. Especially on mechanisms that require ongoing motion such as gears and motors, high quality workmanship is required to ensure that parts interact correctly and without excessive resistances that will cause mechanisms to wear and degrade. One should not underestimate the amount of effort that must be placed on the design, analysis, and testing to create a robust and reliable space mechanism.

Sarafin also includes a number of nontechnical factors and lessons to consider during the development of space mechanisms. Some of these lessons are to keep one individual in charge of the mechanisms development, to include wiring the specifications, drawing layouts, performing preliminary analysis, defining design details, developing test plans, and interpreting results. While this single individual will likely need the help of specialized engineers from various engineers disciplines, having one individual overseeing the entire development reduces miscommunication, misinterpretation, errors, and overall leads to better mechanism reliability. Among other lessons, Sarafin advocates budgeting sufficient cost and schedule for mechanism development and testing. Failure to allocate sufficient time and effort to mechanisms development can lead to low reliability and faulty designs. He mentions that teams can often save schedule by using non-optimal designs. Sometimes using an existing design that is heavier and consumes more power can be better than designing a smaller more efficient mechanism from scratch [39].

A valuable resource that focuses on lessons learned from space mechanisms is the Aerospace Mechanism Symposium (AMS). This conference focuses on problems with design, fabrication, test, and the operational use of aerospace mechanisms. With an emphasis on hardware development, this symposium offers a wide variety of real-world mechanism applications from which other groups can learn [40]. With mechanisms being particularly difficult for space operations, one should always consult resources on previous uses prior to embarking on development of a space mechanisms. Conferences like the AMS provide numerous lessons that enables individuals to learn from the failures or successes of others.

2.3.2 Testing of Space System Structures

Testing is an important step of verifying the quality of the design. There are a number of different ways that system requirements can be verified, but testing can often be the most realistic and rewarding in terms of the knowledge learned. Testing puts engineers in contact with the hardware, and they must think through how to realistically create a test setup. The process of setting up a test, conducting the test, and the results provided allows engineers to identify critical details that can sometimes be overlooked during a computer analysis. However, because we desire to perform realistic testing with actual hardware, test can be very expensive and time consuming. For this reason, it is imperative that engineers understand the system they are testing, how it can fail, and how it is expected to perform so performance anomalies can be identified during a test. Many, but not all, of the topics and lessons discussed are included because of their relevance to the REXIS project. Some of this information will be observed throughout this thesis.

Classes of Testing

There are several classes of tests that teams use for verifying requirements. These classes are development, qualification, acceptance, protoflight, and analysis-validation tests. Development tests are typically low-costs tests used to explore how particular aspect of a design functions. It is a way of demonstrating concept performance to acquire information necessary to decide if the design is suitable for further investigation [39]. An example of this test would be the strength testing of Torlon standoffs on REXIS (See Section 4.1).

Qualification tests are used to show that a design is adequate by testing a single unit. These tests should be done with a test article close to the flight design to gain confidence that the flight design meets requirements. Qualification tests are done when there is uncertainty in how the design will perform [39]. An example of qualification testing on REXIS is the Radiation Cover deployment system testing discussed in Section 3.3.

Acceptance tests are used to show that a particular product is adequate. Acceptance tests are used after a design is verified, but there may be uncertainty in the workmanship of the unit. These tests are performed on multiple of the same product to ensure each one meets development requirements [39]. Examples of acceptance tests on REXIS are the testing of each new Frangibolt actuator in an ambient environment prior to use in an environmental test so that the team knows the particular unit functions correctly (See Chapter 3 for a discussion on Frangibolt testing).

Protoflight tests are performed on the flight hardware to verify the workmanship, material quality, and structural integrity of the design. A protoflight unit is tested to qualification units and then flown [41]. These units are often built when there are not enough resources to build multiple flight units. The REXIS flight model is a protoflight unit, as such, the as-built flight model tested to qualification levels is the same model flown. Flight environmental vibration testing is an example of protoflight testing.

The last type of testing is analysis-validation testing. These test are performed when there is uncertainty in analyses. Data gathered from tests are compared against analyses. This comparison allows models to be correlated to test data so that analysis predictions of performance are more accurate [39]. EM vibration testing served as analysis-validation on REXIS so that finite element models could be correlated to test data (See Sections 4.5 and 4.6).

Categories of Qualification and Acceptance Testing

The large testing classes of qualification and acceptance testing can be broken down further. Different testing categories of these classes are environmental tests, controlled-load test, and functional tests. Environmental tests subject the test article to simulated missions environments to verify the system response against requirements. These test are particularly useful when testing mechanisms or fully integrated systems [39]. REXIS examples of environmental tests include vibration testing (Section 4.5) and thermal vacuum testing of the Radiation Cover (reference Chapter 3).

Controlled-load tests subject the test article to loads or thermal environments that cause the system to experience target accelerations loads, or temperatures. The goal is to verify the system response under specific circumstances [39]. Radiation Cover testing (Chapter 3) also fits in this category as the test units are tests at specific temperatures to verify functionality.

Lastly, functional tests enable system to establish baseline performance that is compared to a later functional test during or after environmental or controlled-load tests. These functional tests determine whether the system behaves as expected prior to stressing it structurally or thermally, and whether the environmental or controlled-load tests cause its nominal performance to change. These tests are particularly useful for mechanisms and electronics [39]. Frangibolt testing before and after REXIS thermal balance testing served as a functional test to inspect whether the actuator was damaged on account of the thermal environment experienced.

Some of the most common types of structural environmental tests are random vibration, acoustic, pyro-technic shock, thermal vacuum, and thermal cycling. Random vibration tests verify the strength and structural life of a system by introducing random vibrations through the system mechanical interface. Like random vibration, acoustic loading verifies strength and life by introducing random vibration but through acoustic pressure. Acoustic loading has the most impact on light-weight structures with large surface areas. Pyro-technic shock tests verify system resistance to high-frequency shock waves. These high-energy vibrations at frequencies up to 10,000 Hz are caused by separation explosives and can often damage electrical components. These tests are useful as analysis is often unable to accurately predict the effects of shock. Thermal balance testing verifies the system performance at hot and cold temperature conditions in a vacuum. This testing is necessary for mechanisms, electronics, and fully integrated systems. Lastly, thermal cycling verifies the life of a system or component through cyclic thermal loading. These tests verify a system's ability to be thermally stressed multiple times [39].

Different types of controlled-load tests can include static loading, sinusoidal vibration, cyclic loading, and pressure loading. Static tests apply constant loads to verify strengths of structures that wouldn't be adequately tested in random vibration. Testing would be performed on system with low natural frequencies or those primarily loaded by steady-state accelerations. Sinusoidal vibration tests are used to excite a structure's natural frequencies. This test takes place primarily with structures with low natural frequencies. Cyclic loading tests are used when structures are not adequately tested by random vibration or acoustic loading. As metallic structures with high natural frequencies are more susceptible to fatigue which occurs in random random, cyclic loading tests are useful for structures with low natural frequencies and with materials that are not well characterized. Pressure tests are useful as proof tests to provide confidence that pressure vessel walls do not have flaws and are able to withstand expected pressures [39]. Static loading is performed on the REXIS spectrometer during structural environmental testing. Sinusoidal testing, while performed during REXIS EM testing, will not be performed during the flight vibration testing because REXIS has not predicted frequencies below the 90 Hz threshold.

Industry Lessons from Testing

Beyond the fundamentals of designing, analyzing, and testing, space systems, a large amount of success is dependent on industry and institutional knowledge. Programs build off lessons learned from previous missions in order to prevent teams from making preventable mistakes. The Aerospace Testing Seminar is one forum that has been created to communicate and exchange knowledge for the improvement of aerospace testing. Topics of this conference range from technical methods for performing more effective tests to resource and personnel management.

Of the many lessons, some include using analysis and testing to drive the design of s space system. Baker advocates that system design flaws are responsible for high budgets and program delays, many of which could have been found with adequate testing. Instead, design flaws are often allowed to persist until they are discovered much later when changes to the design become much more costly. By performing numerous analyses and tests early in the development process, even on concepts that are never used, one is able to learn more about the design space and relationships between performance goals and concept design options. This early knowledge enables one to make more informed decisions and prevents critical design flaws from being discovered late in the project life when changed are significantly more costly and difficult to make as opposed to earlier in the project life. A combination of analysis and testing is also necessary such that analyses enables simulation of expensive and difficult to perform testing, while testing enables one to avoid complex detailed models. Baker provides several examples of systems that illustrate the importance of doing early testing and analysis to drive the system design [42].

Sarafin also espouses the use of testing as essential during the engineering process. Going beyond testing to meet requirements, he advocates for testing as verification and providing confidence that a system will perform as needed. This confidence is essential in a space program because problems will likely not be fixed after launch. Testing throughout a system's development is essential for successful projects. Preliminary development tests enable one to discover to discover information about some aspect of a system in a cost-effective manner when often there isn't enough knowledge to perform a well-informed analysis. These proactive methods of testing can help identify problems in a design before full system integrated testing in which one will be forced to address problems reactively. Sarafin discusses the need for verification testing to focus on the product's requirements and engineering principles, meaning how things behave and what can go wrong. Effective planning enables one to design tests that adequately examine how a system performs against its requirements. Ultimately, resources should not be sacrificed when it comes to performing testing. While high costs are easy to associate with performing testing due to the upfront investment, thorough testing will identify design flaws sooner and prevent more expensive late-game changes from occurring [43].

With testing and analysis as a key area of focus, it is important to understand how these tools can be used to more effectively evaluate and create a system. In certain cases, integrated testing may be easier, cheaper, and certainly more realistic than testing components individually. Of course, this aspect is dependent on the particular system, but engineers should be mindful when time and effort can be saved by combining multiple tests into one. Furthermore, systems may be able substitute many of their electrical components with mass mockups when performing tests used to identify structural response. This setup allows the creation of a representative structural test while keeping electronics available for work. During structural testing such as vibration testing, one must be sure not to overtest the system. Notching is used during vibration testing to prevent overtesting. At payload interfaces, a notch, or dip, will naturally exist in the acceleration spectral density (ASD) at the payload's first fixed base resonant frequency due high payloads structural impedances at that frequency. Therefore, this natural notch must be replicated during testing. Base input random vibration that does not include such a notch during testing will overtest the system [44].

Another notable observation is the need to retain test knowledge within an engineering organization or team. Test knowledge is more than just facts and data, and includes the test process experience. When test knowledge is lost, perhaps due to loss of team members, the survival or the group can be put at extreme risk. Individuals with test knowledge have the experience of how to correctly perform tests, what to avoid to prevent failures, and what factors indicate a potential failure or success. One can equate this testing knowledge and experience to reading about driving a car and actually driving a car. Knowledge retention is crucial to prevent mistakes and avoid repeating old ones, increase team utility and resourcefulness, avoid "single point failures" in individuals, and foster group team growth and understanding, among many other reasons. Patel observed the erosion in Raytheon's test knowledge base on account of various industry circumstances. He provides and discusses several solutions for test knowledge retention including element such as mentoring, technical seminars, focus teams, and formal training [45]. The REXIS team faces similar problems as its engineering team has a high turnover rate due to the limited duration of graduate degree programs.

Conferences such as the Aerospace Testing Seminar provide valuable, recent, and practical lessons to space system development and testing. Those listed above are just a few of the many topics available for reference and exploration. Many of the lessons and topics discussed were included because of their relevance to the REXIS project. Those topics discussed were experienced and evident throughout the structural engineering process of REXIS.

Chapter 3

Analysis and Testing of the REXIS Radiation Cover Deployment System

Analysis and testing of the Radiation Cover subassembly was one of REXIS's most highly focused areas. As the only moving part of REXIS during operation, the challenge of being able to function after two years of cold storage is one of the greatest concerns. Recall from Section 2.1, if the opening mechanism fails and the Radiation Cover does not open, REXIS is unable to acquire any science data from the asteroid. A failure to open will terminate the REXIS mission.

At the same time, the Radiation Cover's use of the Frangibolt is closely monitored because its incorrect functioning has the potential to release contaminates which may jeopardize the asteroid sample. This possibility will interfere with OSIRIS-REx Level 1 science goals of returning a pristine regolith sample of Bennu. For this reason, REXIS is closely scrutinized and much effort must be placed on ensuring the Radiation Cover correctly and safety operates.

With limited funding and personnel available, REXIS must carefully choose which areas of the instrument receive more effort and resources. The Radiation Cover is one area where the REXIS team is allocating substantial resources to reduce risk. Regardless of how good the rest of the instrument performs, if the Radiation Cover does not function properly, REXIS cannot collect science data. Likewise, it can also threaten OSIRIS-REx science goals. For these reasons, considerable effort is warranted in ensuring reliable and safe Radiation Cover performance.

There are several overarching focus areas when it comes to the use of the Frangibolt. The first is whether the Frangibolt actuator will be able to successfully operate at -20 °C after being stowed at that temperature for over two years. The second is preventing damage, both internal and external to REXIS, on account of a Frangibolt actuation. Lastly, the OSIRIS-REx project, and hence REXIS team, is concerned about the instrument's ability to prevent producing excessive contamination on account of the Frangibolt usage. This chapter discusses the efforts taken to understand the performance of the Frangibolt actuator in the REXIS expected thermal environment, different concerns regarding the potential harmful effects of the Frangibolt's use, and the Radiation Cover deployment system qualification test effort.

3.1 Frangibolt Testing and Characterization

The FD04 Frangibolt used by the REXIS Radiation Cover is a reusable SMA actuator. This actuator has an actuated or uncompressed length of 0.540". This is a reusable actuator but must be reset by compression to a pre-deployed length of 0.500". Power applied to this actuator causes the internal heater to warm the SMA until it reaches its transition temperature and fractures a weakened custom Ti bolt. The Frangibolt installation and reset procedure can be found in Appendix B.

Due to the minimal flight heritage of the FD04 Frangibolt, early efforts concentrated on ensuring the actuator could operate at expected REXIS operating temperatures. Frangibolt testing took place in both an ambient environment and in the SSL TVAC chamber. Actuations performed in the TVAC chamber allowed the team to simulate the cold vacuum environment REXIS will experience during flight. Nearly all TVAC actuations were performed on the Radiation Cover subassembly, as opposed to the full spectrometer, due to the volume limitations of the chamber. Figure 3-1 shows the installation of the Radiation Cover in the TVAC chamber with the Frangibolt installed. This particular test uses an Engineering Test Unit (ETU) model of the Radiation Cover, the model used prior to procurement of the EM.

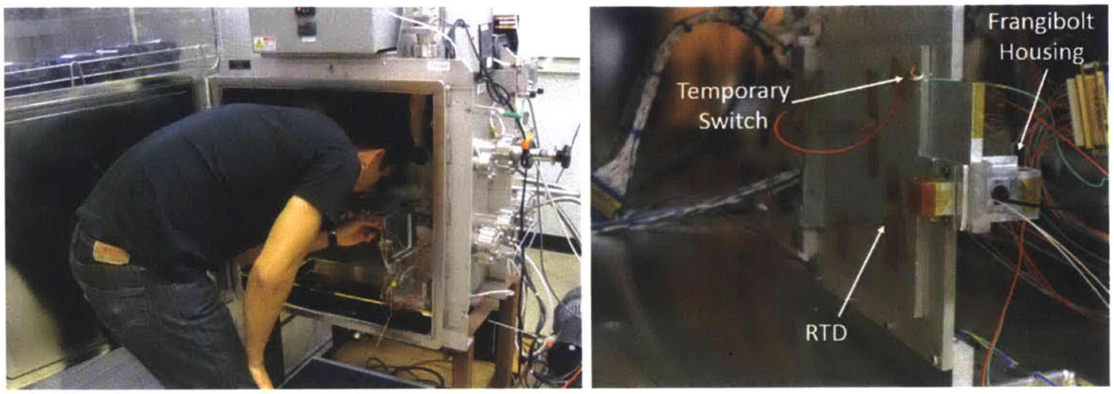


Figure 3-1: Installation of the Frangibolt in the SSL TVAC chamber (left) and the ETU Radiation Cover subassembly with the installed Frangibolt

One can note that the Radiation Cover is mounted such that it opens horizontally. This orientation is used so that the Radiation Cover opening is gravity-neutral, meaning that gravity does not play a role in the Radiation Cover motion. This aspect is important to simulate realistic impact forces as would be expected in a gravity-less environment. For TVAC testing, the subassembly mounts to the TVAC chamber cold plate which is conductively cooled by liquid nitrogen in order to reach desired low temperatures. RTDs are attached at various locations on the Cover to measure the Cover's temperature at the time of actuation. Additionally, a temporary switch used during TVAC testing completes a circuit when the door is closed and opens a circuit when the door opens. The switch signal is fed through the chamber to a multimeter which is monitored during testing in order to cut off Frangibolt power once the mechanism actuates. This switch was necessary because the TVAC chamber did not have any viewing ports by which one could tell when the Frangibolt had actuated.

Early Frangibolt testing focused on characterizing the performance of the Frangibolt while changing several variables. Different conditions included testing the Frangibolt at various temperatures, adjusting the power applied to the Frangibolt, and changing materials of the thermal isolation washers. The primary testing goal was to quantify how long power must be applied to actuate the Frangibolt given the particular testing conditions. The REXIS team used subsequent Frangibolt tests for performance verification tests and to qualify the Switch Washer and overall Radiation Cover deployment system (discussed in Section 3.3). The compiled graphical Frangibolt testing data from July 2013 through April 2015 is shown in Figure 3-2. All test at 23 ℃ are performed in an ambient environment, while all actuations performed below 23 ℃ are performed in a vacuum as well (at least 10^{-5} Torr). This same data is tabulated and can be referenced in Table A.5 of Appendix A (Note that a Switch Washer was not employed until actuation #28).

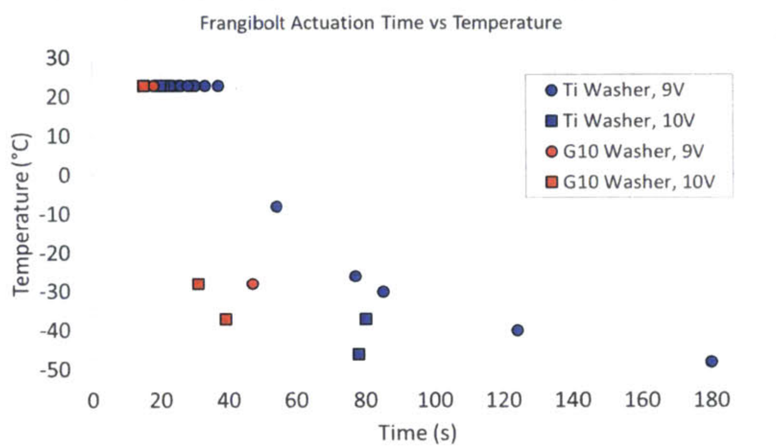


Figure 3-2: Time taken to actuate the Frangibolt under various testing conditions

The first major trend that can be noticed is that the time taken to actuate a Frangibolt increases as the testing temperature decreases. Considering the Frangibolt shape memory alloy expands at a particular transition temperature, the Frangibolt naturally takes longer to reach this temperature when starting at a lower temperature. Furthermore, by observing Fourier's Law of the one-dimensional rate of heat conduction [46]:

$$q''_x = -k\frac{dT}{dx} \tag{3.1}$$

One can see that q''_x, the heat flux or heat transfer rate in the X direction per unit area perpendicular to the direction of transfer, is proportional to $\frac{dT}{dx}$, the temperature gradient in this direction. Because the rate of conductive heat transfer is based on the temperature gradient between two surfaces, the Frangibolt loses heat 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.

Similarly, the use of G10 thermal isolation washers, having a lower thermal conductance than Ti washers [47], also reduced the actuation time. The G10 washers, compared to the Ti washers, better thermally isolate the actuator. With better thermal isolation, the heater can more efficiently warm the shape memory allow and enable it to reach its transition temperature sooner. Lastly, an increase in power applied to the Frangibolt decreases actuation time. This result again is expected; the more power put into the Frangibolt, the faster it reaches its actuation temperature. For most actuations, power was applied manually through an external power supply, although several integrated tests have been performed with the REXIS MEB and software controlling the power.

Along with understanding the Frangibolt's performance in different testing scenarios, there were certain concerns that warranted addressing. One of these large concerns was that the Frangibolt would lose preload on account of vibration during launch. The potential consequence of this event is that the Frangibolt may be unable to exert enough force to fracture the Ti bolt. To address this worry, a Frangibolt actuation was performed with zero installation preload. The mechanism performed successfully with no identifiable differences between this test and other actuations.

Another concern is whether the Radiation Cover wiring harness will place enough resistive torque on the Cover to hinder its opening. Especially considering this harness will remain at sub-freezing temperatures for the long duration cruise, it is unknown how the harness stiffness will change from its initial flexibility in an ambient environment. Resistance torque measurements using a mock harness were taken with a torque watch, leading to the proper sizing for the torsion springs to ensure a large positive torque margin. The equation used for torque margin (TM) is as follows:

$$TM = \frac{\tau_{available}}{S \sum \tau_{resistive}} - 1 \tag{3.2}$$

Where $\tau_{available}$ is the torque provided by the springs, $\tau_{resistive}$ are any torques that resist the motion of the Radiation Cover, and S is the safety factor. Measurements taken with a mock harness yielded a resistive torque value of 3.5 in-oz to bring the Radiation Cover from closed to 110 degree deployment angle. The combined available torque of the Radiation Cover springs when the Cover is fully deployed is 18.3 in-oz. Using a safety factor of 2 (specified by the OSIRIS-REx ERD), the Radiation Cover maintains a positive 1.6 TM. The Radiation Cover deployment including a mock harness was performed during the EM thermal balance test and there were no observable issues. Although the change in harness resistance due to the cold storage in unpredictable, the springs are sized to overpower the expected resistive torques.

3.2 Preventing Harmful Results of Frangibolt Actuations

There are three areas of concern when it comes to preventing harmful effects of the Frangibolt. The first is preventing damage to the actuator itself during actuations. The second is ensuring that a Frangibolt actuator does not harm other aspects of the REXIS instrument, specifically the sensitive CCDs. And lastly, the team seeks to minimize the risk outgassing during operation which would be harmful to the OSIRIS-REx science mission.

3.2.1 Damage to the Actuator

Throughout the entire history of Frangibolt testing, the REXIS team encountered a number of different issues and failures with Frangibolt actuators. A compiled view of the various types of failures experienced are shown in Figure 3-3.

While some of the shown issues have no impact on the Frangibolt performance, others render the mechanism unusable. The various types of tears and chips shown in "A", "B", and "C" of Figure 3-3 are small damages to the Frangibolt insulating jacket. Sources of damage have been attributed to the impact of the Frangibolt actuator with sharp or unforgiving features in the Frangibolt Housing. As mentioned previously, the actuation of the Frangibolt creates a powerful localized shock, causing the Frangibolt actuator to jump significantly within the Housing. The Frangibolt is believed to

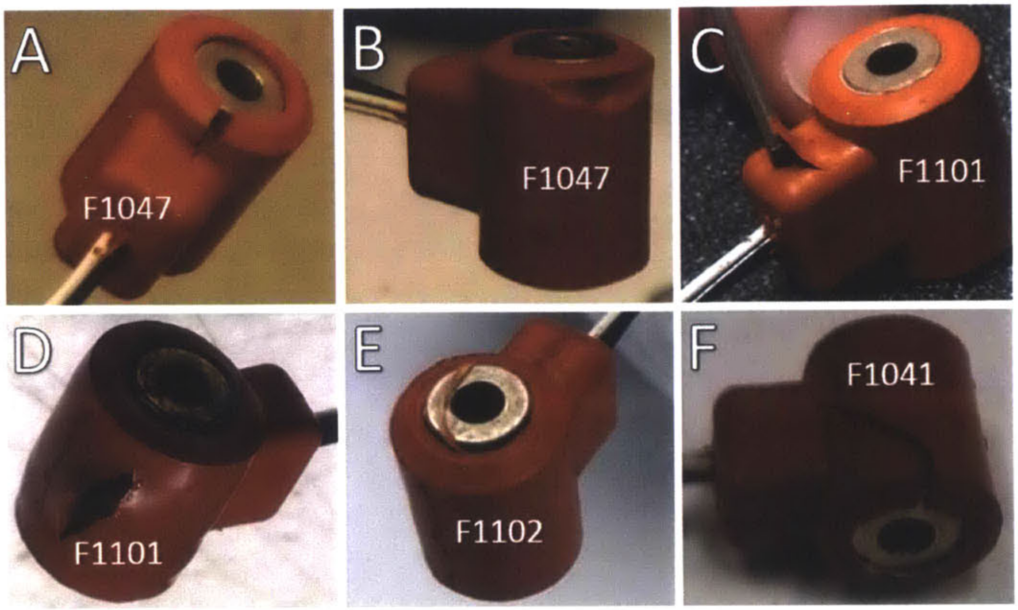


Figure 3-3: Compiled view of different types of Frangibolt issues and failures. The Frangibolt serial numbers are shown on each Frangibolt as well.

have impacted features on Frangibolt Housings such as sharp edges during actuation, causing the creation of these observable tears and gouges. Another potential source of damage was the Frangibolt Housing did not provide enough clearance for the exiting Frangibolt wires. When the mechanism jumped during actuation, the wires would get caught on the hole in the Frangibolt Housing and cause the actuator to twist, thereby impacting areas inside the Frangibolt Housing and causing damage. Experiences such as these led to iterative modifications of the Frangibolt Housing throughout testing such that threatening features have been removed. As an example, one modification is the extension of the wire hole in the EM Frangibolt Housing seen in Figure 3-4. This wire hole was originally designed as a circle. However, this small hole restricted wire movement, leading to the extension of the hole into the slot which is seen in the photo. The FM Frangibolt Housing uses a large oval hole as a result of these experiences (See figures in Section 2.2.4).

It should be noted that these small defects in the Frangibolt insulation jacket do not appear to affect the Frangibolt performance. Subsequent Frangibolt testing of these damaged units performed successfully, even in a cold, vacuum environment. However, these small defects can continue to grow with continued Frangibolt use

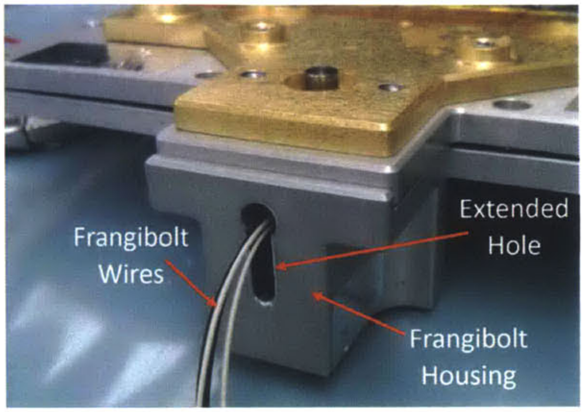


Figure 3-4: Shown here is the EM Frangibolt Housing. The wire hole was originally designed as a circular hole which can bee seen at the top of the slot. This slot was altered to extend downward to the slot shown in the photo.

until the insulation can become noticeably less effective or come off entirely. For this reason, it is desirable to prevent these defects from ever forming.

The Frangibolt shown in "D" of Figure 3-3 received power for too long after it had already actuated, thereby causing the internal heater to fry and burn the unit. This unit is no longer functional after this occurrence. Causes of this failure were created from being unable to detect the Radiation Cover deployment while performing a TVAC test. This test failure is discussed in more detail in Section 3.2.3 as it pertains to the development and implementation of the Radiation Cover Switch Washer.

Picture "E" of Figure 3-3 is an actuator presumed to be failed after taking it to temperatures below its survival limit. This particular unit was used during EM thermal balance testing. After a successful Radiation Cover deployment in the testing, the Radiation Cover heater was turned off, simulating the next phase in REXIS operations. This event caused the Frangibolt to drop to a temperature of -104 ℃ [5], well below the survival limit of the actuator [48]. When thermal balance testing was completed and the unit removed, there was no observable damage to the actuator. However, an ambient actuation performed to verify the Frangibolt's functionality yielded the result in photo "E". Although the Frangibolt did fire successfully in this ambient test, it appeared that the actuation resulted in some threading protruding from within the actuator. It was believed that this is part of the heater element that has debonded from the actuator due to the extreme cold temperatures experienced during thermal balance testing; the low test temperatures were believed to have broken the adhesive bonds holding the Frangibolt elements together. Representatives at TiNi Aerospace advised the REXIS team that this unit was broken and could not be used for further testing. At this point this particular unit was retired.

The final actuator, shown in "F" of Figure 3-3, can be seen with a large crack going along the actuator jacket. The cause of this particular failure is undetermined as it occurred during the Frangibolt reset procedure. Typically, this type of damage has been observed after a Frangibolt actuation, not during a reset. It is believed that there may have been a small, undetected tear or defect in the jacket that may have been present before the reset was performed due to previous Frangibolt actuations (this particular unit had been used in three previous actuations before this large crack was observed). The reset, through compression of the actuator, may have stressed and exacerbated this already existing defect. Two ambient actuations were successfully performed with this unit. However, after the second actuation, the crack worsened such that a large portion of the jacket could be peeled back off the jacket. This unit with the jacket being peeled back is shown in Figure 3-5.

Figure 3-5: Frangibolt S/N F1041 showing the insulating jacket being peeled back with a finger. This damage was first noticed after a Frangibolt reset and worsened during two subsequent actuations.

No further tests were performed with this unit after the defect had progressed to the state shown in Figure 3-5. It is possible that this actuator may still be functional for ambient environment tests, but is not usable during a TVAC test. The failure of this insulation would certainly affect the Frangibolt's functionality during a test performed at cold temperatures.

The REXIS team developed its testing procedures and hardware over time in order to avoid future occurrences of these defects and failures. Avoiding damaging this hardware is important considering the high cost and six-week lead time of the actuators. Failed actuators could put a considerable delay in the team's schedule. Therefore, it was imperative that future failures be prevented. While some defects are cosmetic in nature and do not affect the Frangibolt performance, others make the actuator unusable. The REXIS team found it incredibly important to document when and how these defects occur such that the sources of these problems can be traced. Such examinations have led to numerous modifications of the Frangibolt Housing which was identified to cause a number of damages to the actuators, and also helped the team identify the need for reliable detection methods for the Frangibolt actuation.

3.2.2 Damage to the CCDs

One of the biggest unknowns was whether use of the Frangibolt would damage the internal hardware, specifically the CCDs. When the Frangibolt breaks, a large kickoff force throws the Radiation Cover open as a reaction to the Ti bolt fracture. The bolt breaking and the Radiation Cover hard stop impact against the instrument both generate input shocks of magnitudes that are unknown. The team planned a Frangibolt actuation with a CCD in the spectrometer to test whether it survived an actuation. A fully functioning CCD engineering testing unit within an Al housing was mounted onto the instrument Torlon standoffs. This mounting replicated the stiffness of the is present in the existing DAM. Likewise, the Thermal Strap was attached underneath to completely mimic the structural path present on the real DAM and CCDs. The rest of the spectrometer was built up such that the entire unit was assembled, with the only difference being that a substitute test CCD was installed rather than the DAM. The entire spectrometer was rigidly mounted to a wall in a horizontal orientation to eliminate the effect gravity has on the Radiation Cover during opening. Figure 3-6 shows the final test configuration.

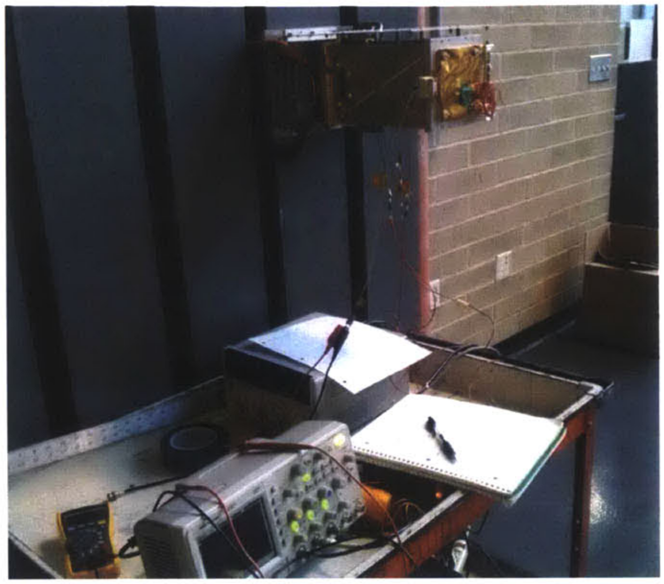


Figure 3-6: REXIS spectrometer horizontally mounted on a wall during a Frangibolt actuation. A functional CCD is present within to determine if the shock from the actuation and Cover deployment will damage the detector.

This instrument assembly and mounting orientation closely replicates the structural path present on the spacecraft. An external power supply was used to apply power to the Frangibolt. With a functional CCD inside REXIS, the Frangibolt was powered and actuated. In order to confirm the CCD survival, a functional test was performed before the Frangibolt shock test as well as after. Data was gathered with the CCD to confirm normal operations and to check for damage caused by broken bond wires, cracks in the silicon crystal, and faults in the traces. The pre-shock functional test established the quality of the CCD. The results of the post-shock functional CCD test were compared against those gathered in the pre-shock functionality test to ensure there were no discrepancies between the two. Evaluation of the CCD before and after the Frangibolt test showed no notable changes in CCD performance. This result helped alleviate the concern that the CCDs will be damaged during mission operations on account of the Radiation Cover deployment.

3.2.3 Damage to the Science Mission

As was mentioned previously and shown in Figure 3-1, all TVAC tests used a temporary switch in place to detect the Cover opening. The switch was composed of two wires, one attached to the Radiation Cover, the other to the Mask Frame. The wires touch and close a circuit when the Cover is closed and open the circuit when the Cover deployment pulls the wires apart. The resistance between these wires was measured outside of the chamber with a multimeter during the test. Deployment of the Radiation Cover breaks the circuit in the temporary switch, allowing observers to see a change in the measured resistance from a value near 0 Ω(closed circuit) to infinite impedance (open circuit). This switch was needed because there are no viewing ports in the TVAC chamber. Therefore, the switch allows the test operators to detect the Cover opening and cut power.

On one particular occasion while setting up the temperature sensors on the Radiation Cover, the wires were secured in such a way that the RTD wires obstructed the motion of the Radiation Cover during opening. When the Frangibolt test was performed, the temporary switch was monitored as normal. However, the typical time for actuation came and went with no signal from the switch. Without any indication that the Frangibolt had actuated, the mechanism was powered for roughly two minutes past its expected time of actuation before the test conductors eventually decided to cut power. Only until after the chamber was vented and opened was the cause of the failure identified. Although the Frangibolt had actuated, the door was held closed by the wires, preventing the switch from breaking. Figure 3-7 shows both the test setup after the chamber was open and the Frangibolt removed, as well as the burnt Frangibolt.

Noticing the collection of wires, it becomes apparent how some of the wires could wrap around the Radiation Cover in a manner dangerous for testing. The Frangibolt is not only entirely inoperable after this burning failure, but it also emits burnt particles of the silicone insulating jacket, the internal heater, and the internal adhesive which joins all the Frangibolt components together. This release of particles became a

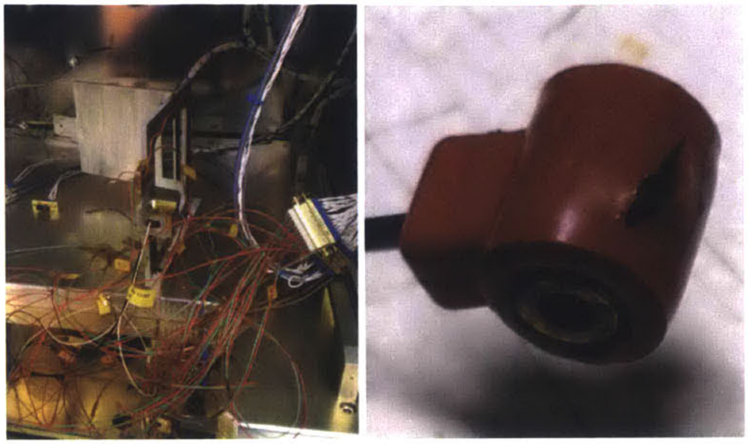


Figure 3-7: The test setup shown after the chamber has been vented and the Frangibolt is removed (left); The burnt Frangibolt due to excessive power appreciation is also shown (right)

significant concern for contamination reasons on OSIRIS-REx. After this test failure, a large part of the Radiation Cover focus shifted towards being able to reliably detect the Frangibolt actuation and cut power immediately.

Although the design for REXIS was to always have a limit switch to detect the Cover opening, this particular test illuminated the situation in which the Frangibolt actuated but the door remains closed. This scenario is possible, considering how the Radiation Cover's long-duration cold storage will impact the its ability to move freely is difficult to predict. The desire for a sensor that can detect the Frangibolt actuation rather than the Cover opening led to the development of a new SW04 Switch Washer from TiNi Aerospace. This Switch Washer is part of the flight Frangibolt stackup and can be seen on its own as well as its placement in the Frangibolt stackup while installed on the EM Radiation Cover subassembly in Figure 3-8.

This Switch Washer closes a circuit when compressed and opens a circuit when preload is lost. The REXIS software monitors the state of the Switch Washer and cuts power to the Frangibolt when the Switch Washer changes to an open state. As a newly developed unit, this particular SW04 Switch Washer model has no flight heritage. Substantial testing effort is required on the Switch Washer in order to qualify its use in the flight Radiation Cover deployment system.

Figure 3-8: TiNi SW04 Switch washer (left) and its placement in the Frangibolt stackup of the EM Radiation Cover subassembly

3.3 Radiation Cover Deployment System Qualification Testing

The REXIS team must be able to show the OSIRIS-REx project that the REXIS Radiation Cover deployment system will not jeopardize to the asteroid sample and OSIRIS-REx mission goals. The two high-level goals of the testing program are:

1. To ensure that the Frangibolt and Switch Washer operate successfully at the REXIS predicted hot and cold environments

2. Measure and verify that worst-case contamination production during a Frangibolt actuation is underneath the required threshold specified by the OSIRIS-REx team

The Radiation Cover deployment system qualification testing is divided into three phases. Each subsequent phase builds on the previous, integrating more components of a flight-like test setup.

3.3.1 Phase One: Switch Washer Characterization

Phase One is a characterization of the Switch Washer hardware. In this phase, experimentation on the Switch Washer gives the REXIS team an understanding of the signals to expect from compressing and uncompressing the Switch Washer. These signals are important to understand so that the REXIS flight software can be programed correctly. Other important goals of Phase One are to establish the required installation torques and bolt preload necessary to change the state of the Switch Washer from open to closed. This result is desired to understand whether the typical installation torque value of 50 in-oz used must be adjusted on account of the Switch Washer. Shown in Figure 3-9, a torque watch was used to measure the installation torque required to change the state of the Switch Washer from open to closed.

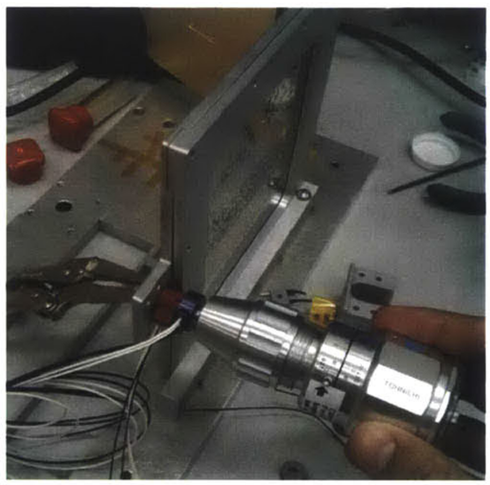


Figure 3-9: Required installation torque necessary to change state of Switch Washer measured

The Switch Washer is an open circuit when uncompressed and a closed circuit when compressed. A multimeter monitored the resistance of the Switch Washer as it was compressed in the Frangibolt stackup by incrementally increasing the installation torque on the stackup locknut. The installation torque was recorded the moment the Switch Washer changed from infinite to the closed circuit resistance of roughly 4.5 Ω. Torque measurements were taken for both the primary and secondary Switch Washer circuits. In addition, these measurements were taken both without and with Braycote 601EF applied to the threads of the Ti bolt. Table 3.1 shows the results from the installation torque measurements of the primary circuit with Braycote applied to the bolt threads. The additional measurements taken without Braycote and the secondary switch with Braycote can be referenced in Tables A.1 A.2 and A.3 of Appendix A.

Table 3.1: Primary Switch Washer installation torque measurements with Braycote on bolt threads

Trial	Torque (in-oz)
1	2.5
2	2.0
3	2.5
4	2.75
5	2.5

These installation torque measurements help determine whether the presence of the Switch Washer significantly alters the preload on the Ti bolt as compared to a stackup without the Switch Washer. In other words, the team performed these tests to see how much of the original preload is taken up by the Switch Washer as opposed to stressing the Ti bolt. While the FD04 Frangibolt is not particularly sensitive to preload, a loss of preload could potentially impair the Ti bolt's ability to fracture during a Frangibolt actuation; it is desired that the presence of the Switch Washer does little to alter the preload on the bolt when installed.

Comparing the results of Table 3.1, to the nominal installation torque of 50 in-oz, one can see that the presence of the Switch Washer in the Frangibolt stackup has little impact on the installation torque. Only about 5% of the specified installation torque is required to actually close the Switch Washer. Furthermore, considering that commercial torque wrenches can have torque errors of ±30% [49], these results show no indication that the REXIS team should alter the previously used installation torque of 50 in-oz when including the Switch Washer.

Next, separate preload measurements taken by compressing the Switch Washer on a scale showed the required preload necessary to change the Switch Washer from an open to closed state; the compressive force recorded from the scale at the transition point of the Switch Washer indicates the needed preload. This test helped indicate the actual force and preload necessary to close the switch. Again, these measurements can help show whether significant preload is taken by the Switch Washer or still mainly transferred to the Ti bolt. The results from the secondary circuit are shown in Table

3.2. Measurements from the primary circuit can be referenced in Table A.4.

Table 3.2: Secondary circuit measurements of load necessary to change the Switch Washer state from open to closed

Trial	Preload (lbf)
1	4.82
2	3.86
3	3.86
4	4.12

The maximum loads required to close the Switch Washer are significantly under the nominal 150 lbf preload created in the bolt during installation. Therefore it can be concluded that a negligible amount of preload is used to close the Switch Washer while the majority is transfered to the bolt. These tests completed Phase One of the Radiation Cover Deployment System Qualification program and confirmed that no change to the nominal Frangibolt installation torque is needed due to the inclusion of the Switch Washer in the Frangibolt stackup.

3.3.2 Phase Two: Ambient Radiation Cover Subsystem Testing

Ambient subsystem-level testing involves actuation of the Frangibolt in an ambient environment while monitoring the Switch Washer to verify its successful operation. The main purpose of Phase Two is to confirm the Switch Washer does not affect the nominal firing of the Frangibolt. These actuations took place using the EM Radiation Cover subassembly. Two tests were performed in order to verify that there were no discrepancies in behavior from one actuation to the next. This phase is considered complete because the Switch Washer successfully indicated the Cover opening with no anomalies.

The REXIS team performed two ambient Radiation Cover deployments using the Switch Washer included in the Frangibolt stackup. The two actuations of Phase Two correspond to actuations #28 and #29 of Table A.5. Power was supplied by the

EM MEB, and the REXIS software successfully cut power to the Frangibolt upon the actuation based on feedback from the Switch Washer. The test setup for these actuations is shown in Figure 3-10.

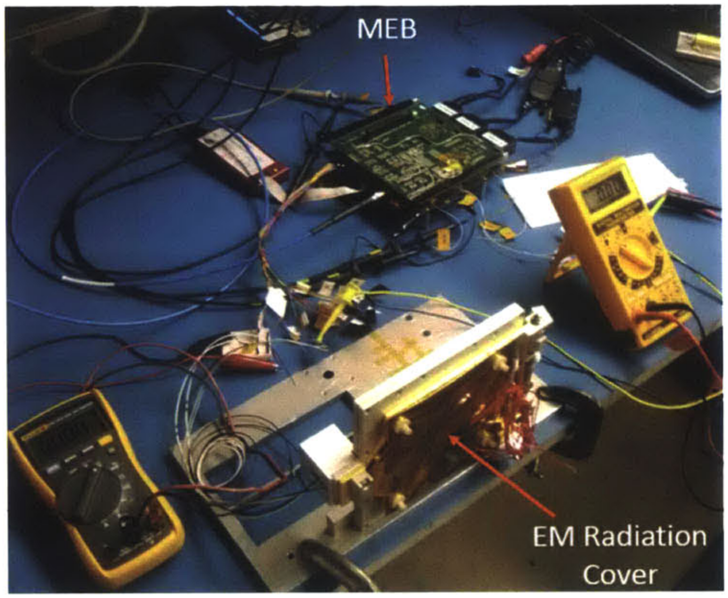


Figure 3-10: Test setup for Phase Two of Radiation Cover Deployment System testing. The REXIS MEB and software control power to the Frangibolt while monitoring the Switch Washer state.

In this test setup, the MEB is connected to the Frangibolt and Switch washer which are assembled and contained in the Frangibolt Housing of the Radiation Cover. Multimeters are in place to verify the supplied voltage and state of the Switch washer throughout the duration of the tests. The results of these tests can be referenced in tests #28 and #29 of Table A.5. As designed, the MEB and software correctly applied and cut power to the Frangibolt in accordance with successful performance of the Switch Washer. These results allowed the REXIS team to complete Phase Two of Radiation Cover Deployment System tests.

3.3.3 Phase Three-Hot: TVAC Radiation Cover Subsystem Testing in a Hot-Case Actuation

Phase Three deployment system testing is Radiation Cover deployment in the SSL TVAC chamber at the REXIS predicted hot and cold vacuum environments. This phase the final and most critical part of testing as it is representative of the environment expected in flight and yields the worst-case contamination levels of the Frangibolt actuation. Two actuations are being performed, one at the expected hot operational case of 30 ℃ and the cold operational case of -30 ℃. These tests allow the Radiation Cover hardware to be tested at their expected operational temperature extremes.

The test setup is as close to flight as possible. The flight model Radiation Cover subassembly is used including the flight harnesses. The EM MEB uses flight software to control power to the Frangibolt. In a similar setup used for TVAC testing that was discussed in Section 3.1, RTDs are placed at various locations around on the Radiation Cover to measure its temperature throughout the test. The recommended placement of these RTDs is shown in Figure 3-11.

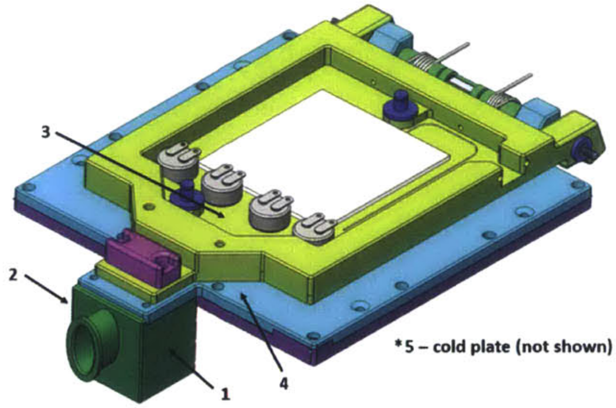


Figure 3-11: Recommended locations of RTD placement

With all TVAC tests, the Frangibolt Housing RTD readings govern the actuation temperature. As no temperature sensor for the actual Frangibolt exists, the readings from the Frangibolt Housing determine the expected actuation times for the Frangibolt. Additionally, along with the Switch Washer, the temporary switch discussed in Section 3.1 is included as a backup signal to help determine the Frangibolt actuation.

The hot-case actuation cycles the Frangibolt deployment system beyond predicted temperature extremes. This test verifies the hardware performance after being exposed to these temperates, and in particular tests the hardware deployment when at the expected hot case. The hot-case actuation takes place at 30 ℃. Although the hot-case operational prediction is 8 °C, 30 °C is chosen for the test to be sufficiently conservative and perform a test that is above room temperature; this value is well above the predicted hot operational prediction with margin. To thermally stress the Radiation Cover subassembly, the unit is first cycled cold, from ambient temperature to -40 °C, which is 15 °C below the worst-case coldest temperature REXIS is predicted to experience, which occurs during a 30 minute heater fault case (30 minutes of inadvertent loss of Radiation Cover heater power). The unit is then cycled to the REXIS hot operational limit of 30 °C at which point the deployment takes place. Throughout the temperature cycling, the state of the Switch Washer is monitored to ensure it remains closed. For this actuation, power to the Frangibolt is cut when a door-opening signal is received from the Switch Washer or the temporary switch; including both of these switches adds redundancy and reduces the risk of damaging Frangibolt hardware. The MEB cuts power when the Switch Washer opens, but operators are standing by to cut power in the event the MEB fails to do so. The hot-case actuation is considered successful if the Switch Washer correctly indicates the Radiation Cover deployment.

3.3.4 Phase Three-Cold: TVAC Radiation Cover Subsystem Testing in a Cold-Case Actuation

The second actuation of Phase Three is a cold-case actuation where the Frangibolt is actuated beyond the predicted cold temperature limits. This test in particular is meant to capture the worst-case contamination the Frangibolt will generate during flight. These contamination values are provided to the OSIRIS-REx project team to determine whether the values are acceptable. The reason this test is a worst - case contamination test is that Frangibolt power is cut based off expiration of the Frangibolt Timer rather than the Switch Washer. This test simulates the scenario in which the Switch Washer fails to indicate the Frangibolt actuation and power is applied beyond the actual deployment of the Frangibolt.

Th cold-case actuation takes place at -30 °C. This value is 10 °C below the REXIS cold operational project requirement (-20 °C) and 15 °C below the cold operational prediction of -15 °C. The Switch Washer is not expected to reach this temperature during flight, but this test shows successful operation outside of flight predictions. The test first cycles the hardware to the hot operational limit of 30 °C, then cycles down to -40 °C (15 °C below the 30 minute heater fault case prediction of -25 °C). The deployment system is then warmed from -40 °C to -30 °C at which temperature the Frangibolt is actuated. No issues are expected from operating at these temperatures as they are all within the Switch Washer vendor-specified operational limits.

Unlike the hot-case actuation, the Switch Washer is not being used to cut power to the Frangibolt. Instead, power is cut when the Frangibolt Timer expiries. The Switch Washer is still in place and monitored to verify it functions at the experienced environment, but does not govern the power application. Instead, the MEB is wired to a closed circuit instead of the Switch Washer. In this way, the Frangibolt deployment and changing of the Switch Washer state does not cause the MEB to cut power. The MEB continues to think that the Switch Washer is closed, regardless of its performance, and cuts power upon the Frangibolt Timer expiration. A Thermoelectric Quartz Crystal Microbalance (TQCM) system is in place to measure Frangibolt outgassing data during this cold-case actuation. Allowing the Frangibolt Timer to expire exposes the Frangibolt to the worst-case power application scenario in that excessive power is applied due to a Switch Washer failure. This TQCM setup measures worst-case contamination levels and these measurements verify whether the REXIS Radiation Cover deployment system meets OSIRIS-REx contamination requirements.

3.4 Technical Lessons From Frangibolt Use

This section summarizes the technical lessons learned from using the Frangibolt in the application discussed through this chapter. Recall from Section 3.1, there are several main performance trends when using the Frangibolt actuator. First, it was noticed that the Frangibolt performance is very closely coupled with the thermal path of the application. The time until Frangibolt actuation increases as the environmental temperature decreases. When the Frangibolt starts at a colder temperature, it naturally takes longer to reach its actuation temperature. Likewise, using thermally isolating washers with lower conductivities (for example, G10 verses Ti) decreases the time until actuation. Washers with better isolation prevent wasteful heat loss to the surroundings and allow the Frangibolt to heat more efficiently. Additionally, increasing the power applied to the Frangibolt decreases the time to actuation. This result is logical as more power to the Frangibolt heater will naturally cause it to heat the SMA faster [28].

Another important lesson learned was that power applied to the Frangibolt after its actuation will quickly cause it to overheat. Once the actuator deploys, there is no longer a thermal connection to the structure, meaning heat cannot be lost to the rest of the structural system. Continued power in this state will rapidly burn the internal Frangibolt heater [28]. For testing, it is desirable to prevent these failures as replacements for the actuator are costly and time-consuming. During operation, the OSIRIS-REx mission dictates that releasable contaminates are a danger to science goals. Other programs that rely on optics could also be hindered by the release of particulate on account of a Frangibolt burning. For this reason, reliable feedback must be provided to cut power quickly after actuation. Furthermore, feedback signals should detect the Frangibolt actuation, and not its secondary effects.

Lastly, testing has shown that there is a significant kickoff force due to the Ti bolt fracture. This reaction force causes the Frangibolt actuator to jump and impact the surfaces around it. During these impacts, the insulating jacket of the Frangibolt can become damaged [28]. While many of these damages do not appear to affect Frangibolt performance, continued use can make the damages more pronounced until performance degrades. For this reason, care must be taken to ensure the designed actuator housing is free of features that can be harmful to the actuator if impacted.

Chapter 4

Design, Analysis, and Test of the REXIS Structure

This chapter examines the structural engineering process taken on REXIS with a focus on the major structural element of the REXIS TILs. As discussed in Section 2.1, the REXIS detectors must meet the low temperature requirement of below -60 °C. REXIS uses a passive thermal system to achieve these low temperatures during the mission. The implementation of the TILs are both a critical thermal and structural interface around which much of the structural engineering process focuses. The discussion focuses on the aspects of the design which are relevant to and largely dominated by the two major mission-specific constraints imposed on REXIS. Furthermore, the chapter explains the use of analysis, testing, and hardware interaction throughout the REXIS development to highlight how these various tools complement one another in the REXIS structural design evolution.

The REXIS engineering team faces not only the typical challenges of developing a space flight project and the unique mission challenged, but must do so on a limited budget. Because REXIS is a student instrument, the REXIS team must develop and construct this system under limited resources, which includes funding, equipment, facilities, and personnel. To develop a fully functional instrument under the given requirements, all resources must be used with maximum efficiency. This need is addressed largely through the division and balance between analysis and testing.

Limited resources ensure that complete or extensive analysis and testing is not always possible; engineers must strike a balance between the two in order to achieve the largest return on the effort invested.

Another essential method utilized in development is the interaction with hardware for accessing the design. The REXIS Engineering Model (EM) is the first complete model of REXIS procured. Extensive use of this model proved to be a valuable tool to evaluate the existing system design and develop modifications implemented into the final Flight Model (FM) design.

This chapter discusses the steps taken along the structural development of REXIS from the design and procurement of the EM through the design of the FM. The discussion focuses on the aspects of the design which are relevant to and largely dominated by the two major mission constraints imposed on REXIS. Furthermore, the chapter explains the use of analysis, testing, and hardware interaction throughout the REXIS development to highlight how these various tools complement one another in the REXIS structural design evolution.

4.1 Early Stages of the Thermal Isolation Layers

Driving the cold REXIS temperatures during the mission is the need to keep the CCD detectors below their operational requirement temperature of -60 C. As seen in Section 2.2.1, this requirement is challenging due to the DAM's close proximity to the warm EBox, thereby necessitating the use of an effective thermal system to keep the CCD detectors below their operational requirement temperature. One major element of this thermal system are the TILs, which separate the top of the EBox and the DAM. Both TIL layers have a low thermal conductivity that prevents heat from conductively transferring to the CCDs from the warm EBox. The TILs are both a significant thermal and structural interface, thereby warranting considerable attention to develop a viable design.

In the fall of 2013, the Tower TIL consisted of five Torlon 5030 standoffs while the DAM TIL consisted of four Torlon standoffs. Each standoff was a solid 1.06" long Torlon cylinder with a diameter of 0.39". Each standoff was tapped to accept an #8-32 fastener directly into the standoff. The Tower TIL in particular is a major structural interface due to the significant proportion of REXIS mass that it supports. This early design used Torlon in a main structural capacity typically not used with low strength materials.

Lack of significant data on the structural characteristics and performance of Torlon led to the need to integrate early testing to access the validity of Torlon standoffs for this important structural interface; this interface supports some of the largest stresses experienced by REXIS as will be discussed in Section 4.3. Torlon standoff development testing consisted of pullout and shear Instron tests to determine the failure load and failure mode for these standoffs. Several runs were performed to generate the value for the tested failure load. Expected predicted loads at each TIL were found by calculating worst-case reaction axial and shear forces through a variety of finite element method (FEM) analyses (reference section 4.3). Static loading, random vibration, and thermal distortion analyses all generated predicted reaction forces due to the different loading cases. The most conservative result of these analyses was compared to the tested Instron results to generate the design margins of safety (MS), using the following MS equation:

$$MS = \frac{\sigma_{allowable}}{(FS)\sigma_{design}} - 1 \tag{4.1}$$

Where $\sigma_{allowable}$ is the limit or failure stress, σ_{design} is the predicted stress the system will experience, and FS is the factor of safety. Note this MS equation is also applicable with loads, as opposed to stresses. Table 4.1 shows the minimum tests failure loads from strength testing, the maximum predicted FE loads, and the margins of safety generated.

Despite what appeared to be significantly high MS calculated from the predicted and tests loads, large uncertainty surrounded the use of Torlon for the Tower TIL. One key factor contributing to this uncertainty was the failure mode observed during testing. Figure 4-1 shows the failure mode of thread pull-out from the standoff.

Table 4.1: Minimum failure loads of Torlon standoffs during strength development testing compared against maximum FEA predicted loads [6]

	Failure Load (lbf)	FEA Predicted Load (lbf)	Margin of Safety
Tension	843	113	+4.0
Shear	375	44	+4.7

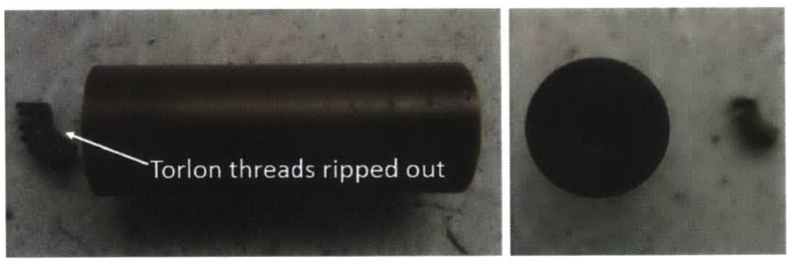


Figure 4-1: Torlon standoff after being tested on the Instron pull-out test. Two views of the same tested standoff show the failure mode in which the internal Torlon threads are ripped out of the standoff

This failure mode is consistent between both the tensile and shear test cases. For this reason, changes to the structural body of the standoff does little to strengthen and prevent a failure in the threads. Weakness of the threads brought concerns regarding how Torlon threading would behave under the fatigue of vibration loading and how yielding of the threads impacts future loading ability. Other concerns included a lack in confidence in the reliability of the testing results due to the limited statistical data, an unknown ability for Torlon to maintain bolt preload, an unknown installation torque given the thread weakness, and the risk of thread damage due to multiple assembly and disassembly. Furthermore, because the Tower TIL is the main structural interface between the EBox and the rest of the instrument, reliable performance at in these standoffs is crucial. Overall, the known weakness of the threads and the overwhelming uncertainty surrounding the Torlon performance eventually led the team to redesign the Tower TIL despite what first appeared as promising results.

4.2 Redesign of the Thermal Isolation Layer

With a number of significant concerns and the limited ability to exhaustively test all possible test scenarios, the REXIS engineering team deemed it necessary to pursue a different option for the Tower TIL. The desire to avoid major redesigns in the event of a vibration test failure also supplemented these concerns. At the time, the REXIS team was preparing for its Critical Design Review (CDR) and the procurement of its EM, which would be closely followed by EM vibration testing. Failure in a post-CDR vibration test would cause a severe and costly hindrance to the team. The risk of this vibration failure and the potential consequences were far more dire to REXIS than the guaranteed cost and effort needed for a TIL redesign. An active, rather than reactive change to pursue a more robust TIL design seemed prudent.

The key design trade was finding a balance between a high strength material and one with low thermal conductivity. Unfortunately, many reliable and well characterized structural materials such as metals have high thermal conductivities. In comparison to the high thermal resistance provided by Torlon, switching to a metal such as aluminum or steel would greatly compromise the CCD temperature and hence performance.

Titanium was identified as a viable candidate due to its high strength but relatively low thermal conductivity in comparison to most metals. The thermal resistance (R_T) due to conduction across the TIL interface is summarized as [46]:

$$R_T = \frac{L}{kA} \tag{4.2}$$

Where L is the length of the standoff, k is the thermal conductivity of the material, and A is the cross-sectional area of the standoff. Maximizing the length of the standoff increases the thermal conductivity but increases the bending moment of the standoff and hence bending stresses. Likewise, minimizing the cross sectional area of the standoff improves thermal performance but reduces the standoff strength.

Close collaboration between the structural and thermal system engineers ensued to develop a TIL design that was structurally sound while maintaining system temperature requirements. Analysis using structural and thermal models proved valuable for this phase as various iterations of designs could rapidly be explored, avoiding the need to test intermediate designs. Various designs were evaluated until the current TIL was selected. The selected TIL from the redesign uses a Tower TIL of four Ti standoffs, and an unchanged DAM TIL of four Torlon standoffs. Each Ti standoff consists of a hollow cylindrical post with a tri-flange design (See Figure 4-2) to withstand loading in multiple directions. The design focuses on minimizing the cross-sectional area of the cylinder to decrease the thermal conductivity but maintain sufficient strength in the design to withstand expected loads.

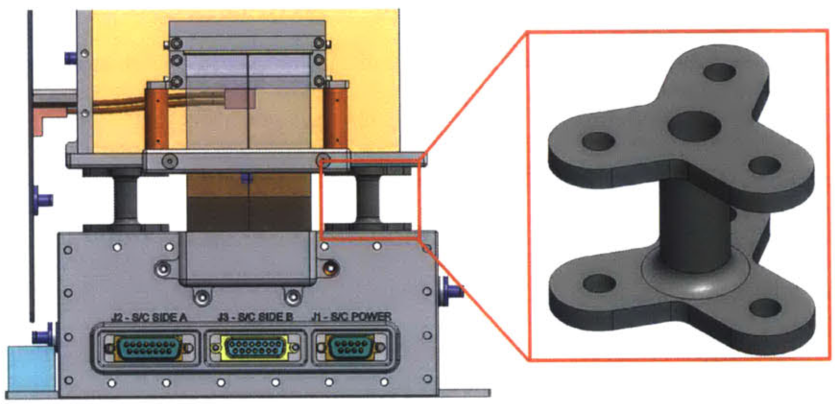


Figure 4-2: Ti Standoff used in the Tower TIL

This new Tower TIL design maintains positive margins of safety against analyzed loading cases. Likewise, the use of a well-known material eliminates the uncertainties associated with fatigue and preload capabilities. For this reason, the REXIS team can feel confident in their design and analysis results and can avoid performing intermediate testing on these standoffs as was done with the Torlon standoffs. The DAM TIL, which suspends only the DAM as opposed to the entire Tower, was preserved as the original Torlon design. Predicted loads at these joints are sufficiently low to significantly reduce the various uncertainties and risks previously discussed.

During the evaluation of various structural standoff designs, finite element analysis (FEA) is used to predict expected operational loads which are applied in stress and MS calculations. Section 4.3 discusses the methods and analyses used to calculate the expected REXIS forces for all standoffs from the initial Torlon standoff design to the final Ti design.

4.3 The REXIS CDR Finite Element Analysis

The foundation for all REXIS structural analysis is the FEM model. FEA is a crucial tool for structural analysis as it allows the engineer to subject their system to environments to which it is difficult to test. These computerized models of REXIS can then be queried to examine the test results, whether they be particular forces, stresses, displacements, or other desired quantities. FEA in many cases saves time and effort in the design process. REXIS FEA pre- and post-processing is done with Femap while the analysis is performed with Nastran.

Structural testing, while possible though random vibration and sine burst testing, is time-intensive and requires the procurement of the system, which is certainly a non-trivial task. Additionally, a failure during these major environmental tests causes huge cost and schedule set-backs for the project. While testing was required with the Torlon standoffs because their performance was uncertain, the same is not true with the Ti design. These computer analyses enable one to gain confidence in how a design will perform. Therefore testing is conducted to validate the expected performance, rather than explore how the design performs. Other times, the use of testing for particular requirements is not feasible. One example is the REXIS requirement to maintain detector alignment, which can shift as a result of thermal deformation. The only way this requirement can be verified is through analysis as these thermal deformations are not observable during testing.

Specifically regarding the TIL design, finite element (FE) modeling is employed to perform static loading analysis, thermal distortion analysis, modal analysis, and random vibration analysis. These analyses give the REXIS team confidence in the final chosen design and allows them to proceed towards EM hardware procurement and eventually EM environmental testing. The following sections describe each analysis performed and the result of each analysis case as it pertains to the TIL.

4.3.1 Static Loading Analysis

Static analysis is used as a bounding case for accelerations experienced during launch. A Mass Acceleration Curve (MAC) dictates an upper bound acceleration level for all components of a given mass and will typically be the most conservative analysis case to which one designs. The MAC is derived from analytical and flight data and includes the vibrational acceleration effects due to both transient events such as liftoff and staging, and mechanically transmitted random vibration accelerations [4] [31]. This curve is dependent on the given launch vehicle. Shown in Figure 4-3 is a typical MAC for a launch vehicle (note that this MAC was not used for REXIS).

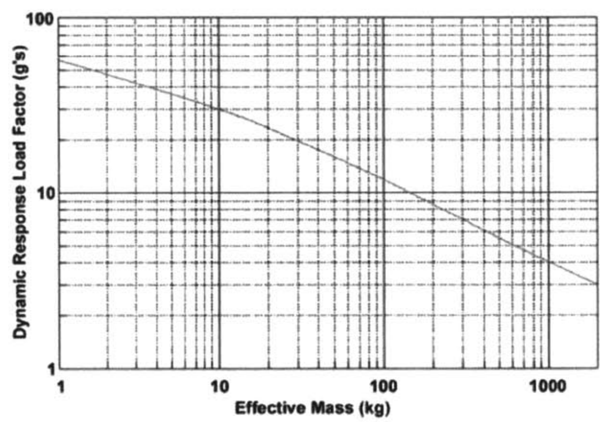


Figure 4-3: Typical Mass Acceleration Curve [4]

REXIS is analyzed to 40 g's in accordance with its NTE mass of 7.5 kg and the MAC for the Atlas V launch vehicle used in this mission. This acceleration of 40 g's is applied to the REXIS instrument separately in the mutually perpendicular X, Y, and Z axes. Post-processing of the static acceleration loading case helps to identify the weak points of the REXIS structure. A contour plot, shown in Figure 4-4, of the REXIS FEM model subjected to the MAC loading in the X axis helps one quickly identify areas of high stress that require further investigation. This figure shows three views to provide a better view of the instrument at various angles.

One can see that the highest stresses occur at the base of the Tower TIL standoffs and the Baseplate bolt holes. Logically, this result makes sense. With the base of the instrument constrained to the spacecraft, the structure acts, in a simplified manner, as

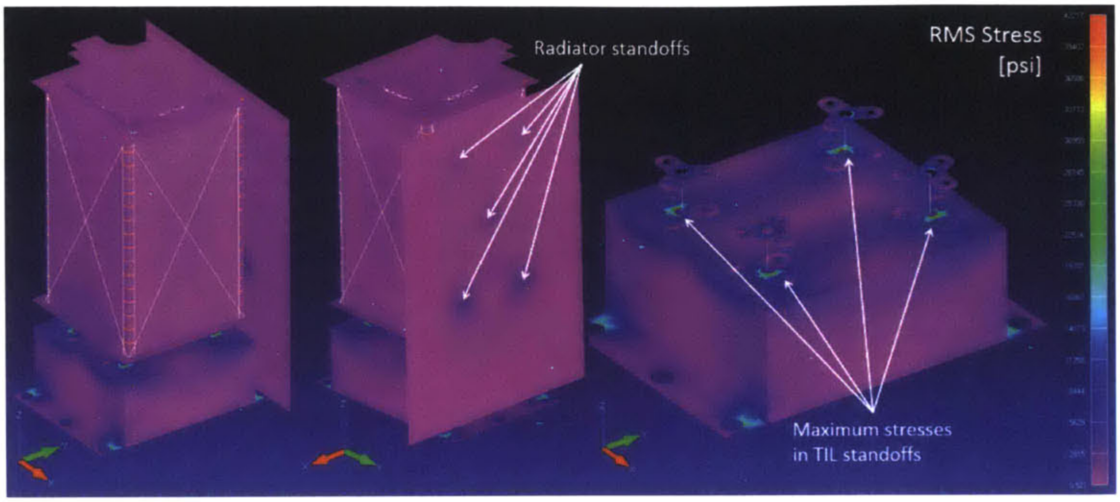


Figure 4-4: Stress result of the MAC loading case analysis in the X axis

a cantilevered beam. The bending stresses due to this loading are concentrated at the Baseplate holes and at the four Tower TIL standoffs. Considering the proportionally significant mass the Tower TIL must support and the small cross-sectional area that supports this mass, it is expected that the Ti standoffs experience the largest stresses.

Knowledge of these-high stress areas allowed detailed analyses to be tailored based on the specific failure location. Further investigation of these weak areas was performed by extracting the predicted loads from the MAC loading cases out of the model. The forces extracted are reaction forces in the X, Y, and Z axes in each standoff for each loading case. Axial and shear reaction forces were calculated and used in simplified bending axial stress equations to determine margins of safety for the various structural elements.

Many different failure modes were analyzed to verify that positive structural margins were met across all failure modes. The limiting failure mode, is due to a combined loading case of bending and axial stresses. FEA MAC loading analysis yielded maximum predicted Ti standoff reaction forces of 92 lbf in shear and 201 lbf loaded axially occurring at the end of the standoff.

Treated as a cantilevered beam with these forces applied to the end, the standoff was analyzed; recall that the main body of the standoff is a hollow cylindrical post. The bending stress ($\sigma_{bending}$) for the beam is as follows [34]:

$$\sigma_{bending} = \frac{My}{I} \tag{4.3}$$

Where

$$M = F_{shear}L \tag{4.4}$$

$$I = \frac{\pi}{64}(d_o^4 - d_i^4) \tag{4.5}$$

M is the bending moment, y is the distance from the standoff's neutral axis of the location analyzed, I is the standoff's second moment of inertia, F_{shear} is the reaction shear force on the standoff, L is the standoff length, d_o is the outer diameter of the standoff, and d_i is its inner diameter.

The axial stress (σ_{axial}) of the standoff is as follows [34]:

$$\sigma_{axial} = \frac{F_{axial}}{A} \tag{4.6}$$

Where

$$A = \pi(d_o^2 - d_i^2) \tag{4.7}$$

F_{axial} is the reaction axial force in the standoff and A is the cross-sectional area of the standoff. Equations 4.3 and 4.6 form the basis by which the TIL standoff is analyzed. Output forces from each type of analysis performed is fed into these equations to verify positive MS are met with each analysis case.

4.3.2 Thermal Distortion Analysis

Thermal distortion analysis is needed on REXIS for two reasons. The first being that thermal distortion stresses are of concern as a result of the dissimilar materials used in the TIL. The second reason is that the detectors must maintain tight alignment requirements despite the thermal deformations that occurs as a result of large temperature gradient in the TIL. Thermal FEA analysis allows the prediction of REXIS's performance under varying thermal environments without the need for testing.

During the mission, REXIS will experience different thermal environments. Analysis is performed at both the bounding hot and cold cases predicted during the mission. Survival at these bounding cases will ensure that REXIS is not at risk of thermal distortion failures, either structural or alignment-related, at any point during the mission. The cold survival cruise case occurs after REXIS has operated and is the bounding cold environment. The hot case occurs during asteroid science observations [50].

Thermal models of REXIS produced in Thermal Desktop predict instrument temperatures at numerous locations and at various instances in the mission. The thermal model predictions for the Orbit Phase B mission hot case are shown in Figure 4-5. The total instrument is shown as well as a close-up view of the EBox and DAM interface.

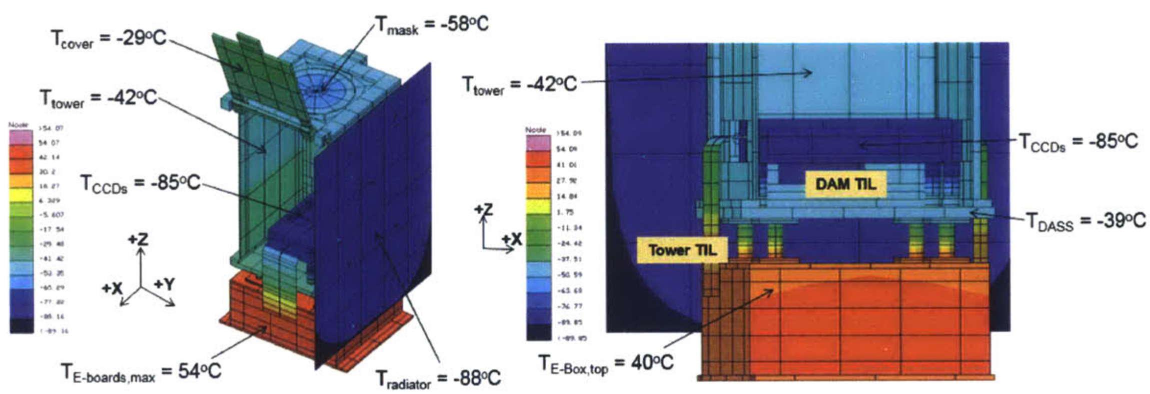


Figure 4-5: Thermal Desktop temperature predictions during Orbit Phase B Hot Case [5]

This figure depicts the drastic temperature gradient that is present on account of the low CCD operating temperature requirement. The temperature gradient across the Tower TIL is approximately 80 °C while the gradient across the DAM TIL is approximately 45 °C. These gradients translate into thermal deformations and stresses at the interfaces due to thermal expansion and contraction. Not only are temperatures different across this interface, but each material's coefficient of thermal expansion (CTE) is different. Torlon, Ti, and Al, the three materials present in the TIL, all have different coefficients of thermal expansion, meaning that each material will expand or contract by a different magnitude than the other materials for a given temperature. These large temperature gradients and CTE mismatches lead to thermal distortion of the instrument, which inputs stresses on the materials and can shift the CCDs out of alignment.

Temperature output predictions from the REXIS thermal model become inputs to the CTE mismatch FEA. Femap is used to calculate the forces at interfaces due to the thermal deformations across the instrument components. These forces are again compiled into worst case tensile and shear forces which are used with bending and axial stress calculations on the standoff and bolt interfaces to determine the safety margins. Figure 4-6 is a stress contour map of REXIS during due to the temperatures predicted in the Orbit Phase B Hot Case.

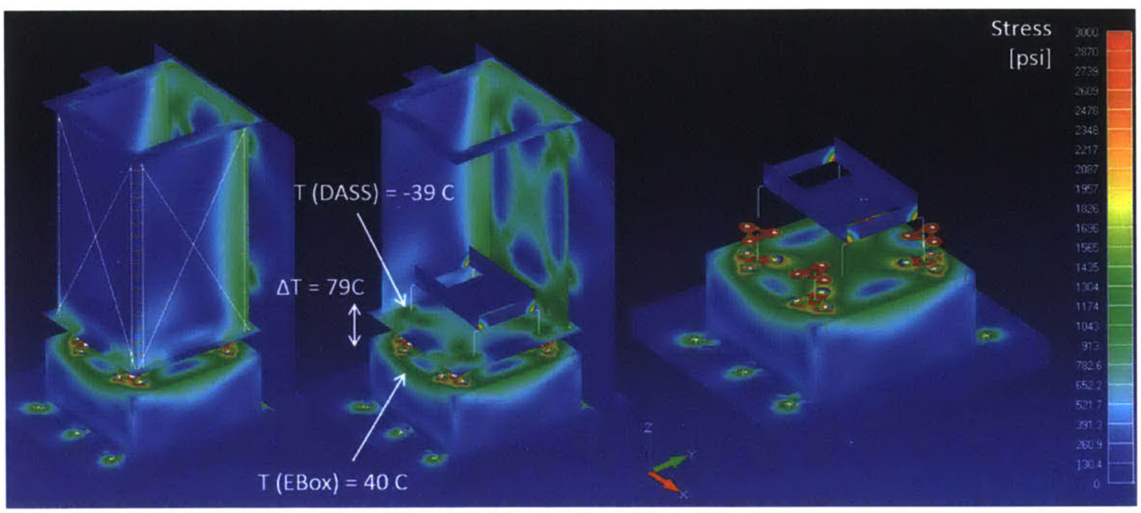


Figure 4-6: Stress result of the CTE mismatch loading case analysis

The calculated maximum tensile and shear forces at the standoff interfaces were lower than what was predicted on account of the MAC loading case. As REXIS is designed conservatively to withstand the worst case scenario, a positive margin of safety against the MAC loading case ensures that REXIS is also able to withstand the thermal deformation loads expected to occur.

Querying the model from the thermal distortion analysis for node displacement allowed REXIS to evaluate the spectrometer's ability to maintain alignment. These displacements, as a result of material contraction and expansion, can be converted into translational and rotational shifts in the CCD detector plane. Examination of these displacements verified that the expected thermal environment and consequential structural distortions do not put the CCDs outside of their alignment requirements for the mission.

4.3.3 Modal Analysis

The modal analysis is an important step in the REXIS analysis phase as its results indicate what natural frequencies stimulate the system. Additionally, the results of the analysis dictate testing requirements to fulfill, specifically whether a sinusoidal vibration test is necessary. The OSIRIS-REx Environmental Requirements Document (ERD) specifies that any instrument with a first mode natural frequency below 90 Hz shall perform a sinusoidal vibration test. OSIRIS-REx puts a lower bound on instrument modes because lower natural frequencies can couple with the sower modes of large spacecraft components and cause structural failures. Any opportunity to avoid incurring more required testing is beneficial from a project management standpoint due to minimal REXIS funds and schedule. Naturally, no project can afford to enter vibration testing without an idea and expectation for system modes because the consequence of failure can be devastating. For this reason, the modal analysis is a crucial element throughout the system design process. This analysis allows a team to predict a system's modes so that they can make changes to the design's stiffness if modes need to be raised. The REXIS design is constantly analyzed as hardware decisions are made to inspect how a change impacts the REXIS natural frequencies.

The model constraints are those due to the Baseplate mounting bolts to the spacecraft. These bolt locations are constrained in all degrees of freedom except rotation about the Z axis. As with all structural analyses performed prior to CDR and prior to any EM vibration testing, models are constructed using the NTE mass. This NTE mass helps provide conservative predictions. Estimations for the component masses were done using CAD estimations as well as measured fastener masses.

Once the model is constructed with the current best estimate of mass appropriately applied to each component, the extra mass needed to bring the instrument mass to the NTE mass is allocated to the model. This extra mass is smeared across the Radiation Cover. Doing so causes REXIS to act more like a pendulum and results in more conservative natural frequency predictions. If REXIS meets all natural frequency requirements with a conservative model, no further work is needed. However, if REXIS fails to meet requirements, conservatism can be reduced until a more realistic model is constructed. Figure 4-7 shows the first 10 REXIS natural frequencies and a depiction of the first REXIS mode shape, which is a flapping of the Radiator.

Mode	Freq. [Hz]	Component(s)	Modal Effective Mass [%]					
			T_x	T_y	T_z	R_x	R_y	R_z
1	48	Radiator	0	2.5	0	0.04	0	0
2	70	Mask	0	0	0.07	0	0	0
3	72	Radiator	0.03	0	0	0	0.04	4.1
4	90	Truss	42	0	0.02	0	95	1.5
5	110	Truss, Radiator	0	30	0.30	58	0	0.16
6	124	Radiator	0	0	0	0.02	0.09	8.0
7	130	Radiator, Mask	0	11	0.43	32	0	0.11
8	140	Mask	0	0	0	0	0	0
9	142	Mask	0	0	0	0	0	0
10	156	Radiator	0	1.4	0.22	4.2	0	0.06

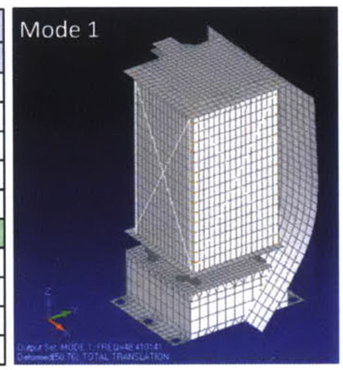


Figure 4-7: First 10 REXIS natural frequencies predicted with NTE mass model and depiction of first natural frequency mode shape

Also shown in Figure 4-7 is the mass participation factor of each natural frequency in the six degrees of freedom. This chart shows what percentage of the REXIS mass is stimulated at each natural frequency and in what degree of freedom this mass acts. As one can see from the highlight cells, proportionally small amounts of mass participate in the first three modes. Although these three modes are below the 90 Hz requirement, they each have such low quantities of mass acting in resonance that do not threaten the instrument and other spacecraft components.

The Radiator, a thin plate of Al and the CAM, an even thinner, smaller sheet of steel, have such small amounts of mass, that although their natural frequencies occur underneath 90 Hz, they have a minimal risk of being a danger to any other aspect of the instrument. Only until the fourth predicted natural frequency at the 90 Hz limit does REXIS experience major mass participation. This mode is a rocking mode of the entire structure about the Y axis; one can discern this information by noticing the mass participates in the translational X degree of freedom and rotational Y degree of freedom. The stiffness of the Ti standoffs is largely responsible for bringing the rocking instrument mode above the 90 Hz frequency limit. The TIL interface contains a lot of compliance in which a Torlon design, being much more flexible, produces lower major mass modes.

Using an NTE mass for the REXIS model, one expects that the natural frequency predictions to be conservative. This information can be examined with the following equation for a structure's natural frequency (ω_n) [32]:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{4.8}$$

Where k is the structure's stiffness and m is its mass. With this information in mind, this model should be giving worst case scenario estimates for the instrument resonance frequencies; an increase in mass will decrease the system's natural frequencies. Due to the low mass participation factors of the first three modes which fall underneath the 90 Hz requirement and the conservative prediction of a 90 Hz rocking frequency, it was decided that no design or structural change was needed to proceed to EM vibration testing. The team felt confident that testing would verify the analysis was conservative and that no failures would occur as a result of the sub-90 Hz predicted frequencies.

4.3.4 Random Vibration Analysis

Random vibration analysis is the last type of major FEA structural analysis performed on REXIS. As with previous analyses, forces extracted from the analysis output are used in stress calculations of localized areas to determine margins of safety. REXIS is tested at 12.85 G's RMS from 20 to 2000 Hz; the specific Acceleration Spectral Density (ASD) graph provided by the OSIRIS-REx ERD is not shown.

Unlike previous models, the boundary condition constraints for the random vibration analysis differs in that a seismic mass is used underneath the base of REXIS. This mass is given a quantity of 10^6 lb as to be massive in comparison to the instrument. The REXIS Baseplate bolt holes are rigidly connected to the seismic mass. The random vibration motion is applied to the mass. This configuration simulates the actual vibration test setup; the instrument attaches to a rigid structure which shakes and mechanically transmits motion to the instrument.

As with previous models, the NTE mass is utilized to provide a conservative stress calculation. The vibration spectrum is applied to the model in the X, Y, and Z axes. The contour stress output plot from the random vibration analysis in the X axis is shown in Figure 4-8.

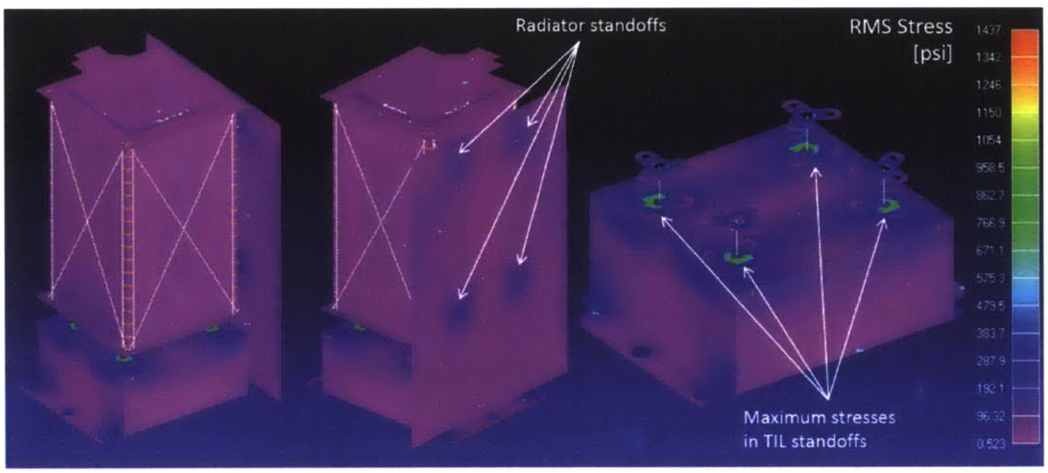


Figure 4-8: Stress contour plot of the REXIS model vibration analysis in the X axis

Once again, the Ti standoff interface is identified as the area of highest stresses. Although visually similar to the MAC loading case in that the high stress areas are localized in the same regions as expected, the output stresses are much lower than those seen in the MAC analysis case. This outcome is to be expected as the MAC loading case is an upper bound acceleration loading which is meant to encompass random vibration. Designed to survive the MAC accelerations, REXIS is predicted to survive all expected stresses due to launch and in-flight loads. Testing of the instrument confirms if the design is sufficient as expected or whether design modifications are needed.

4.4 The REXIS Engineering Model Assembly

Completion of the REXIS CDR finite element analyses described in the previous section was a critical milestone before procurement of EM hardware. These analyses gave the REXIS team confidence that the EM is designed to withstand the expected environmental loads and that it will not experience failure during EM environmental testing. With this confidence, the custom mechanical hardware was procured.

Assembly of the EM hardware served multiple purposes. Clearly, the instrument required construction so it could proceed through testing, but other major goals of the assembly were to practice for the flight assembly and to learn what changes were desired for the FM. For this reason, the EM assembly took place in the SSL cleanroom and included precautionary measures and procedures to limit contamination of the hardware. Cleanliness standards were maintained by cleaning the hardware before entry into the room and requiring that all working personnel don cleanroom garments to prevent transfer of contaminates from one's clothing or body to the hardware. These measures are all necessary, especially on the flight model assembly, because of the stringent contamination requirements OSIRIS-REx imposes on REXIS. Working in a realistic assembly environment, as would be experienced on the flight unit, is essential for gaining an understanding of the working conditions to expect, establishing effective assembly procedures, and allowing the flight assembly to occur more safely.

The other main objective of the EM assembly was to identify any issues with the EM that should be resolved on the FM. Certain components may have interference or fit issues, assembly may be difficult, a procedure might be cumbersome or dangerous, or some part of the design might need modification to meet requirements. Whatever the case, the assembly provided a hands-on experience with the hardware and allowed the engineers to closely inspect and evaluate the instrument. This valuable opportunity enabled the team to identify and track problems fixed on the flight design.

In accordance with the four main spectrometer subassemblies, the instrument assembly follows this categorized fashion. The EBox, DAM, and Radiation Cover subassemblies are separately constructed and are later integrated together during the Tower assembly. The following sections discuss the EM assembly so that the reader obtains a familiarity with the structure and the process of constructing it. A high level description of the assembly takes place and small assembly details are avoided in this discussion.

4.4.1 EM Electronics Box Subassembly

The assembly begins with the construction of the EBox subassembly. The Ti standoffs of the Tower TIL attach to the EBox Top Plate. This step is followed by fastening the two EBox Side Panels to the Top Plate and attaching the instrument Baseplate to the undersides of the Side Panels. The results of these three steps are shown below in Figure 4-9.

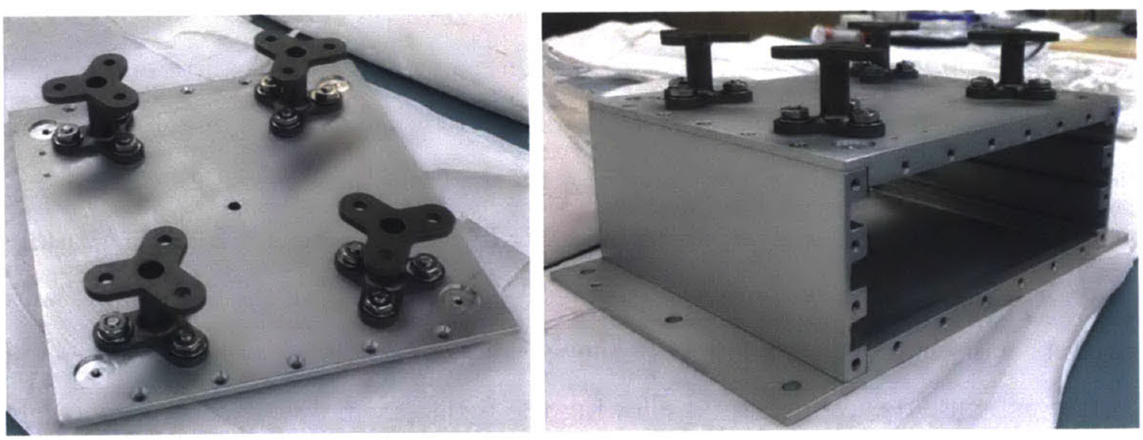


Figure 4-9: Partial assembly of the EM spectrometer EBox

The second TIL layer of Torlon standoffs is assembled by attaching four Torlon standoffs to the top of the DASS. This plate then bolts to the top portion of the Ti standoffs that sit above the EBox Top Plate. At this point, the instrument's TIL is completed as the DASS rests on top of the Ti standoffs and the four Torlon standoffs attach to the top of the DASS. Finally, the EBox Front and Back Panels are attached, resulting the completion of the EBox structure. The separated DASS with Torlon standoffs and the final EBox structure is shown in Figure 4-10.

With the structure complete, the only remaining parts of the EBox are the elec-

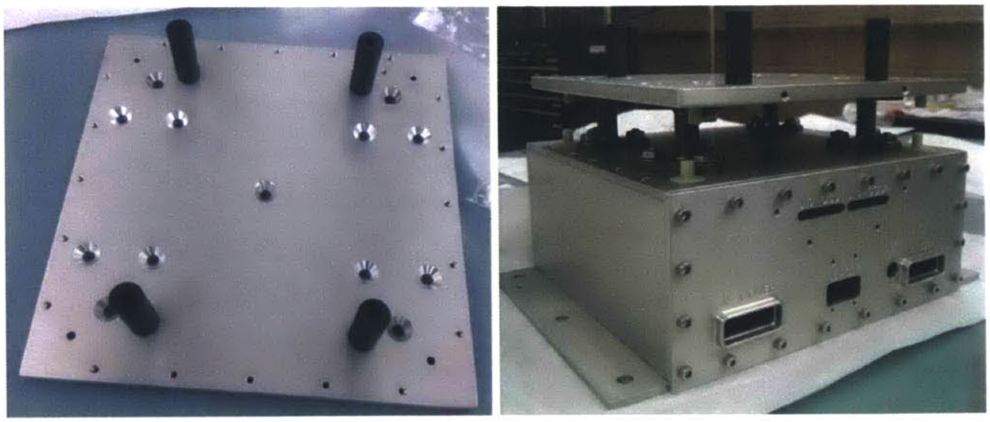


Figure 4-10: DASS with Torlon standoffs attached and the completed EM EBox structure

tronics boards the box houses. In an effort to parallelize the development of REXIS, the REXIS structural EM was separated from the electronics EM. In other words, the assembled structure did not include the EM electronics boards as they were required for testing and use elsewhere. However, the presence of these boards have important effects on the instrument's structural and thermal performance and these effects must be captured during the EM environmental tests.

To mimic the effect of the electronic boards during testing, two separate sets of surrogate boards were developed and installed into the EBox. A set of structural surrogate boards was used during the EM vibration test and a separate set of thermal surrogate boards was used for the EM thermal balance testing. Each set of surrogate boards consisted of three individual boards that slid into the slotted regions of the EBox. Both sets of surrogate boards can be seen in Figure 4-11, where the structural boards are shown on the left while the thermal boards are shown on the right.

The purpose of the structural surrogate boards was to replicate the mass of each electronics board to include their mass contribution during vibration. Aluminum blocks were sized and adhered on each board to appropriately represent the actual mass of each board. Likewise, the thermal surrogate boards were meant to replicate the heat dissipation of the electronics boards at different phases of the mission. To control the heat generation, these boards contained resistance heaters spread across the surfaces of the boards. Electronics modeling determined the amount of power

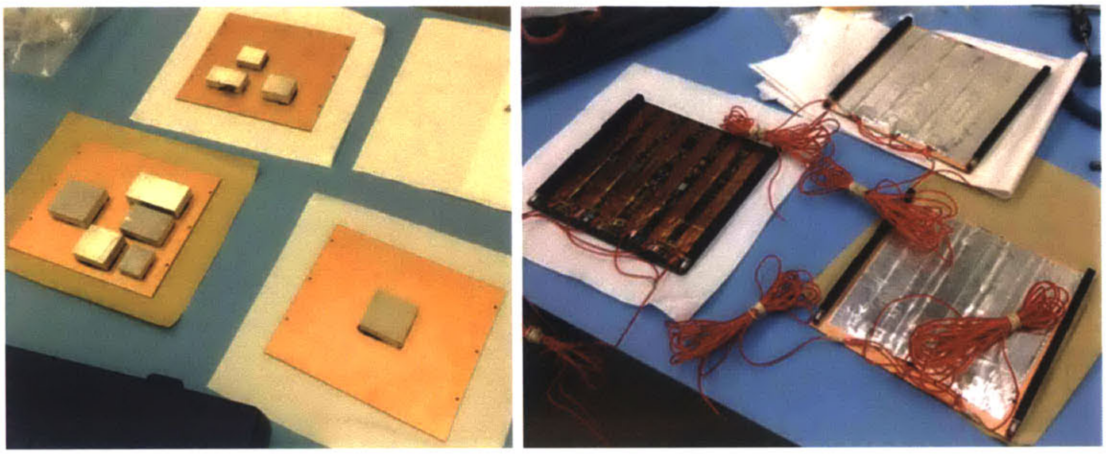


Figure 4-11: Structural (left) and thermal (right) surrogate boards used during EM vibration and thermal balance testing

usage at various times during the mission. During thermal balance testing, appropriate power applied to these resistance heaters generated a realistically representative amount of heat from the surrogate boards. While unable to test the actual electronics boards during EM environmental testing, these surrogate boards allowed the REXIS team to elicit operationally representative performance from both a structural and thermal point of view.

4.4.2 EM Detector Assembly Mount Subassembly

The assembly of the DAM is a strictly controlled procedure due to the involvement with delicate CCDs. The EM DAM assembly took place at MIT Lincoln Laboratory cleanroom facilities rather than in the SSL cleanroom. In order to assemble the DAM, a custom assembly jig suspends the DAM in such a way that it can be easily accessed from all sides including underneath. Figure 4-12 shows the jig before any DAM component has been placed on it.

Construction of the DAM begins with attaching four CCD Holders to the DAM Array Base. The DAM Array Base serves as the centerpiece for the DAM and also the interface for the Thermal Strap. These CCD Holders are U-shaped components which connect to and physically secure the underside of the CCD substrate with epoxy. The two Side Radiation Shields are attached on either side of the Array Base.

Figure 4-12: Assembly jig used during the DAM assembly

This portion of the DAM, shown in Figure 4-13 is now ready to be placed on the assembly jig.

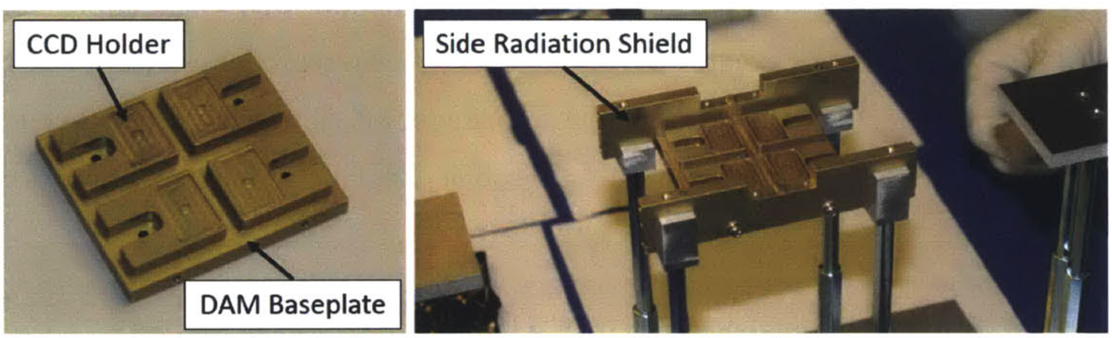


Figure 4-13: Assembly jig used during the DAM assembly

Before integration of the CCDs, the ^{55}Fe Side Collimators are attached to the Side Radiation Shields. Each CCD package, constructed by MIT Lincoln Laboratory, rests upon the DAM Tee. This Tee aligns itself and the connected CCD to the DAM before the CCD is epoxied in place. Epoxy is placed on the cutout of the CCD Holder before the CCD slides into its resting location. Once the CCD is in place, a fastener from underneath the DAM connects to and holds the Tee and associated CCD package in place during the epoxy curing process. Figure 4-14 shows the application of the epoxy to the CCD Holder and attachment of the third of four CCD packages to the DAM.

Once all four CCD packages are in place, the Top and Bottom End Radiation

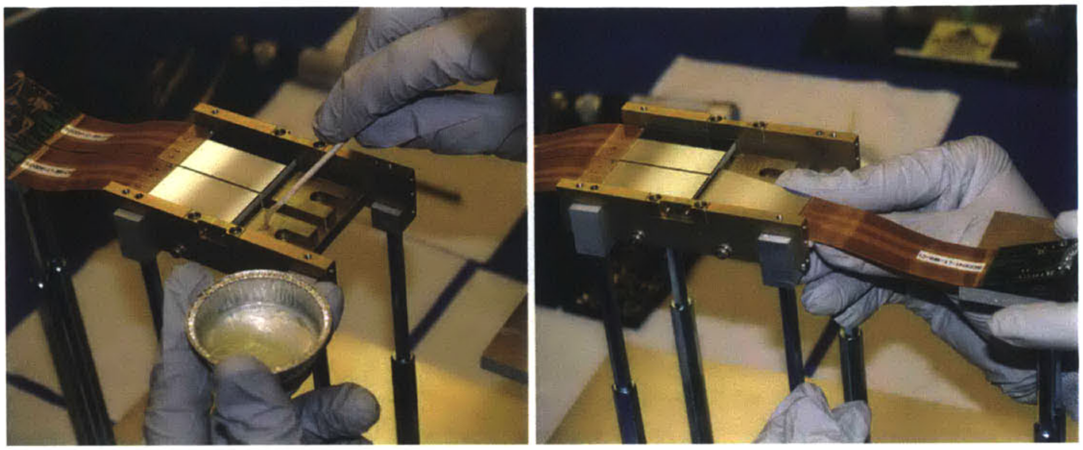


Figure 4-14: Integration of CCD packages to the DAM

Shields are attached. These components surround the Flexprints and connect to the ends of the Side Radiation Shields. Next, the Bottom and Top End Collimators are attached to the Top Radiation Shield. The Top Radiation Shield holds additional ^{55}Fe sources and the associated collimators. The Side and End Collimators limit which CCD pixels are illuminated by the ^{55}Fe calibration source; Figure 2-4 can be referenced to show the collimation. The Top Radiation Shield is placed over the existing DAM structure and attached to the Side Radiation Shields. The nearly complete DAM assembly is shown in Figure 4-15.

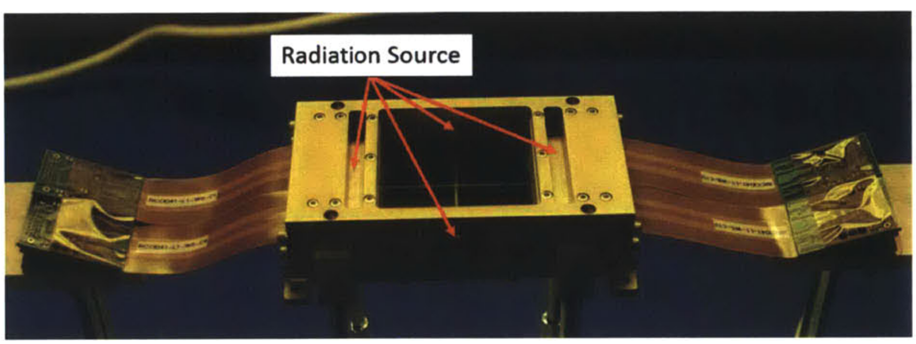


Figure 4-15: DAM assembly without ^{55}Fe sources

The remaining components of the DAM assembly are installation of the radioactive ^{55}Fe sources. Figure 4-15 also shows the location where sources are placed in the assembly. These components are simply inserted and screwed down into the existing cavities created for them. This assembly completes the DAM subassembly which can later be integrated with the spectrometer.

It should be noted that as with the EM electronics, the functioning EM DAM was not utilized in the structural EM during environmental testing. Instead a mock DAM consisting of the same package and DAM subassembly shown here was used. The only difference between the mock and the EM DAM was that the mock had non-functioning CCDs. The mock DAM is an identical structural replica of the EM DAM, therefore it provided realistic structural response data during vibration testing. Additionally, the mock DAM was used during thermal balance testing to verify the existing thermal system. Measurements on the mock DAM during thermal balance system enabled the REXIS team to verify that the thermal system is able to achieve desired temperatures on the CCDs.

4.4.3 EM Radiation Cover Subassembly

The Radiation Cover subassembly begins with building the Mask Frame portion of the assembly. The CAM is clamped and tensioned clamps between two halves of the Mask Frame, the Lower and Upper Mask Frames. Alignment features on the CAM and Mask Frame components ensure that the CAM can only be installed in one orientation so that the pixel patten is aligned as desired.

The Radiation Cover attaches to the Upper Frame at the hinge. Four Vespel SP-3 Bushings are inserted into the hinge of the Radiation Cover and Upper Mask Frame and provide the surfaces upon which the stainless steel Shaft rests and rotates. The Bushings in the Radiation Cover and Mask Frame are concentrically aligned and the shaft is pushed through these Bushings. Before the Shaft is pushed through the two ending Bushings, three Rulon J Sleeves are placed around the shaft followed by two torsion springs. These torsion springs wind about the Shaft and their legs fit into holes drilled into both the Mask Frame and Radiation Cover. Once the Sleeves and springs are successfully inserted, the shaft can be pushed through all four bushings. Locknuts attached to either end of the threaded shaft keep all the hinge components in place.

These previous steps complete the main structure of the Radiation Cover subassembly and allow for installation of the temperature control components of the

Radiation Cover. A Cover Heater is installed in the center area of the Radiation Cover. The FM uses set of four thermostats which are placed on the Radiation Cover as well. This heater keeps the Radiation Cover deployment system above the required temperature threshold of -20 ℃ during the cruise to Bennu. Feedback from the thermostats regulate the duty cycle of the heater to keep the Cover within a desired temperature range and within REXIS's power budget of 10W average power. Both the Cover Heater and thermostats are attached with epoxy. As with the DAM assembly, the internal ^{55}Fe Cover Source can be installed to the underside of the Radiation Cover at a later point when desired.

The final aspect of the Radiation Cover subsystem is the installation of the Frangibolt actuation deployment system. This installation stows the Cover in the closed position until it is ready for deployment. However, due to some bolt inaccessibility when the Cover is closed, the Frangibolt deployment system must be installed once the Radiation Cover subassembly has been integrated with the spectrometer Tower. For this reason, this portion of the assembly is described at the end of the Tower installation, Section 4.4.4.

4.4.4 EM Tower and Full Instrument Integration

The Tower assembly integrates the EBox, DAM, and Radiation Cover subassemblies together to form the full REXIS spectrometer. Building off the EBox, +Y Tower Panel screws to the DASS. This action is followed by the attaching of the -X Tower Panel to the DASS and securing the -X and +Y Panels together. Before attaching the Radiator to the +Y Panel, the Thermal Strap bolts to the spectrometer-facing side of the Radiator. Once attached to the Radiator, the Thermal Strap feeds through the slot in the +Y Tower Panel and the Radiator attaches to the +Y Panel using the five stainless steel standoffs. The resulting structure is shown in Figure 4-16.

Installation of the DAM is the next and most difficult part of the assembly. Special care must be taken with the following steps due to handling of the delicate CCDs. In order to fasten the Thermal Strap to the underside of the DAM, the DAM must be tilted such that the CCDs point towards the +Y direction. The Thermal Strap is bent

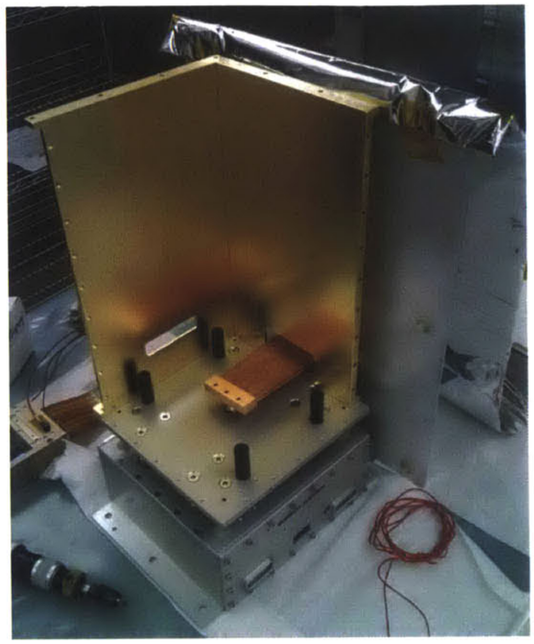


Figure 4-16: Partial integration of the +Y and -X Tower Panels, Radiator, and Thermal Strap with the EBox

upwards and allows personnel to access and fasten the bolts connecting the Thermal Strap to the DAM. Once connected, the DAM returns to a horizontal orientation, the Flexprints feed through the slot in the -X Panel, and the DAM mounts to the four Torlon standoffs. Figure 4-17 shows the Tower assembly just after installation of the DAM.

As one can see in Figure 4-17, the CCDs of the DAM shown in these figures are damaged. Recall from Section 4.4.2, that the DAM and CCDs used for EM vibration and thermal balance testing were non-functional units. The mock DAM provided an identical structural and thermal replica for testing purposes, but allowed the team to parallelize development of the functioning CCDs and DAM with their own separate testing.

After securing the DAM, the remaining -Y and +X Tower Panels attach to the DASS and to their adjacent Panels while the Flexprints feed through the slot in the +X Panel. The Radiation Cover subassembly, still open, can now bolt down to the top of the Tower Panels. The nearly complete spectrometer is shown in Figure 4-18.

The finishing touches to the structure are the attachment of the Flexprint Shields

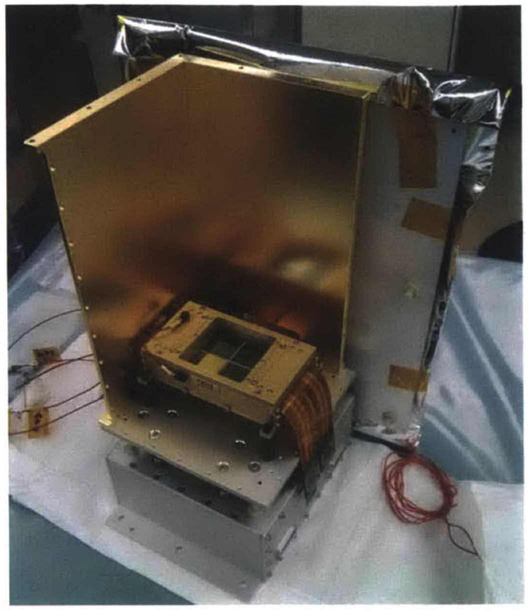


Figure 4-17: The Spectrometer assembly just after the DAM is attached to the Torlon standoffs

which cover portions of the exposed Flexprints, and the installation of the Frangibolt actuation system. There are two sets of Flexprint shields, one covering the slots on the Tower Panels, and the other set covering the slot and connectors to the EBox Video Board. The Flexprint Shields are connect after the Flexprints attach to the Video Board; keep in mind that the EM assembly utilizes the surrogate boards and not the actual electronics boards; during testing, the Flexprints were secured to the EBox with screws.

Extreme care must be taken with the Frangibolt installation, the final action in the assembly. The installation procedure is detailed with specific techniques, steps, and tools necessary to properly prepare and install the Frangibolt deployment system. However, this section will just cover the high-level actions required for the assembly. The first step is to verify the length of the Frangibolt. If larger than its target compressed length of 0.500" $\pm$ .005", a special compression tool is used to reset the Frangibolt to this length.

To prepare the Frangibolt stackup assembly, the threads of the custom Ti bolt are lubricated with Braycote 601EF to reduce friction during the installation. One Ti Thermal Isolation Washer is place around the bolt, the Radiation Cover is closed

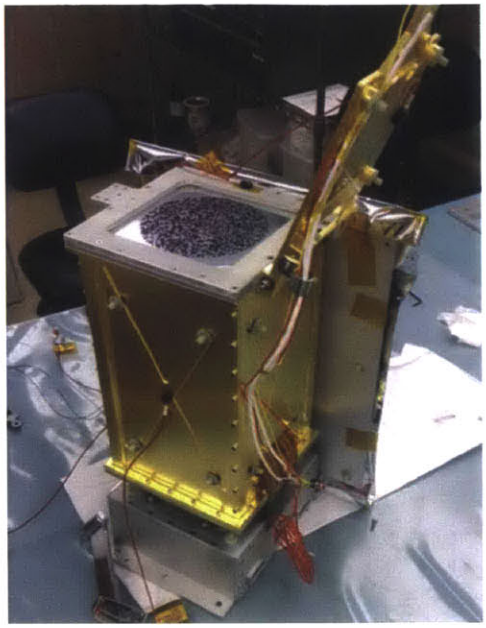


Figure 4-18: Nearly complete EM Spectrometer with the open Radiation Cover

with one hand, and the Ti Bolt enters concentric receiving holes in both the Radiation Cover and the Upper Mask Frame. With the bolt going through both the Radiation Cover and Upper Mask Frame, a second Ti washer is placed on the bolt, followed by the Frangibolt actuator. For the EM, a third and final Ti washer is installed underneath the actuator and the whole bolt stack-up is held closed with a locknut. The flight design replaces this third Ti washer with a TiNi Aerospace SW04 Switch Washer used to detect the Radiation Cover deployment.

Once the actuator is installed and the locknut torqued to its specified installation torque of 50 in-oz, the Frangibolt Housing and Bolt Head Retainer are attached. These components contain the deployment system hardware during the actuation. Installation of the Frangibolt deployment system completes the structure assembly of the REXIS spectrometer which can be seen in Figure 4-19.

Throughout the assembly photos, one can notice accelerometers attached to various parts of the instrument. These sensors were instrumented on the structure simultaneously with the assembly and used during the EM vibration test. Also attached to the spectrometer, which can be seen in this photo, are other components such as the MLI buttons and wiring harness. The MLI buttons are fastened to the structure

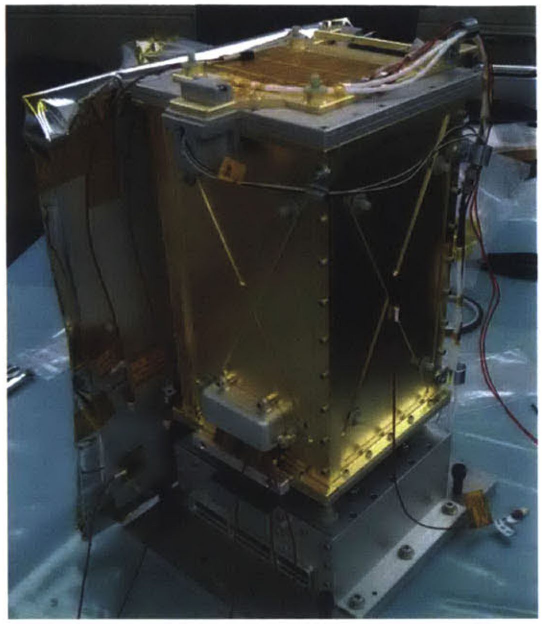


Figure 4-19: Completed EM spectrometer assembly including accelerometer instrumentation used during the EM vibration testing

at locations where it is desired to mechanically fasten the MLI. The wiring harness that can be seen in the previous photo is non-functional but is representative of what was expected for flight and was included for vibration and thermal balance testing to include its impact on system performance.

4.4.5 EM MLI Application

Integration of the MLI blankets, while interspersed through the structure assembly, was omitted in the previous sections as it takes place throughout many of the subassemblies. A high level overview of the MLI blanket installation is discussed in this section.

As discussed in section 2.2, REXIS uses eight separate MLI blankets to completely insulate the spectrometer. MLI is adhered to the spectrometer with G10 MLI buttons and adhesive tape. The buttons mechanically fasten the blankets in place while custom blanket connections are held with double sided transfer adhesive and Kapton tape. The EM G10 MLI buttons attached to the spectrometer using a variety of button designs to include epoxying, fastening with a screw, and threading the button into a threaded hole. Button locations included the Tower Panels, EBox top, DASS, Radiator, and Radiation Cover. Epoxied buttons required surface preparation of the hardware which included abrading and removing any coatings on the hardware surfaces. MLI buttons were attached to all hardware components prior to their subassembly integration.

As the spectrometer assembly progresses, certain hardware surfaces become inaccessible for MLI application, notably the faces trapped between the Radiator and +Y Tower Panel and the surfaces between the EBox top and DASS. Unable to be removed after the spectrometer assembly, these blankets are known as Trapped MLI. For this reason, several MLI blankets are installed during some subassembly construction. The completed spectrometer covered in its EM MLI blankets is shown in Figure 4-20. The brown and red wires seen in this photo lead to temperature sensors and the thermal surrogate boards respectively, which were used during thermal balance testing.

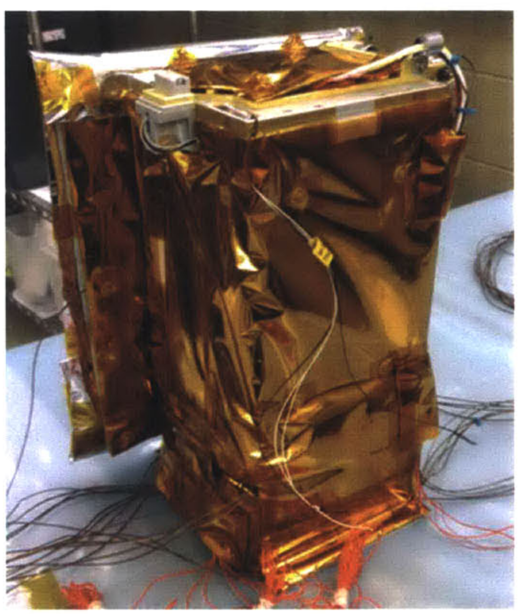


Figure 4-20: Completed EM spectrometer assembly including MLI installation and temperature sensor instrumentation

4.5 Engineering Model Vibration Testing

EM vibration testing was the most important event in terms of validating the REXIS structural design. In the attempt to avoid making as many changes as possible to the design, the EM structure was meant to be as flight-like as possible. The two overarching goals of EM vibration testing were to ensure the current design is able to survive the expected mission vibration launch loads and to update FEA models to more accurately predict margins of safety. Survival of EM vibration testing loading environments enables REXIS to maintain its current structural design. Likewise, model correlation allows better predictions for how any implemented changes affect the structural performance. Failure in this event would cause catastrophic issues for the project as major redesigns would need validation though additional testing before procurement of the FM. These considerations greatly influenced the decision to change to a more robust TIL design as was previously discussed in sections 4.1 and 4.2.

REXIS EM vibration testing took place at the end of April 2014 at the MIT Lincoln Laboratory environmental testing facility. As can be seen in many of the EM assembly photos of Section 4.4, accelerometers were attached to the spectrometer during the hardware integration. After delivering the instrument to MIT Lincoln Laboratory, additional accelerometers were attached to the structure to allow for greater data collection. These accelerometers are located on key areas of REXIS expected to be stimulated by the frequency response. These selected location were based off the mode shapes derived from the finite element modal analysis.

The REXIS Baseplate bolts to the Lincoln Labs shaker table through an interface plate that accepts the bolt pattern for the Baseplate and the shaker base. A rigid cube on the shaker table allows REXIS to be mounted independently in each of its axes for testing. The REXIS EM vibration test encompasses random vibration, sine burst, and sine vibration testing in the X, Y, and Z axes separately. Despite the low mass participation in the Radiator and CAM modes predicted below 90 Hz (reference Section 4.3.3), the sine vibration was still performed as a safety precaution. The spectrometer mounted to the shaker table cube in each of its three axes is shown in Figure 4-21.

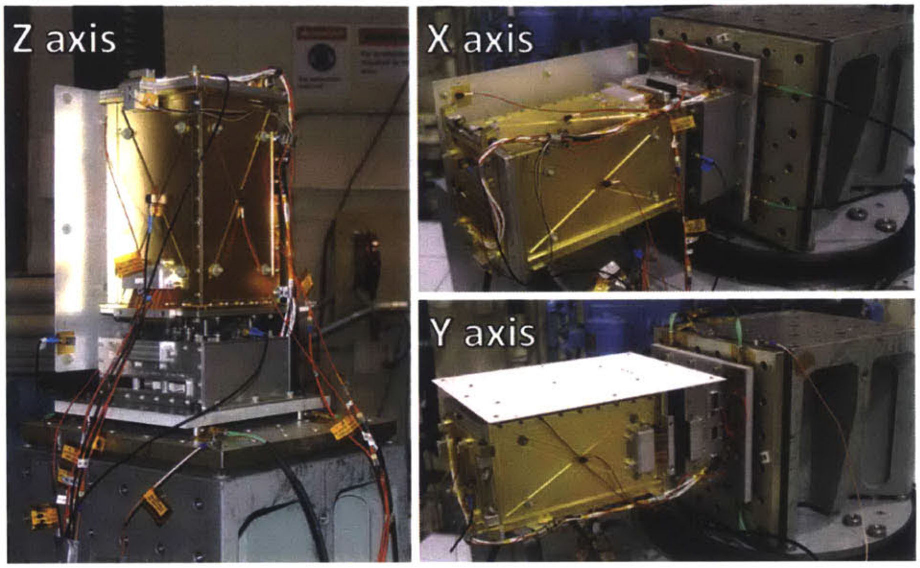


Figure 4-21: EM REXIS spectrometer mounted in its X, Y, and Z axes during vibration testing

For both the random vibration and sine burst tests in each axis, testing levels start at -18dB of the full level specification and are increased to -12dB, -6dB, and then the full level test. This process is done in order to prevent over testing the instrument without first being able to identify how it behaves at lower test levels. These low-level tests allowed the team to and compare test performance against model predictions and structural analysis margins to ensure that a test performed at full level will not cause the structure to fail. Having invested substantial resources into procurement of this model, it is important to carefully monitor its testing performance to avoid preventable failures.

Additionally, these -18dB white noise or random survey vibration tests are used to identify the spectrometer natural frequencies. A random survey vibration test is performed before and after each test performed at full level. If part of the instrument were to break during a test, the structure's natural frequencies would shift due to a change in the structure's stiffness. A comparison of the pre- and post-vibration white noise tests show whether any natural frequencies have shifted or changed. Any discrepancies between the two tests indicate a failure in part of the structure.

The vibration test is considered successful when a number of criteria are met. Included in this success criteria are that testing to all specified test levels are completed and data is successfully acquired. It is important that no visible structural damage or degradation is observed as a result of testing either during the test of during the post-test hardware inspection. Imperative for the mission is that the Frangibolt does not fracture during vibration, causing the Radiation Cover to open. And lastly, a comparison of pre- and post-vibration white noise tests show that no significant shifts of discrepancies between the two natural frequency signatures. Typically, an instrument functional test would be performed, but as the structural EM placed through vibration testing did not have functional electronics, there was no functional testing to be performed other than a Frangibolt actuation after the completion of vibration testing.

The instrument is closely monitored during each test and visually checked between each testing phase. This monitoring helps identify whether any damage occurs during any phase or testing. Throughout all testing, no structural issues were visually or audibly detected. An inspection of pre- and post white noise frequency signatures also confirmed that no structural damage occurred as a result of testing. A comparison of a random survey is shown in Figure 4-22. This comparison is the output of an accelerometer from the white noise tests performed before and after the full level random vibration test in the Y axis. The location of the accelerometer shown is on the center of the -Y Tower Panel.

As can be seen from this figure, the random survey performed prior to and after the full level test overlap almost identically. This observation indicates that there are no structural failures in any locations that are connected to the -Y Tower Panel. A failure in bolts or connections with this plate or large structural failures in important interfaces would have altered the spectrometer stiffness and some frequency shifts would be identified. Comparison of before and after random survey signatures of all accelerometers were consistent in that no shifts in natural frequencies occurred. It should also be noted that no instrument frequencies were stimulated during the sine

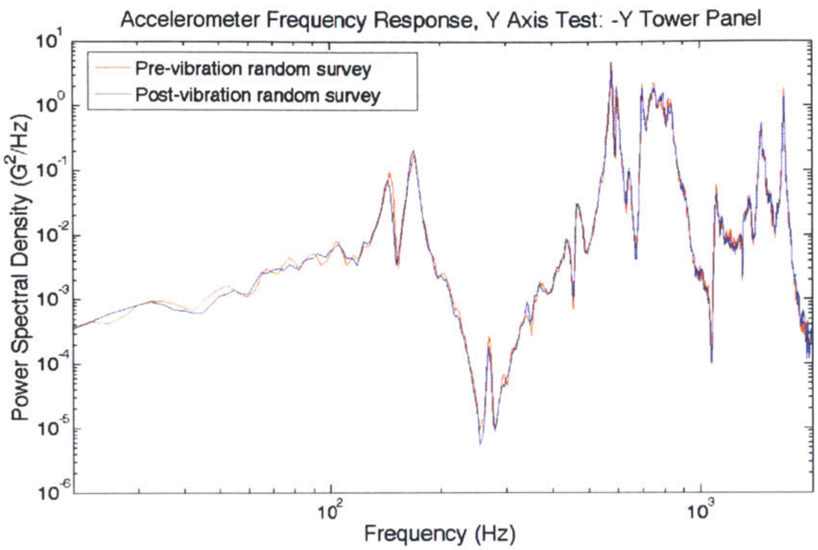


Figure 4-22: Random survey comparison before and after the full level random vibration test in the Y axis. Accelerometer location for this particular graph is in the center of the -Y Tower Panel

vibration test, indicating that the low mode predications were too conservative.

With the structure intact and no observed issues, vibration testing was complete, leaving the only remaining item of the Frangibolt actuation. REXIS was transported back to the SSL at MIT where the Frangibolt actuation was performed. The mechanism actuated as expected with no anomalies. Completion of all test phases with no identified issues, either visually, audibly, or through data comparison, labeled EM vibration testing as a success.

4.6 Post-Vibration Model Correlation

Finite element model correlation took place shortly after completion of EM vibration testing. Correlated models allow one to more accurately analyze the existing design as well as perform more accurate predictions of how design changes will impact the system. These higher fidelity models enable one to recalculate more realistic margins of safety for their system. Likewise, any design changes from the EM and FM can be modeled with greater accuracy and confidence.

Model correlation is a process of identifying aspects of the FEM that make it behave differently than the actual tested unit. The goal is to change these aspects such that the FEM becomes closer to the tested unit so that more realistic loads and stresses can be calculated out of the model. Since the REXIS structure had no issues during testing, a high-fidelity model is not necessarily needed to investigate a failure. The goal of the REXIS structural correlation was to correlate the first several main structural frequencies within 5% of the tested data. The main structural modes are defined as the first bending modes that incorporate the largest percentage of mass participation. These modes are the most significant from a stress point of view because the low modes correspond to larger displacements, which create larger strains and stresses. Model correlation enables the prediction of more accurate forces, which are used to update MS calculations. Throughout the correlation, both random vibration model predications and the modal analysis are used to identify differences between the EM and the FE model.

4.6.1 Pre-correlation Model Predictions

Model correlation begins by examining the original model prediction results and comparing them against the test results. Figures 4-23, 4-24, and 4-25 show the results of accelerometer outputs for the major bending modes in the X axis, Y axis, and the Y axis Radiator modes respectively. These particular accelerometers were chosen as they provide the most useful data regarding the frequency response of the spectrometer. Although a number of accelerometers were cross-referenced and used during the correlation, the output from these three locations will be compared in this section.

These plots are shown as an example of the FEM predictions plotted against the actual test data. The input spectrum is included as well for context. One can immediately see large discrepancies between predicted and actual values on this chart. As mentioned, the goal of model correlation is to align the first predicted model major mass bending modes with the vibration test results within 5%. Recall that the mass participation can be determined for each mode as was done in Figure 4-7. Although the Radiator modes have a relatively small amount of mass participation (<5%) it was desired to align the the first Radiator modes because the CDR model

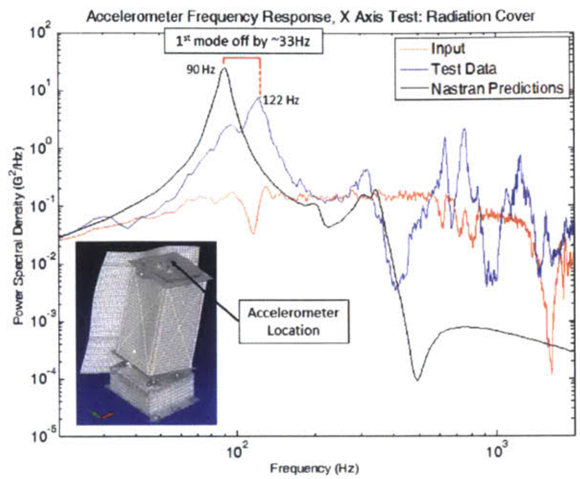


Figure 4-23: Test response and pre-correlation model prediction of accelerometer output on the Radiation Cover during the X axis random vibration test

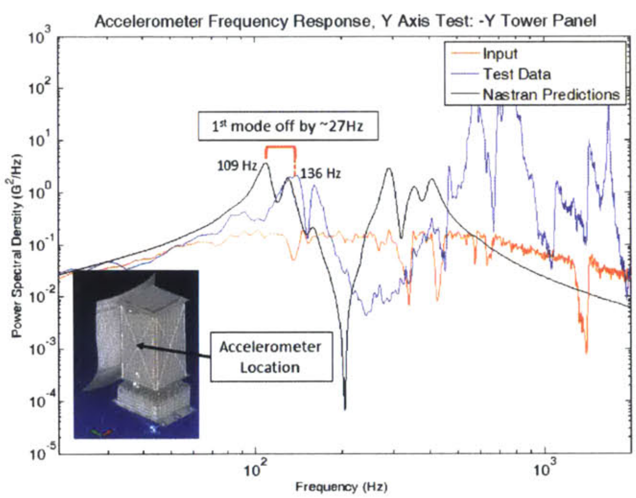


Figure 4-24: Test response and pre-correlation model prediction of accelerometer output on the -Y Tower Panel during the Y axis random vibration test

predictions were so far off from the tested results. One should note that the model predictions attenuate at high frequency because data was not requested at these higher frequencies. Information at these very high frequencies is not needed as model correlation is only performed to the few lowest major mass modes.

4.6.2 Model Correlation Steps and Methods

Updating the models begins by addressing areas where there are known inaccuracies between the model and reality. Sometimes there are design aspects that are inten-

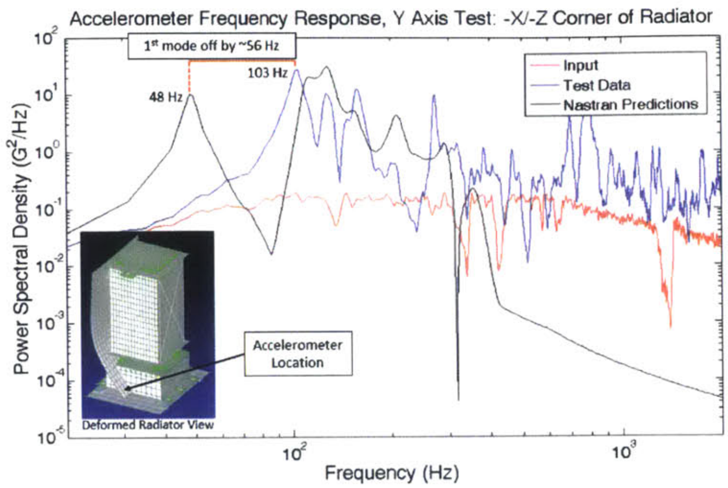


Figure 4-25: Test response and pre-correlation model prediction of accelerometer output on the -X/-Z corner of the Radiator during the Y axis random vibration test

tionally left out of a model for conservatism or other reason. These areas will be updated first. Next the model must be compared against the test results to identify discrepancies between predicts and test performance. Differences between the model and the physical system need to be identified and adjusted. In the case of the REXIS FE structural model, one of the most significant known differences between the EM tested unit and the FE model was the mass discrepancy. The FE model mass was purposely allocated at the upper NTE limit in order to create conservative predictions. As the actual EM has about 17% less mass than the NTE mass, it was expected that all predicted modes were and conservatively inaccurate and lower than the test results.

Knowing this mass discrepancy in the model, allocating the appropriate mass was the first step taken. Component masses in the model are updated with the actual part masses. Doing so has a major impact on the model predications considering that the instrument modes are largely governed by the spectrometer mass. The next areas to verify and update are the interface and component dimensions. If model interfaces or components are given dimensions that are incorrect, the structure's overall stiffness and natural frequencies will be different than the built unit.

Updating the Radiator mass, size, and interface to the Tower dimensions, all of which were different between the CDR model and EM test unit, brought the model

Radiator frequencies to match the testing results. As one can see from the chart, the first Radiator natural frequency occurs just over 100 Hz. This result alleviated the need for sine vibration testing during flight vibration testing and confirmed why no low modes were identified during the EM sine vibration testing.

The remainder of the correlation focused on aligning the major mass modes of the structure, which are various rocking modes of the entire spectrometer in the X and Y axes. With model masses and dimensions being equal to the test unit, the methodology for further correlation is identifying and addressing aspects of the model with unrealistic stiffnesses. In REXIS's case, often the model was less stiff than the as-built EM unit which is why the model predictions are below the tested results. These updates are a process of trial and error in which changes are made to the model and the results are inspected to verify whether the correct issue is being addressed. Many iterations of changes were necessary to find and change the most important differences between the model and test unit.

The process used to identify how the instrument behaved during vibration testing was cross referencing accelerometer output. Comparing data from different accelerometer locations during the same test helped indicate the stimulated mode shape. For example, multiple accelerometers showing the same frequency spike indicates that the entire structure moves together, whereas a frequency spike observed only on one component indicates that there is local resonance. These comparisons help determine the general mode shape of the test unit and relate the test data to the modal analysis.

The lowest major mass modes are REXIS rocking in the instrument X axis followed by a rocking mode in the Y axis. These large rocking modes incorporate the largest mass participation factor and being the lowest frequencies, also have the greatest instrument displacements. These large displacements dominate the stresses felt by the structure during random vibration. The large stresses identified in the Ti standoffs in Section 4.3 are due to this instrument bending. Figure 4-26 shows a deformed view of the structure in the two lowest major mass modes.

To align these modes, a series of model updates were made to the original CDR FE model. A discussion and summary of the various techniques used during the REXIS

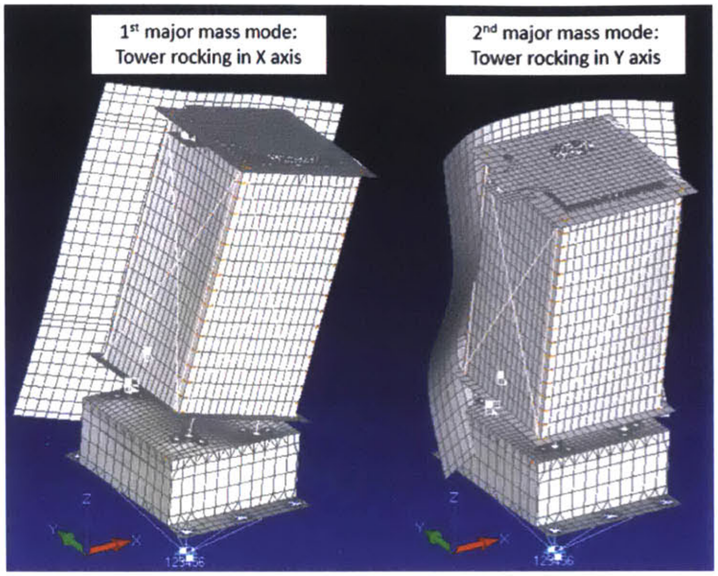


Figure 4-26: Deformed view of the REXIS FEM depicting the two lowest major mass modes: the instrument rocking in the X and Y axes separately

model correlation are provided. However, the discussion will focus on a high-level look at the changes implemented rather that describe every step; the process is iterative and many attempts and alterations were undone as their implementation had little or no effect on the model performance.

As mentioned previously, the main goal and focus of model correlation was to match the model as close to the actual test unit as possible. Naturally, every feature and component of the actual model cannot be modeled without excessive effort, and doing so is not necessary. However, there are sometimes certain components which warrant the modeling of localized mass. Increasing fidelity of the REXIS model, components which were previously given a smeared mass in the instrument Panel were modified to be point masses at specified locations. Examples, include the Flexprint Shields, the Frangibolt Housing and stackup, and the Thermal Strap. Doing so moves the instrument center of gravity and therefore the mode frequencies as the mass of these components were previously smeared into larger components.

Rigidity was added to the REXIS model in many locations to incorporate the stiffening aspects of the fasteners in different assemblies. Previously, the Al plates of the model were connected by coincident nodes without the inclusion of fasteners.

To increase the stiffness that the steel fasteners add to the Al structure, RBE2 rigid elements were added been nodes that represent where fasteners are incorporated. This addition helps stiffen regions such as the perimeter of the EBox Top Plate, which has a lot of compliance in the model. This tactic was employed in areas where many fasteners are present and the interfaces between components are, in reality, more stiff than how the model was represented. This stiffening technique was applied to EBox, Ti standoffs, and Tower Panels.

When correlating the model to the test unit, one must also consider the boundary conditions of both the model and of the instrument during the test. The model originally constrained only the Baseplate bolt holes. However, the rest of the Baseplate was free to deform. Naturally, with the actual instrument mounted on a rigid plate, the Baseplate deformation is significantly resisted because it cannot deform in the REXIS -Z direction. This discrepancy caused the model to be less constrained and have lower rocking modes; restricting the movement of some of the Baseplate modes increased these modes such that they more closely aligned with the test results. This consideration is an important reminder that correlation of the model should be matched to the test environment to account for the impact the test configuration has on the results.

Another aspect of the correlation was refining the model mesh to achieve convergence on the natural frequency predictions. Larger element sizes in the mesh limit the locations where the system can deform, thereby making the system stiffness artificially high. Refining the element size into a more fine mesh causes parts of the system to behave more continuously like the actual system. Refining of the mesh was done until further refinement caused negligible changes in frequency predictions.

4.6.3 Post-correlation Model Predictions

Through inspection, experimentation, and iteration of the various techniques mentioned previously, a correlated REXIS FE model was created. This model obtained mode frequency matching within the goal of 5% on the lowest major mass modes. As discussed, correlation on these modes are the most significant as greater displacements occur at lower frequencies. These higher displacements correspond to increased stresses.. The correlated results of the same accelerometers shown in Section 4.6.1 are shown in Figures 4-27, 4-28, and 4-29.

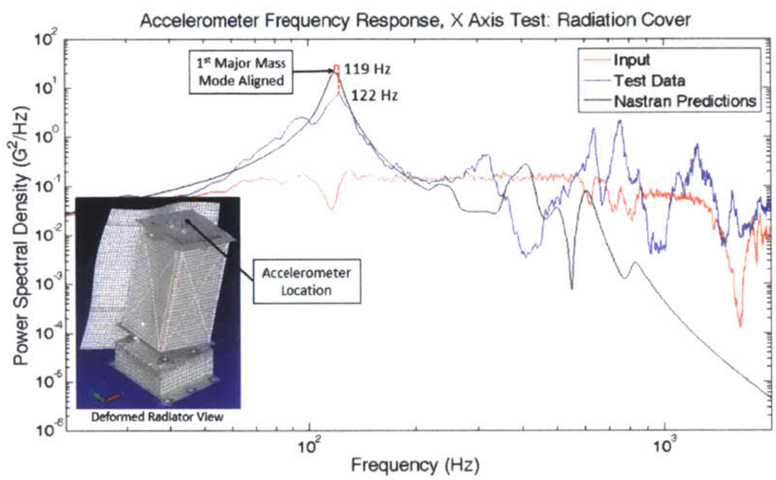


Figure 4-27: Test response and post-correlation model prediction of accelerometer output on the Radiation Cover during the X axis random vibration test

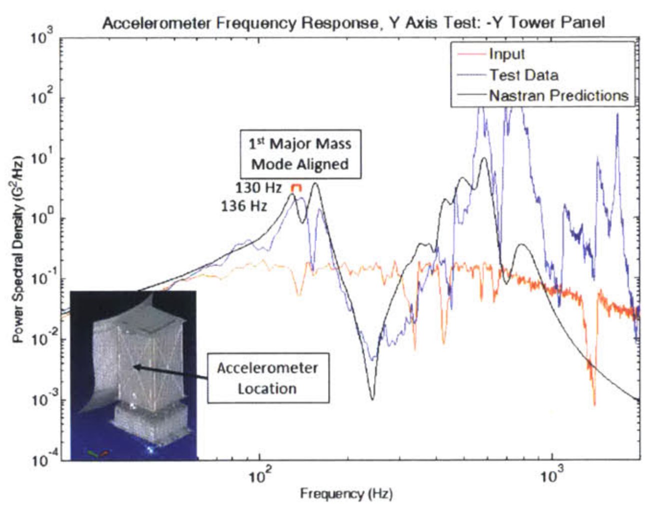


Figure 4-28: Test response and post-correlation model prediction of accelerometer output on the -Y Tower Panel during the Y axis random vibration test

A summary of the correlation results, comparing the pre- and post-correlation model predictions is shown in Figure 4-30. One can see that the original error between the prediction and the test results is significant. After model correlation, the error in frequency prediction has been reduced within the goal of 5%.

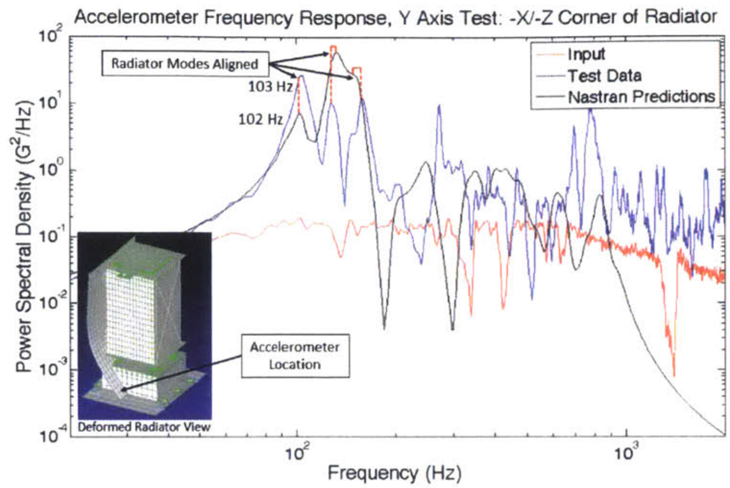


Figure 4-29: Test response and post-correlation model prediction of accelerometer output on the -X/-Z corner of the Radiator during the Y axis random vibration test

Test Axis	Accelerometer location	Test Result (Hz)	Pre-correlation prediction (Hz)	Pre-correlation % error	Post-correlation prediction (Hz)	Post-correlation % error
X	Radiaiton Cover	122	90	26.2	119	2.5
Y	-Y Tower Panel	136	109	19.9	130	4.4
Y	-X/-Z Radiator Corner	103	48	53.4	102	1.0

Figure 4-30: Summary of the results for the major REXIS modes. One can see the percent error has been reduced to below 5% in the post-correlation model

Surviving vibration testing provided the REXIS team more slack in terms of correlation accuracy. The results of environmental testing confirmed the structural design; as long as the model was conservative and maintained positive margins, extensive effort in model correlation could be avoided. After model correlation was complete, the model was updated in accordance with any changes made from the EM to the flight design. The major analysis cases, static loading, CTE mismatch, modal, and random vibration, were repeated on the newly developed flight FE model. More confidence can be placed in these predictions having used a model correlated to test results. These updated analyses were used to ensure the flight design maintains its structural MS.

In the case of REXIS, after incorporating the appropriate flight model updates, the worst case calculated stresses were lower than those calculated during the CDR analysis, increasing the MS. The dominating reason behind the decrease in flight stress calculations was the reduction in mass from using the NTE instrument mass at CDR whereas the flight model used a best-estimate mass based off the known EM mass and expected flight modifications. As the EM was designed against more conservative loading and maintained positive margins, the structural design was validated.

4.7 Engineering Model to Flight Hardware Modifications

Soon after vibration testing, the structural EM underwent thermal balance testing, in which REXIS was exposed to the various temperature environments expected at all phases of the mission. This testing took place in a large TVAC at MIT Lincoln Laboratory and was used to evaluate the REXIS thermal system, which of course is coupled to the structure. Thermal balance testing confirms whether REXIS will meet its temperature requirements throughout the mission. A Radiation Cover deployment in its operating environment also occurred during thermal balance testing. This test was the first opportunity for REXIS to deploy the Radiation Cover with the fully integrated structure at its predicted thermal environment. Thermal balance testing was the last full system-level environmental test of REXIS performed with the structural model.

The results of EM assembly, vibration testing, and thermal balance testing provided valuable input regarding the existing REXIS design and formed the foundation for the decisions made on hardware updates. These hardware updates began shortly after completion of thermal balance testing. The reasons for making changes to the structure are classified under three main categories. These categories are as follows:

1. An aspect of the design does not currently work.

2. An identified change will be easier or safer from a handling and assembly standpoint.

3. A certain change will improve system operational performance.

4.7.1 Fixing the Problems

This category of changes describes any modifications that were done because some part of the instrument did not work as desired. This point can includes aspects of the design that did not meet requirements, parts did not fit together as they should have, or there was some aspect that prevented full functionality of the instrument. While REXIS did not have any issues meeting requirements, there were a number of components that had mechanical interferences that prevented assembly.

One of the major issues occurred on the DAM components that mount to the Torlon standoffs. Fillets between this piece and the mating side wall of the DAM overlapped and prevented a tight fit between the parts. For this reason, the DAM mounting regions did not sit over the standoffs. Similarly, the Flexprint Shields on the EBox impacted some of the bolts on the perimeter of the EBox Front and Back Panels. This interference prevented the shields from being attached to the EBox. Lastly, the connector slots in the EBox Front and Back Panels are too small for the connectors chosen for the mating spacecraft and SXM harness connectors.

Although these issues prevented a problem-free assembly, all problems were solvable though minor machining. In the case of the DAM and Flexprint interferences, small features were ground down such that the small overlap in material was removed and the parts could be successfully assembled. The EBox connector issue was not a problem during EM testing as these harnesses were not used; however, this undersizing of the slots was something that clearly needed modification for the FM.

Minor changes to component features, bolt placement, and dimensions were sufficient to resolve all of the interference issues encountered on REXIS. Conservative structural and thermal analyses before any hardware procurement helped create a REXIS design that met all structural and thermal requirement during testing. For this reason, major design changes due to system failures were avoided.

4.7.2 Improving Handing and Assembly

Hardware assembly was one of the most valuable experiences as it gave the REXIS team an intimate look at the physical structure. Access to the instrument and the process of building it from the bottom up was crucial for determining what parts of the design were easy to assemble and what aspects contributed to difficulty during the assembly and handling. Because REXIS has delicate hardware, notably the CCDs, cumbersome procedures should be avoided as much as possible to reduce the risk of damaging the hardware during assembly.

Additionally, REXIS faces many challenges as a result of being a student instrument. One of the main impediments was the lack of available tools, equipment, and facilities to which many aerospace enterprises have access. For this reason, there are a number of processes which are difficult to perform in a lab not fully equipped for space hardware assembly. Avoidance of elaborate processes which require extensive facilities and equipment is desirable.

For these two reasons, a number of REXIS modifications were done so that the flight assembly is safer and can be done with less expenditure of resources. The most prominent example of improving the ease of assembly is adjusting how the Tower Panels mate to one another. The largest change that reduces required resources and effort on the flight design is modifying the MLI button design.

The EM Tower Panels were all built using the same template. In other words, the primary structure of each Tower Panel is the same where only the additional features such as Flexprint holes are different between the Panels. Each Tower Panel contains threaded holes on the left side and clearance holes on the right. A top view looking down on just the components of the Tower subassembly is shown in Figure 4-31. In this figure, the red arrows indicate the direction that fasteners attach the Panels together.

The clearance holes of one Panel line up with the threaded holes of the adjacent Panel, allowing them to fasten together. Unfortunately, because of this design, the Radiator must be attached only after both the -X and +Y Panels have been attached.

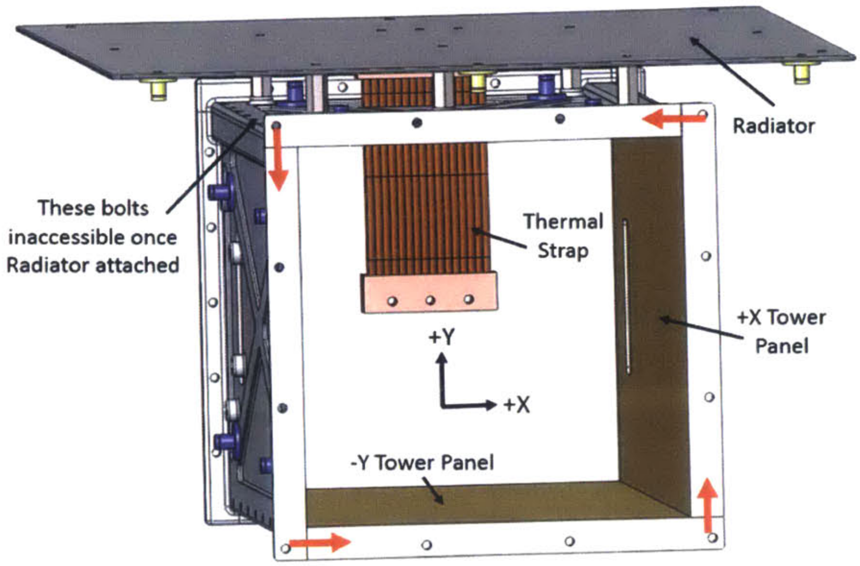


Figure 4-31: Top view of the Tower subassemblies. Red arrows indicate the direction from which screws fasten two Tower Panels together.

The result is that the -X Panel is not removable without first removing the Radiator. A photo of the assembled structure at this current state can be referenced in Figure 4-16 of Section 4.4.4. The presence of this Panel severely limits one's mobility when trying to assemble the DAM and creates situations that pose the risk of damaging the CCDs during assembly. For this reason, the -X and +Y Panels were adjusted so that the screws joining these two parts come in from the -X side of the instrument. The result is that the -X Panel can be installed or removed when the Radiator is in place and there is much more space to maneuver and install the DAM.

Regarding the MLI button design, recall that the EM REXIS design employs three different types of buttons. The first type is attached with epoxy while the other two are attached using threads, either with a fastener or with the button itself screwing into a threaded hole. Attachment of the buttons with epoxy not only requires hardware surface preparation, but an extensive process and procedure to mix and cure the epoxy. The equipment and expertise needed to accurately perform these procedures are again, not easily accessible in a student lab. A simple modification, which changed all previously applied epoxy buttons to versions that could be attached with threads, completely eliminated the need to handle with the extensive epoxy procedures in this application.

4.7.3 Increasing System Performance

The final types of hardware modifications fall under the category of improving the performance of the system. This statement includes both directly improving how well the system performs, whether it be gaining structural or thermal margin, but also includes reducing risk. For example, a lot of uncertainty surrounds the functionality of the Radiation Cover's operation during the mission. Adjustments of the Radiation Cover design such that it has a greater chance of operating effectively were done. In this case, system performance includes how resilient and robust the design is against failure.

Changes on the Radiation Cover were largely performed in order to improve the chances that it opens effectively during flight. These changes included ensuring that aspects of the design do not impair the freedom of motion of the door when opening, providing a safe operational temperature for the Frangibolt deployment system hardware, and minimizing the mission risks associated with a Frangibolt actuation. Modifications to the Radiation Cover, Frangibolt Housing, and MLI design all contribute to making a safer and more robust Cover. Some specific changes to the Radiation Cover and the rationales for doing so are described.

On the EM, the entire perimeter of the Radiation Cover is pressed against the Upper Mask Frame when in the closed position. Being held closed for multiple years at very cold temperatures creates the risk of cold welding of the components. For this reason, the entire Radiation Cover was elevated from the Mask Frame by .015". This gap is small enough to ensure that radiation cannot hit the CCDs when the Cover is closed, but is also large enough to prevent the two surfaces from touching during cruise. A localized region around the Frangibolt is the only portion of the Cover that remains touching the Mask Frame. Furthermore, this region of contact is coated with Teflon-impregnated anodize to further reduce the risk of surface cold welding. Not only does a large amount of contact between the Radiation Cover and Mask Frame minimize the risk of cold welding, but it also focuses conductive heat transfer towards the Frangibolt Housing. The result is that heat does not bleed as much to the rest of the structure and the Radiation Cover Heater more efficiently heats the Frangibolt deployment system.

Although the EM Radiation Cover and Frangibolt deployment system functioned effectively by remaining closed during vibration testing and successfully actuating and opening during thermal balance testing, the team decided to invest more effort on the Cover. The multi-year cold storage of the Frangibolt is impossible to mimic, and therefore difficult to predict what effect it will have on the Radiation Cover's ability to operate. Because the Cover's functionality is critical for REXIS to achieve its science mission, the effort to reduce the risk of the deployment system and Radiation Cover was deemed worthwhile.

Chapter 5

Lessons Learned as a Structures Engineer

When faced with limited resources, whether it be money, personnel, to time, programs are forced to make decisions on where they want to focus their effort. These circumstances sometimes cause teams to cut corners, mismanage how much effort they focus on certain areas, or inefficiently utilize their resources to obtain desired goals. The following lessons discuss areas that resource-constrained teams may be tempted to overlook, but should be given strict attention. Each lesson is provided in context of the REXIS structural design to provide clear examples of how each lessons is relevant to structural engineers.

Section 5.1 discusses major topics to consider during the design of a space system structure. Keep in mind that design is iterative and will occur throughout the system's development. Following these design lessons learned, Section 5.2 discusses important focus areas when it comes to analyzing or testing a space system. As resource-constrained teams are often unable to extensively pursue both detailed analysis and testing to address all system risks, this section will highlight how teams can make decisions regarding whether to use one method over the other.

5.1 Lessons from Design

5.1.1 Consider the Impacts of Procedural Complexity in the Design

When designing a system, it is important to consider handling, assembly, or integration procedures. Complex procedures increase the probability of making mistakes and inadvertently damaging hardware. This point is especially relevant when working with delicate or sensitive hardware. Ideally, the design should facilitate safe and easy processes involved with handling hardware. It is important to consider, and when possible, minimize the amount of complexity needed to perform procedures such as handling, test setup, and inspection, of sensitive hardware.

The REXIS CCDs are incredibly delicate and require limited handling. Early design decisions placed the Radiation Cover on top of the DAM for the REXIS PDR design. The Radiation Cover was later moved to the top of the Tower Panels, as was presented in Chapter 2. Comparison of the PDR and CDR REXIS designs is shown in Figure 5-1.

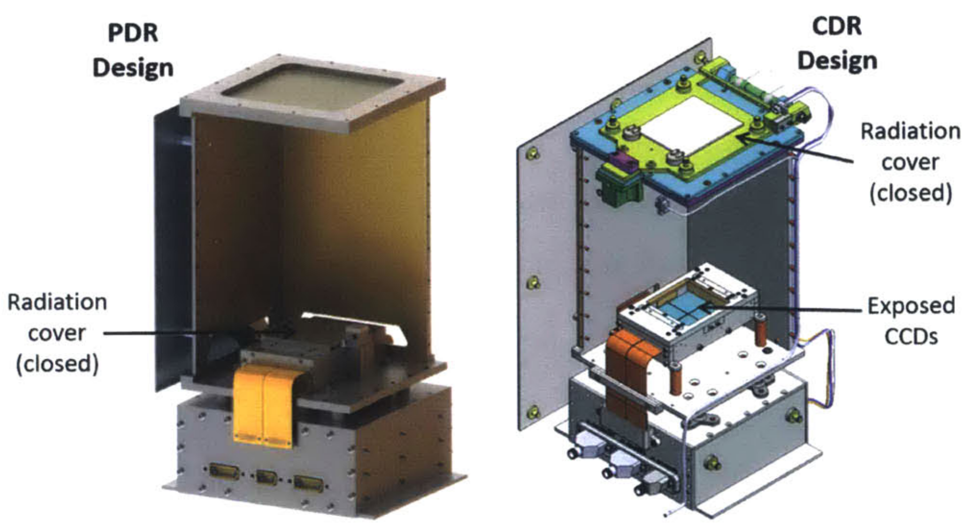


Figure 5-1: PDR REXIS design (left) has a small Radiation Cover on top of the DAM, covering the CCDs. The Radiation Cover was moved to the top of the Tower Panels as shown in the CDR design (right) [6].

This PDR design creates a lot of potential issues due to the Frangibolt's proximity to the CCDs. Since the Radiation Cover and Frangibolt assembly are attached to the DAM, all Frangibolt resets must take place around the CCDs. One can recall that there are a number of small components in the Frangibolt stackup such as Thermal Isolation Washers and locknuts that are very easy to drop. Working with these small components around the CCDs greatly increases the probability of damaging the CCDs. The REXIS team considered the complexity that putting the Radiation Cover on the DAM created and how big of a threat this complexity was for the CCDs and moved the Radiation Cover to the top of the Tower Panels. With the DAM protected inside the Tower, there is no risk of accidentally dropping or touching the CCDs during Frangibolt resets.

Integrated operations with the spacecraft must also be considered. Frangibolt installation complexity limits what REXIS can do once integrated with OSIRIS-REx. The Frangibolt setup requires a fairly complex and precise reset and installation procedure (See Appendix B for the complete procedure). For this reason, REXIS is prohibited from firing and resetting the Frangibolt at the OSIRIS-REx Assembly, Test, and Launch Operations (ATLO). As a result, REXIS will not be able to test the Radiation Cover deployment while integrated with the spacecraft. Although the team is able to gain a high level of confidence through stand-alone REXIS testing, fully integrated testing with the spacecraft would provide the most flight-like and realistic test setup to ensure interfacing with the spacecraft creates no issues that affect the REXIS Radiation Cover deployment.

Attention to system complexity and how procedures and operations can be affected is an important step in minimizing potential issues during the project development. In some cases, such as the moving the Radiation Cover, large changes are warranted because difficult procedures can pose unacceptable risks to the system. Careful planning and attempts to minimize complexity when possible will save time, effort, and help avoid problems later in the system's development.

5.1.2 Use Sensitivity Analysis Early in the Design Process to Guide Design Efforts

A sensitivity analysis should be used as early as possible to help drive the design. This analysis helps one focus effort and attention on areas that have a greater impact toward desired system performance. In this way, one can most efficiently change design variables to work within the design space. This point is especially true when a design feature is used to accomplish competing goals. It is often true that on programs with various subsystems, optimization of each subsystem does not necessarily equate to optimization of the whole. Gaining more margin or higher performance in one subsystem will often degrade performance in another. Furthermore, while there are often conflicting goals between subsystems, the gain or loss of performance on each side is not always linear with respect to one another; a significant change in the structural design may only have a minor affect to the thermal design, and vice versa. For this reason, a sensitivity analysis is useful to help understand which parameters and variables of the design drive the performance characteristics of interest. Resources for general sensitivity analysis as well as discipline-specific sensitivity analysis methods are available for further research [51] [52].

When used early in the design process, a sensitivity analysis can save time, money, and effort by helping a team create a more effective and efficient design. This analysis can provide information regarding which design variables have the greatest impact on the system performance. Therefore, teams can focus attention to modifying design features and aspects that more effectively alter system performance characteristics. The result is that exploration of the entire design trade space can be avoided. Instead, the most important variables can be identified and adjusted.

One significant design trade performed on REXIS took place with the design of the Thermal Isolation Layers. This design trade is discussed in Sections 4.1 and 4.2. As mentioned in Sections 2.1 and 2.2.2, the CCDs must remain below an operational temperature requirement of -60 °C. The thermal system is designed to keep these detectors very cold by thermally isolating the detectors from the heat-generating electronics in the EBox with the TILs. Good thermal isolation can be achieved by minimizing the avenues for heat flow and by using interface materials with low thermal conductivities, typically composites. At the same time, these layers are critical structural interfaces. Desired structural integrity can be achieved with many and bulky supports and the use of high-strength materials, typically metals, which unfortunately have relatively high thermal conductivities.

In this scenario, the REXIS team desires to minimize the thermal conductivity across the TIL interfaces while maintaining enough structural strength to withstand operational loads. By examining the thermal resistance and stress equations in Sections 4.2 and 4.3.1, one can begin to determine which design variables have the largest impact on both thermal and structural performance. The REXIS team was able to use a high-strength material with a stiff standoff design and relatively low thermal conductivity for the Tower TIL, and a weaker but much more thermally resistive TIL design for the DAM TIL. These designs effectively accomplish both thermal and structural requirements. These goals were achieved by focusing by focusing on the characteristics and variables driving the structural and thermal performance in the design of each standoff.

5.1.3 Design With Machining and Assembly in Mind

It is important to design hardware that can be easily fabricated and assembled, and handled safely. Systems that are difficult to create and assemble increase the risk of error and damage, as well as fabrication costs and time. Engineering tools such as Computer Aided Design (CAD) software enables engineers to create complex designs with relative ease. However, although a design may appear to work on a computer, it may not be possible to machine or put together given the constraints of equipment or human capabilities. For this reason, a familiarity with machining processes, tools, and techniques is desired.

Providing poorly designed parts to a fabricator can create cost and schedule issues to the team. The cost of machining a part is directly related to the complexity of the part, as the complexity dictates the amount of labor hours that go into creating the part. In some cases designs are not possible to build. These scenarios force engineers to redesign their parts. In situations where a part is difficult but still possible to machine, the machinist can construct the part at the expense of the engineer's budget. Difficult and numerous features increase the number of times the machinist has to reorient the piece in a different machine or different axis for cutting, which increases the construction cost of the part. These complex parts are not only expensive but also take longer to machine and therefore, eat into the project's schedule. Understanding how a piece is built can help one avoid designing parts with unnecessarily difficult features. This skill can help the engineer make intelligent part designs that will save the project both considerable time and money.

Engineers must also keep in mind the assembly of the system. The system should be designed in a way that allows for easy and straightforward assembly. Difficulties can include having certain screw holes that are unreachable with bulky torque wrenches or other tools, or lacking sufficient maneuverability space to perform procedures in a constricted area. Considering all fasteners should be installed to a verifiable torque value, a torque wrench or other contrived method using adapters and modifications is necessary. Parts made without the foresight of human interaction can contribute to difficult assembly procedures. These awkward procedures increase the risk of damaging the system during assembly. They also reduce the ability to access certain parts of the system for detailed examination without excessive effort.

One REXIS example is the assembly steps that involve integrating the DAM and Radiator onto the spectrometer. As discussed in Section 4.7.2, the left side of each EM Tower Panel contains threaded holes to accept fasteners, and the right side of each EM Tower Panel contains clearance holes to mate with the associated threaded holes of the adjacent Panel (reference Figure 4-31). This EM design was chosen due to the ability to recycle one Panel design for all the Panels, each only requiring minor modifications on each face depending on specific features needed such as the cutouts for the Thermal Strap or Flexprints.

While this particular design initially saved time creating CAD models and mechanical drawings, it created large inconveniences during the actual EM hardware assembly. Due to the overlapping nature of the Panels and the orientation from which fasteners must be inserted to connect the Panels, the fasteners which connect the -X and +Y Panels together are inaccessible once the Radiator installed. Due to this fastener orientation, the -X Panel cannot be removed unless the Radiator is removed.

The assembly is further complicated by the Radiator connection to the DAM through the Thermal Strap. Because the Thermal Strap connects to the back of the Radiator on one end, and the underside of the DAM on the other, the Radiator cannot be removed from the spectrometer without disassembling the DAM from the Torlon standoffs. Due to the weakness of the Torlon threads, it is undesirable to perform multiple installations and removals of the DAM from the standoffs to prevent loss of structural integrity in the Torlon threads. Not only is the -X Panel irremovable until a series of components are taken apart, but the presence of the Panel in the first place makes assembly and disassembly of subsequent parts such as the Thermal Strap to the DAM and the DAM to the Torlon standoffs difficult. The -X Panel obstructs the space in which personnel can maneuver and reduces the area available to effectively integrate the DAM into the spectrometer. The -X Panel's presence creates a hazard especially for the DAM installation by increasing the likelihood of impacting the CCD and forces the assembly personnel to contort the Flexprint cables in ways that could be potentially damaging.

While this Tower Panel design was initially chosen because it was easy from a design point of view, handling experiences with the EM helped illuminate the need to redesign the Tower Panel interfaces so that the DAM installation is less difficult. For the FM, the +Y Tower Panel is the only Panel required to install the Radiator and DAM. This change is beneficial from a handling point of view as it frees up a large amount of space for personnel when assembling.

5.1.4 Consider These Factors When Deciding to Make a Design Change

Choosing to make a design modification is ultimately an evaluation on the return on investment. One must ask whether the benefits from the change will outweigh the resources needed to make the change. Often knowing when to make a design change or whether a change is worth the effort can be difficult. This section provides examples of different scenarios and factors to consider when deciding to make a design change. One must keep in mind that the design process is iterative and will take place throughout the entire development of a system. However, the relative ease and freedom of design changes decrease as the project progresses. As the project become more developed, changes to the design become increasingly more difficult, more costly, and more time-intensive to make.

There are a number of reasons why a team might want to make a design change, but also many factors that discourage changes. On the one hand, system modifications will tend to improve the system performance; however, they can require large cost, effort, and time investments that can be detrimental to the project development. Especially when a team is limited by its few resources, making a design change can either prove to be a game-changing decision, either beneficial or harmful to the program. This section discusses situations when changes may or may not be desirable when developing a system.

Make Changes When the Current Design Does Not Meet Requirements

A design change will be necessary when the system does not meet its requirements. Requirements are in place to ensure that the system is able to achieve its performance goals. If a system cannot meet its requirements, it will not effectively be able to complete the mission. Consider the REXIS example where the CCD temperature must be below -60 ℃ during the operational phases of the mission. If during environmental thermal balance testing, it is discovered that the current thermal system is unable to maintain a detector temperature below the specified threshold of -60 ℃, a design change must be made. Perhaps the Radiator can be sized larger as to reject more heat from the system, or greater thermal isolation can be provided to the detectors. In any case, failure to meet a requirement necessitates a design change as the requirements dictate the success criteria for the system.

This point assumes the violated requirements are not flexible. In some cases, a previously conceived requirement may not actually be "required", allowing the team to modify it and create some design freedom. Depending on where a team may be in the project development, re-scoping the requirements and making them less stringent is more feasible than making a design change, which involves procurement of new hardware. One note to consider is that sometimes there is a disconnect between the individuals who draft the system requirements and those who ultimately design the system. It is important that when certain requirements are driving a significant part of a design or are very difficult to meet, the team investigate whether the as-written requirement is necessary or whether there is some room for compromise. At times, requirements will be unnecessarily strict, and an attempt to meet these requirements will drain effort, resources, and time, all of which are valuable on low-budget projects. It is advisable that teams verify the need for difficult or limiting requirements before expending significant effort to meet them.

It is important to ensure the system requirements accurately reflect the goals of the mission so that the system is designed to achieve this mission. As such, it is important that good communication takes place between those writing the performance requirement and those designing the system. Furthermore, those designing the system must understand the requirements derived by the science team and the reasons behind these requirements. If they do not, much effort can be spent attempting to meet requirements which turn out to be unimportant. See Chodas for a more in-depth discussion on system requirement tracking through the design process [53].

On the other hand, there can be situations in which requirements are changed or new ones are introduced such that the current system no longer meets requirements. This situation can occur when engineers learn more about their system and the mission. In accordance with the need to meet requirements, if modifications or requirement additions cause the current design to fall out of compliance, modifications are required.

Consider Changes When the Modification Will Save Money, Schedule, or Required Labor

In certain situations, design changes can save resources by easing and reducing the cost of hardware procurement, assembly, handling, or operations. This point can be the case when an existing design requires significant excessive effort, cost, or other resource, either to fabricate or use with the system. Teams must consider and examine whether a change can save more resources than will be spent making the change. A change that simplifies and reduces the demand for resources can be beneficial if it saves funds or frees up a team's schedule. Designs that require complex and expensive machining, processing, or assembly procedures can unnecessarily drain resources and put strain on a project. Although design changes will require some upfront effort, time, and budget investment, it is possible that the resource savings outweigh the amounts spent. Similarly, it may beneficial for a team to make a design change that is more costly, but will save time and effort, which may be more valuable to a team depending on where in the project life a team is.

One REXIS example that falls under this category is the change from EM to FM MLI button design. The REXIS team made a change to the MLI button design that greatly reduced the complexity of button installation and was much more feasible given the limited facilities and equipment available to the REXIS team. The EM used MLI buttons that adhered to the structure both with epoxy and with threading. The epoxied buttons contained a flat underside and adhered to the spectrometer at custom locations desired for mechanical attachment of MLI blankets. The use of this particular design for the buttons proved to be difficult. Surface preparation, including ensuring no material coatings are present at the epoxy locations and surfaces are abraded, add costs and effort. Additionally, flight specifications dictate a rigorous mixing and curing process for epoxy adhesives that is difficult to achieve with REXIS lab limitations. Proceeding with this design would be difficult and require the cost investment towards new equipment and facility capabilities and the time investment to learn how to perform the epoxy curing process to specifications. The REXIS team solved this issue with a simple change to use all threaded MLI buttons and to adjust the placement of these buttons on the spectrometer.

Consider Changes When the Modification is a Safer Design, Either From an Operational or Integration and Handling Viewpoint

Some changes should be made because doing so reduces the risk of operational failure or the risk of damaging a system during assembly, integration, or test. As discussed in Section 5.1.3, machining and handling should factored into the design. Therefore, the next generation of a design may require changes if the current design creates unnecessary risks to the system. A design change can be well worth the resource investment if it prevents flight hardware from being damaged due to handling prior to ever launching (reference the integration example discussed in Section 5.1.3). Likewise, teams should try to invest resources into system design areas where a failure could be mission-ending. Many aspects of one's system will be surrounded by large uncertainties, often due to lack of knowledge of the true operating conditions or how particular hardware will respond in a space environment. Especially when high-uncertainty aspects of the system are also closely tied with high consequence of failure, it is desirable to have as much protection against failure as possible.

The operational concerns of the Radiation Cover and Frangibolt system fall under this category. Failure to open the Radiation Cover is a critical failure for REXIS as it means the instrument in unable to collect any data from Bennu. In this case, effort spent to reduce the Radiation Cover risks is appropriate because REXIS cannot be successful without the Radiation Cover performing correctly. Even though the EM Radiation Cover design functioned sufficiently during testing, further effort was invested a Radiation Cover failure has a mission-ending consequence. To alleviate the risks that the Cover will not open during flight, various changes were made. One important modification implemented was the reduction of the total metal-to-metal contact area between the Radiation Cover and the Upper Mask Frame; lowering this contact area reduced the risk that the surfaces cold weld together. This minimization of contact area also improves heater efficiency, and coupled with a new MLI layout design, the Radiation Cover thermal system should be more effective. Keeping the Frangibolt warm is one of the most important ways REXIS attempts to mitigate the unknown effects that the multi-year cold storage will have on the Frangibolt.

Avoid Changes to a Functioning but Non-optimal Design

Teams should avoid making design changes to a design that meets requirements, even if there are identifiable areas of improvement. If an aspect of a system functions as desired, one should avoid making design changes simply because it can be "better", especially if the system has successful test history. These points become increasingly more important as the project progresses. Recall that design freedom is maximized early in the project life cycle and decreases with time. A design change late in a project's life may incur the need to update CAD models and drawings, revisit a number of analyses, revise documents, and perform additional testing. Additionally, these changes are not isolated from the rest of the system. An adjustment in one aspect of the design will impact another region. Therefore, when a structural engineer makes a hardware change, the thermal system may be impacted, requiring additional effort on the part of the thermal engineering team to verify all thermal requirements are still met; a seemingly simple hardware design often demands a large amount of work on multiple individuals. The further the team is in the project's development, the more intertwined subsystems become, making late changes time and cost consuming. By minimizing the amount of unnecessary changes to the design, one frees up resources to be allocated to more difficult and pressing areas of the project.

While many downstream effects from a desired or implemented change can be traced and identified, there is the potential threat that certain impacts are not recognized beforehand. Changing a functioning design that has been verified with testing introduces the risk that the project moves forward with an untested design. This scenario is dangerous due to the unknown risks that may emerge at a later time. A large threat exists where one creates a problem that is not identified until much later, by which point there is not enough room in the schedule or it is prohibitively expensive to modify.

One REXIS example is the design of the flight Thermal Strap. Recall this Thermal Strap connects the DAM to the Radiator with flexible copper braids. A good thermal connection between the DAM and Radiator, through this Thermal Strap, is essential for maintaining CCD temperature requirements. When the EM strap was procured and installed, the flexible braids bowed outward, causing considerable lateral forces in the X axis, the axis in which the Thermal Strap was compressed (See depiction in Figure 5-2).

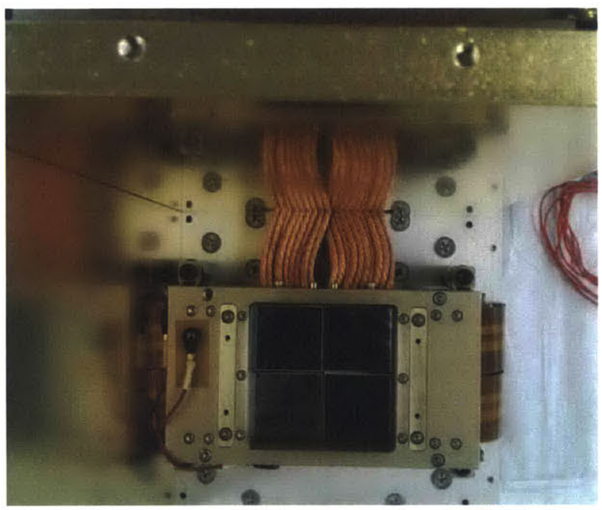


Figure 5-2: Top view looking down on the DAM within the Spectrometer. One can see the Thermal Strap bowing outwards once installed.

Several potential issues to REXIS emerged as a result of the experiences encountered when installing the Thermal Strap. The first concern was that this lateral force, as its quantity was unknown, could damage the threads of the Torlon standoffs which have been identified as weak points in the standoffs; minimal loading is desirable for the Torlon standoffs due to their known weakness. The second concern was that the CCDs could be damaged during installation. Integrating the DAM onto the Torlon standoffs proved to be difficult when having to oppose and overcome the lateral forces supplied from the Thermal Strap.

During the design update phase from the EM to the FM, the REXIS team ultimately decided to make no changes to the existing Thermal Strap design despite some of the assembly concerns. Changes to the design potentially could introduce additional issues. Provided with manufacturing tolerances of +/- .050" on the Thermal Strap length, specifying the Strap length smaller could have resulted in a Thermal Strap with nearly no slack. Furthermore, deformation predictions between the Radiator and DAM were uncertain. It was preferable that the Thermal Strap have excess slack and provide lateral forces, than to have no slack and risk failures due to high stresses caused by the trap's inability to absorb deformations. Although there were issues during assembly with the Thermal Strap, the team members knew the dangers and were prepared to handle these issues. The team decided it was safer to continue with a design that had known flaws and allowed our instrument to pass environmental testing, rather than change the design in the attempt to solve some issues, and risk inadvertently introducing new problems.

5.1.5 Build and Interact with Hardware as Early as Possible

Physical interaction with hardware proved to be one of the most valuable sources of information to the REXIS team. Working with hardware enables one to examine a current system design and discover issues that are difficult to find when the design resides in a non-physical computer model. For this reason, it is important to build prototypes and test units of the hardware as soon as possible. The earlier a team is able to start working with hardware and building their system, the sooner they will be able to identify issues that require fixing. The sooner these problems can be discovered, the more time, effort, and money will be saved making a better design. When handling the physical system, one is forced to consider and evaluate many factors including assembly, handling, and performing tests and inspections. A lot of factors do not become illuminated until one is able to physically interact with the system.

The majority of modifications made from the EM to the FM were a result of working with the EM. The EM assembly experience informed the REXIS team of many existing issues with the EM design. Some of these issues included parts that did not fit together as they were intentionally designed. Other problems such as difficult assembly procedures were a result of how the parts were designed to integrate together. The ability to go through the actual instrument assembly showed areas where changes would be valuable for the flight design.

Furthermore, being able to conduct testing with the EM forced the team to consider all the various factors that are required to perform the test as well as evaluate the performance of the system. Factors such as sensor instrumentation, cabling, mounting hardware, and data acquisition software are introduce questions which must be thought through. The sooner testing begins, the sooner inevitable issues will be encountered. Therefore, teams are able to more quickly discover and solve problems. Ultimately, programs will save resources by discovering and addressing problems through the early procurement and interaction with hardware.

5.2 Lessons from Analysis and Test

5.2.1 Consider These Factors When Selecting Analysis or Test

Resource-constrained projects will encounter situations where both extensive analysis and testing cannot be performed to examine a part of a system. Project teams will need to make decisions regarding whether they choose to invest in an analysis or a test to answer questions. The return on investment should always be examined when choosing to allocate resources towards an analysis or test. The goal is to choose the method that provides the most effective result with the lowest expenditure of resources. This section presents various factors that teams should consider when deciding whether an analysis or test is more beneficial.

Consider the Goal of the Analysis or Test

The information one wishes to acquire about their system should drive whether an analysis or test is appropriate. For example, designing a structural feature requires a very different approach from understanding whether a mechanism or a fully integrated system will function in the space environment. Sometimes an analysis is sufficient to provide all of the information desired. In other cases, testing is preferred to better understand how a system will behave under certain operating conditions, information that analysis may be unable to provide.

Consider the differences between the need to design a structural element and the need to verify system requirements. Analysis is a valuable method for the former because analysis allows one to create a workable design without having to fabricate multiple units. On the other hand, analysis is only effective if the assumptions under which an analysis is created match the as-built unit. Sometime assumptions can be violated without one's knowledge. For this reason, it is important to ensure that analysis assumptions are valid for the system under inspection. As uncertainty in the analysis increases, more margin should be allocated to the analysis results. In many situations, testing is a useful preferred method for verifying requirements as testing can often put a system through a more realistic and representative environment as compared to an analysis.

As systems become more integrated, it becomes more valuable to perform testing. Consider a fully integrated system that must be examined under environmental loading conditions, whether they be structural or thermal performance. A structural analysis or thermal analysis may be able to provide information regarding if the system will meet structural or thermal requirements, but it is much more difficult to obtain answers that include other engineering disciplines. For example, a random vibration analysis or thermal analysis will do little to answer whether the electronic components will function correctly after experiencing these loading environments. Multidisciplinary interactions are much more difficult to capture in analyses and often warrant the use of testing to fully understand system performance.

An example where analysis is valuable is structural analysis. Because it is very expensive and time consuming to procure hardware. It is desirable that the hardware is designed to survive expected loads. It is not realistic to build structures through trial and error using multiple tests. Rather, the structure is analyzed to ensure it is strong enough to withstand expected loads, and then procured to analyzed design.

Later, the structural design is verified through structural testing. Analysis is used for the design, testing is used for the requirements verification. These steps were taken by REXIS. Once the team was confident in the design created through analysis, the EM was procured and verified through structural environmental testing.

Likewise, sometimes significant aspects of a design are too complex to effectively model. An example is determining whether the Radiation Cover will open in its operating environment. One uncertainty in this equation is whether torsion springs have enough torque margin to overcome resistive torques. These resistive torques can be due to a number of factors including resistance from harnessing and friction in the hinge, issues that can both be made worse by the extreme temperature environment experienced. In particular, developing a realistic model to capture the resistance from a Radiation Cover harness is difficult for many including nonlinear reaction forces caused from the harness and unknown knowledge of how the thermal environment will affect the harness stiffness. Answers to these questions can more readily be attained by working with actual hardware and performing a test such as measuring torques on the actual hardware and deploying the Radiation Cover in a flight-like environment.

Consider the Confidence in the Results Provided by the Analysis or Test

It is important to consider the fidelity of the analysis or test and how confident one is in the results. Analyses that are easy to perform but lack sufficient fidelity or provide results that one cannot confidently use, are not very effective. When there is large uncertainty in the results provided by an analysis, it may be prudent to use a more realistic and representative test.

Recall from Section 4.1 the design, testing, and analysis of the original Torlon standoffs for the Tower TIL. Basic test results from pull tests of the standoffs, combined with analysis force predictions generated structural MS. Although analysis showed positive MS against pull and shear forces, the design eventually changed to a more robust Ti standoff design. The team made this change because there was uncertainty in the reliability of the analysis results. The analysis performed did not sufficiently examine different types of loading such as fatigue loading occurring during launch vibration or even few cycles of stress near, but underneath, the yield stress. Attempting to answer these questions can be difficult using analysis when the characteristics of Torlon or other analyzed subject is not well known. While the analysis techniques were not necessarily incorrect, attempting to apply these analysis techniques to a material that is not well understood created uncertainty in the results. Because the TILs are such critical interfaces, the team made a design change to use a material where analysis predictions are much more trustworthy.

In this particular example, the Torlon analysis had a lot of uncertainty in regards to how well Torlon would perform under environmental loads. An actual environmental structural test, such as random vibration, would have done a much better job at showing whether the Torlon design was sufficient. Howecver, to avoid the risk of a test failure after procuring REXIS hardware, the REXIS team changed the design such that analysis could be trusted. In this way, analysis on the new design could much better predict how the Ti standoffs would perform.

As discussed previously, the REXIS team primarily used testing to understand and examine the performance of the Frangibolt and Radiation Cover deployment system. There were large uncertainties surrounding how the system would perform in the low-temperature and vacuum environment. Analyses cannot provide sufficient results for the team to confidently answer these questions. Instead, testing was more effective as the team as able to put the hardware through realistic environmental conditions.

Consider the Resources Required to Perform an Analysis or Test

Similarly to the previous point, one driving factor in the decision is whether performing an analysis or test requires less resources. Analyses can sometimes be much reasonable than testing in certain situations. Complex tests that require a realistic vacuum and thermal environment while also simulating gravitational forces expected in space may simply be to difficult, time consuming, and costly to perform. Computer software that is able to replicate these scenarios can be more useful. Additionally, complex testing can be very expensive and difficult to perform for resource-constrained projects. Similarly, certain analyses can be difficult to set up and yield nebulous answers, whereas a test can provide more clear and decisive results.

Regarding REXIS, Section 3.2.2 talked about how there were concerns that the shock from either the initial Frangibolt actuation or the impact from the Radiation Cover hitting the back end of the Mask Frame might damage the CCDs. Also discussed is how the shock test performed with a live CCD helped show that the CCDs will be able to withstand a Frangibolt actuation. However, prior to this test, the REXIS team had spent some time attempting to quantify shock felt by the CCDs on account of the actuation. Initial efforts were spent acquiring accelerometers, calibrating them, and trying to measure acceleration data from input shock sources. The goal was to provide the acceleration data from a Frangibolt actuation to CCD expert personnel at MIT Lincoln Laboratory in order to compare our data against environments to which CCDs are known to have been exposed. This comparison would show whether the shock condition of the Frangibolt actuation is something the CCDs have been tested to before and would help determine if the CCDs would be expected to survive this condition.

However, pursuing this option did not unfold as planned. The team experienced difficulty in establishing an effective data acquisition setup for the accelerometers due to facility constraints. Furthermore, initial attempts at sensor testing and calibration shows the accelerometers behaving inconsistently between one other. Lastly, questions remained whether MIT Lincoln Laboratory would have useful statistics or testing data against which the Frangibolt shock could be compared. Attempting to derive a conclusion from a more analytical approach of this shock question was proving difficult and time consuming.

Reevaluating the position the REXIS team was in and what needed to get accomplished, a different course of action seemed necessary. The team investigated options for a more simple approach that could provide a more definite answer to whether or not the CCDs would be damaged from a Frangibolt actuation. This search led to the discovery of a non-flight engineering CCD unit available for testing with a Frangibolt actuation. Described in Section 3.2.2, this live CCD was installed in the REXIS spectrometer and a Frangibolt actuation was performed. CCD functional tests performed before and after the Frangibolt actuation confirmed that no damage occurred as a result of the shock. Performing this test proved to be much easier than the previous method and also provided a much more clear answer. Spending a little more effort initially to determine how effective possible approaches were in solving this problem could have saved a lot of time and effort.

5.2.2 Evaluate These Test Aspects to Avoid Failures

It is necessary to understand the various ways in which a system can fail under test and operation. System failures can cause programmatic problems due to the cost and time associated with replacing broken hardware. In order to avoid the consequences that testing failures can have, this section highlights important areas that should be considered when performing any tests. While some effort is required to ensure testing is safety carried out, the potential consequences of failing to do so are much more sever. This section discusses several techniques and methods for failure analysis followed by some key areas where is focus is needed.

Understand How the Test Article can Fail

Prior to all hardware testing, it is important to identify and address all the potential ways the test article can behave or fail during the test. Additionally, one should consider how these failures can impact the mission. The purpose of this lesson is to encourage engineers to expand their viewpoints and consider aspects of their hardware not previously identified. Often times individuals become focused on what a piece of hardware should do and perhaps begin to neglect what it should not.

Recall that the REXIS ability to gather science data relies on the Radiation Cover's ability to open upon the arrival to Bennu; if the door fails to open, the CCDs have no view of the asteroid and REXIS cannot complete it's science goals. This concern drove the focus of the Frangibolt actuator to be whether it could actuate at a temperature of -40 ℃, the cold operational requirement at the time, after being kept in cold storage for over two years. Significant effort was spent to ensure the Frangibolt could operate at these low predicted temperatures, that the Radiation Cover springs had sufficient torque margin to overcome any resistive torques due to harnesses, and that the Radiation Cover design was resilient against the risks caused by it expected operating conditions.

For a long time, the primary Frangibolt efforts were concerned with ensuring it could operate under its expected operating environment. The threat of contamination from a Frangibolt overheating was discovered by a chance accident (See Section 3.2.3). While the REXIS team was aware of the danger of overheating, this failure helped encourage the project to look into the contamination threat it posed to OSIRIS-REx. Since the identification of this risk to the spacecraft, REXIS has put significant effort to mitigate the contamination risk due to the Frangibolt overheating.

It is possible that had the REXIS team considered all the failure modes, or asked the manufacturer what will happen to the Frangibolt if exposed to different scenarios including excessive power application, the team may have ultimately selected a safer mechanism. It is hard to speculate what the outcome there might have been with a greater understanding of the Frangibolt, but these sorts of inquiries and examinations can help identify issues earlier. This early diagnosis can allow teams to either make design changes while there is still design flexibility or begin working on a solution to the problem earlier.

Ensure the Test Setup is Safe

It is important that the safety of the test setup is considered when designing a test. There are situations where a test failure can occur as a result of an unsafe test setup, even when there is nothing wrong with the system design. Extensive effort goes into ensuring that a design is predicted to pass its loading conditions and will satisfy its requirements. Equal amounts of consideration must go into the test setup under which the test article will be placed. Considering the cost and effort that is often used to perform complex tests, one must be sure not to induce a failure as a result of how the test was conducted. Furthermore, one does not want to confuse a failure due to the test setup as a failure due a poor design because one may spend resources creating unnecessary design changes. The test setup will influence the performance of the test article and one must design the setup so that its unintended influences are minimized. Relatively small amounts of upfront effort to inspect the test setup can save large cost and schedule delays that can result from a test failure. If not carefully prepared or inspected, a mistake in the setup can cause significant damage to the test article.

The Frangibolt overheating discussed in Section 3.2.3 is one example of a harmful test setup. The system itself was performing in the same conditions as all others, but the test setup was different in such a way that led to a failure. The REXIS setup procedure did not include verifying the unobstructed motion of the Radiation Cover which was essential for feedback on cutting power to the Frangibolt. Without a through inspection of the test setup in place, certain unsafe factors were not caught until a problem occurred. Safety analysis techniques may have helped the team identify that a failure in the feedback would cause an overheating of the Frangibolt. This feedback failure could be traced back to factors that prevent the switch to change state, such as the door not opening. While it is not guaranteed that this problem would have been caught and the failure avoided, an inspection can help reduce the chances of accidental mistakes leading to costly failures. Thinking through and examining the safety of a test setup is an important step for avoiding costly and problematic system test failures.

Ensure Feedback Measures All Quantities of Interest

Feedback signals should measure the desired quantities of interest during a test, rather than relying on indirect measurements to describe the performance of a desired quantity. The reason is that indirect measurement signals can sometimes be inconsistent with a system's performance. For example, consider again the Frangibolt overheating problem in Section 3.2.3. There were two desired quantities of interest when it comes to Radiation Cover deployments. First, the team desires to know when the Frangibolt actuates so power can be cut. And second, the team wishes to know if the Radiation Cover opens successfully upon Frangibolt actuation. The temporary switch in place during this overheating example was a direct measurement of the Radiation Cover opening. However, it was also being used as an indirect measurement signal of the Frangibolt actuation. In other words, power was being cut to the Frangibolt when the temporary switch opened, even though the Radiation Cover position doesn't necessarily indicate the condition of the Frangibolt. As was seen in this particular failure example, there is the scenario that the Frangibolt actuates but the door does not open due to physical interferences. Therefore, the signal (Radiation Cover position) is not always consistent with the quantity of interest (Frangibolt actuation). While measurement of the Frangibolt actuation is difficult and can be more easily monitored through the door position, the risk of false negative is possible, as was experienced. When using feedback signals, it is important to consider what these measurement are indicating and whether the measurements are the direct values needed or a indirect signals of a desired quantity.

For the REXIS project, this failure reinforced the need for a robust and reliable actuation detection method. A signal that directly measures the actual Frangibolt state rather than the Radiation Cover position is essential to prevent overheating the Frangibolt. This particular test failure was a major driving force towards the Switch Washer eventually included in the Frangibolt stackup. The Switch Washer measures whether the Frangibolt is compressed or not, allowed one to know if the Frangibolt is still tightly torqued in the stackup or whether it has actuated. This method more directly measures the state of the Frangibolt rather than an effect that may or may not occur when the Frangibolt actuates. The scenario that the REXIS Radiation Cover does not open in flight, despite a Frangibolt actuation, is plausible considering the Radiation Cover will be stowed closed for over two years. This cold storage could impair the Cover's freedom of motion.

Utilize Formal Failure Analysis On Critical Areas of the Design

In addition to the consideration factors listed above, it is important to consider and include formal failure analyses on critical areas of design. While resource-constrained teams cannot realistically complete the subsequent failure analysis methods for all components and tests, they should be used on high risk aspects of the design. Several failure analysis methods are briefly listed. Sources are provided for further investigation on how these methods can be employed.

Popular methods for failure analysis include Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) [54] [55]. These methods examine potential ways in which a system can fail. FMEA and FTA techniques help one to determine a system's failure modes and then trace these failures to an outcome. These analyses typically look at various possible component failures and the result of such failures. They can be very beneficial for identifying areas where greater redundancy is desired or understanding what sorts of protection are needed to prevent unwanted failures.

Leveson introduces safety analysis techniques that examine unsafe intra-system interactions as well as external factors that lead to dangerous situations[56] [57]. The safety analyses introduced by Leveson go beyond probabilistic failure analyses, such as FMEA and FTA, to capture typically overlooked factors that contribute to system failures. Some of these factors include human interaction with a system and the disconnect that can exist between an individual's mental model of a system and its actual state. The techniques presented by Leveson help illuminate situations that are unsafe and can cause accidents even when there were no failures in the system performance.

Chapter 6

Conclusions

6.1 Thesis Summary

This thesis covered the design, analysis, and testing of the REXIS FM structural design being flown on OSIRIS-REx. The flight structural design was presented in detail, discussing how this design allows REXIS to achieve its science mission within its imposed mission constraints. There are two constraints the drive the REXIS design. A low CCD temperature requirement led to the creation of an important thermal and structural interface, the TIL. Significant effort went into designing, analyzing, and testing this critical interface. Secondly, the need to protect the CCDs against radiation damage resulted in the creation of a one-time deployable Radiation Cover. The cold-storage coupled with contamination requirements caused the REXIS team to put significant effort towards the design, analysis, and testing of its Radiation Cover deployment system. The main steps through the structural development relating to these two major REXIS elements were presented. As the REXIS team has limited resources, it must choose to spend its resources intelligently. The discussion in this thesis shows the decisions the team made in regards to how effort was allocated to create a functioning structural design. It is important to remember that the REXIS team cannot eliminate all risks. Instead the team operates under a risk-tolerant philosophy in which it uses its resources to address the most critical risks while accepting less severe ones. Effective risk management was an essential aspect of the REXIS development so that resources could be spent in the most important areas. Lastly, this thesis presents lessons learned regarding the design, analysis, and testing of small space systems. These lessons discuss areas the author believes should be given attention when operating in a limited-resource environment. There are many factors which can increase cost ot delay a project, and the lessons discussed in this thesis attempt to address some major points that could help teams conserve their resources throughout a system's development.

6.2 Concluding Statements

When faced with tight resource constraints, it is essential that projects teams utilize their resources most effectively. Furthermore, with so much pressure to create a fail-proof system, it can be difficult to remain within a given budget or schedule. Attempting to address every potential risk and make a system ultra-reliable is likely to make it run over schedule and budget. Instead, it is important to evaluate which areas of a system are most critical and which risks have the biggest impact on the system. Furthermore, knowing which tool to use, whether a form of analysis, test, or combination of both, for solving questions is a valuable skill that can help one allocate resource efficiently. There can be many aspects that pressure teams to overlook certain areas of designing, analyzing, and testing. The lessons learned in this thesis provide particular areas that have been valuable throughout the REXIS development. The examples and lessons presented in this thesis are meant to give future teams factors to consider in order to help reduce the over cost and length of a space mission program.

Appendix A

Tables

Table A.1: Primary Switch Washer installation torque measurements without Braycote on bolt threads

Trial	Torque (in-oz)
1	5.0
2	4.25
3	3.6
4	4.0
5	5.25
6	4.0
7	5.0

Table A.2: Secondary Switch Washer installation torque measurements without Braycote on bolt threads

Trial	Torque (in-oz)
1	7.0
2	6.0
3	4.75
4	4.0
5	4.0
6	8.0
7	6.0

Table A.3: Secondary Switch Washer installation torque measurements with Braycote on bolt threads

Trial	Torque (in-oz)
1	2.75
2	2.5
3	2.5
4	3.0
5	3.0
6	3.0

Table A.4: Secondary circuit measurements of load necessary to change the Switch Washer state from open to closed

Trial	Preload (lbf)
1	3.86
2	3.90

Table A.5: Frangibolt Actuation Summary

Test #	Date	Actuator S/N	Switch Washer S/N	Temp (°C)	Voltage (V)	Washer Material	Time to Actuate (s)
1	7/18/2013	F1048	-	23	9.0	Ti	23
2	7/25/2013	F1048	-	23	9.0	Ti	26
3	7/25/2013	F1048	-	23	9.0	Ti	29
4	7/30/2013	F1048	-	23	9.0	Ti	33
5	8/8/2013	F1048	-	-26	9.0	Ti	77
6	8/9/2013	F1048	-	-48	9.0	Ti	180
7	8/20/2013	F1048	-	23	9.0	Ti	37
8	8/26/2013	F1047	-	23	9.0	Ti	21
9	9/9/2013	F1047	-	23	9.0	Ti	23
10	9/10/2013	F1047	-	-40	9.0	Ti	124
11	10/9/2013	F1047	-	-28	9.0	G10	47
12	1/21/2014	F1101	-	23	10.0	Ti	21
13	1/21/2014	F1101	-	23	10.0	Ti	20
14	1/22/2014	F1101	-	23	10.0	G10	15
15	1/23/2014	F1101	-	-46	10.0	Ti	78
16	1/24/2014	F1102	-	-37	10.0	Ti	80
17	1/25/2014	F1102	-	-28	10.0	G10	31
18	1/25/2014	F1102	-	-37	10.0	G10	39
19	1/25/2014	F1102	-	23	9.0	G10	18
20	4/2/2014	F1102	-	23	9.0	Ti	24
21	4/30/2014	F1102	-	23	9.0	Ti	30
22	5/6/2014	F1102	-	-30	9.0	Ti	85
23	5/21/2014	F1102	-	-8	9.0	Ti	54
24	5/28/2014	F1102	-	23	9.0	Ti	30
25	10/2/2014	F1041	-	23	9.0	Ti	25
26	10/3/2014	F1041	-	23	9.0	Ti	23
27	12/15/2014	F1041	-	23	9.0	Ti	26
28	1/23/2015	F1041	1002	23	9.38	Ti	28
29	4/8/2015	F1041	1002	23	10.35	Ti	17

Appendix B

Frangibolt Reset Procedure

The following discusses the procedure for resetting the Frangibolt and associated deployment system hardware on REXIS. This scenario assumes that the Frangibolt has already been actuated and needs to be reset and reinstalled. This procedure will describe the exact steps needed to carry out this operation. It is important to note that the Radiaiotn Cover subassembly can only be installed onto REXIS without the Frangibolt installed. Therefore, Frangibolt must be installed on the Radiation Cover once the instrument has been fully assembled. If a subassembly test is performed, this procedure can, however, be used for a reset and installation of the Radiation Cover subassembly.

B.1 Installation Requirements

B.1.1 Frangibolt Stackup

- Custom TiNi #4 Titanium (Ti) Fastener (REX-RC-012)
- Ti Thermal Isolation Washers (x2) (TiNi P/N: WI-2821)
- Switch Washer (TiNi P/N: WI-3596)
- Frangibolt Actuator (TiNi P/N: WI-2953)
- Locknut (MS21043-04)

B.1.2 REXIS Hardware

- Fully assembled REXIS spectrometer (REX-INST-002)
  - Several REXIS components are listed separately as they are removed and installed during this procedure
- Frangibolt Housing (REX-RC-011)
- Bolt Head Cap (REX-RC-006)
- #4-40 thread x 3/8" , socket head cap screws (x6) (NAS1352N04-6)

B.1.3 Reset/Installation Equipment

- Tray (to store loose pieces)
- Braycote 601EF
- Calibrated torque wrench
  - Able to torque to value of 90 in-lb (For Reset Tool)
  - Able to torque to value of 50 in-oz (for torqueing locknut)
- Frangibolt Reset Tool (TiNi P/N: WI-3549)
  - Including insert for Reset Tool
- Vice (to clamp reset tool)
- Pliers (for gripping small/tight surfaces)

B.1.4 Required Personnel

A minimum of two individuals are needed for the Frangibolt installation. One individual holds the Ti bolt in place while the other torques the bolt to the appropriate installation torque

B.2 Frangibolt Reset

This section covers the tasks needed to remove an already fired Frangibolt and reset it such that it is ready to be installed. The steps specifically regarding the compression of the Frangibolt in the Reset Tool are provided by TiNi aerospace [7]. Since the Frangibolt is actuated, special care must be taken not to drop the loose pieces contained by the Frangibolt Housing and Bolt Head Cap. Within each components are the following trapped pieces:

Frangibolt Housing (REX-RC-011):

- Frangibolt Actuator (TiNi P/N: WI-2953)
- Ti washer (TiNi P/N: WI-2821) (x1)
- Switch Washer (TiNi P/N: WI-3596)
- Locknut (MS21043-04)
- Shaft of broken Ti bolt

Bolt Head Retainer (REX-RC-006):

- Head of broken Ti bolt
- Ti washer (TiNi P/N: WI-2821) (x1)

The following steps list the actions needed to Reset the Frangibolt actuator:

1. Disconnect the Frangibolt and Switch Washer from the REXIS harness by disconnecting the connectors from these components.
2. Unscrew the four #4-40 x 3/8" screws holding the Frangibolt Housing to the Upper Mask Frame (REX-MA-103) and remove the Frangibolt Housing while capturing all loose components.
   (a) The Frangibolt Housing will slide down the Frangibolt and Switch Washer wires until the connector is fed out of the front hole in the housing.

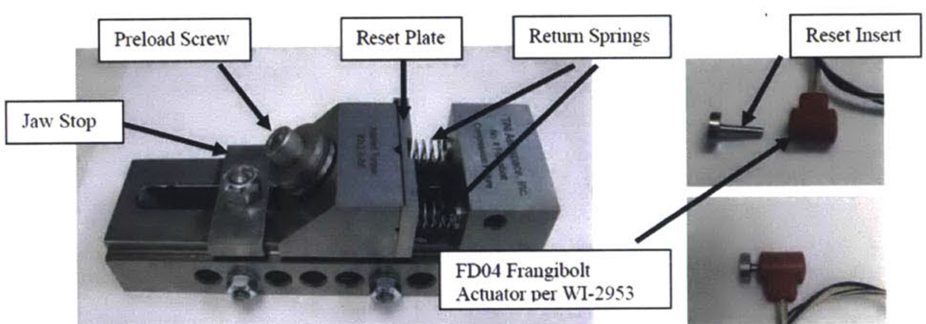
3. Unscrew the two #4-40 x 3/8" screws holding the Bolt Head Cap to the Radiation Cover Panel (REX-RC-021) and remove the Bolt Head Cap while capturing all loose components.

4. Store the Frangibolt Actuator, Switch Washer, Ti washers (x2), and locknut for re-installation. The broken bolt (shaft and head) are no longer needed).

5. Throughout the reset and installation, fill out the Frangibolt Test Log, REX-CD-043. This document records data regarding the Frangibolt used, the installation, and the test results.

6. Gather the following items for the Frangibolt reset (See Figure B-1 for picture of Reset Tool, insert, and Frangibolt)

    - Frangibolt Actuator (TiNi P/N: WI-2953)
    - Frangibolt Reset Tool with insert (TiNi P/N: WI-3549)
    - Calibrated torque wrench (able to torque value of 90 in-lb)
    - Vice



Method: The #4 Frangibolt is reset by compressing in a precision vise torqued to achieve the target force of 1,000 lbf.

Figure B-1: The Reset Tool with the insert and Frangibolt [7]

7. Prior to resetting of the Frangibolt, it should be measured with calipers to verify its actuated length. This actuated length should be 0.540"±0.005"

    (a) Do not measure where the seam of the actuator jacket is located as this could be a weak point and cause a tear

(b) Also note that the insulation jacket of the actuator will be longer than the compressed length of alloy (0.500") so the jacket will need to be compressed to accurately measure the alloy length

8. Place the Reset Tool in a vice to hold it in place during the reset.

9. Place the Insert provided into the Frangibolt. This insert ensures that the Frangibolt is aligned properly and compressed to the correct length. Slide the Frangibolt/Insert Assembly into the slot machined into the Reset Plate and hand tighten the preload screw, ensuring the insert head is at the bottom of the groove and flat against the back of the groove (See Figure B-2).

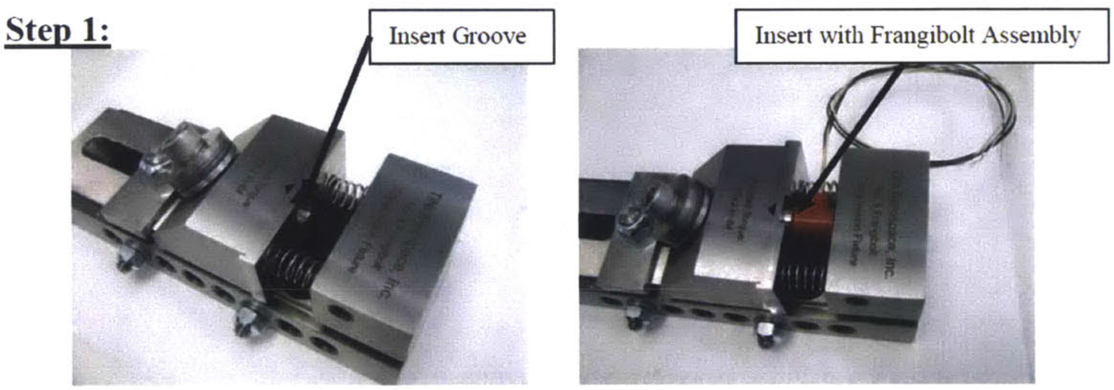


Figure B-2: Placement of Frangibolt in Reset Tool [7]

10. Using a calibrated torque wrench, tighten the Preload Screw clockwise, until 90±2 in-lbs of torque is reached. Back out the Preload Screw enough to remove the actuator from the tool, and measure the actuator (See Figure B-3).

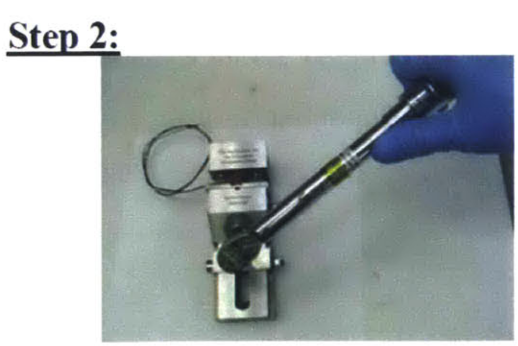


Figure B-3: Compression of Frangibolt [7]

11. The actuator length should correspond to the values below. If value is outside of this. double check measurements and compress again if necessary (See Figure B-4)

    (a) Do not measure where the seam of the actuator jacket is located as this could be a weak point and cause a tear

    (b) Also note that the insulation jacket of the actuator will be longer than the compressed length of alloy (0.500") so the jacket will need to be compressed to accurately measure the alloy length

Step 3:

Part Number	Compressed Length	Tolerance
WI-2953	0.500	+/- 0.005

Figure B-4: Frangibolt measurement [7]

12. Once the Frangibolt is successfully reset to 0.500"±0.005", return to REXIS for installation of the Frangibolt with a new bolt on the Radiation Cover

B.3 Frangibolt Installation

At this time Frangibolt stackup will be assembled onto the Radiation Cover. It should be noted that the following photos are taken from an installation of the Radiation Cover subassembly removed from the rest of the spectrometer. As the reset should be performed with the full assembly, and these photos are only meant to show how the Frangibolt assembly fits on the Radiation Cover door and Mask Frame and not to imply that the Frangibolt should only be performed on the Radiation Cover subassembly.

The following materials are required for the installation process:

- Reset Frangibolt Actuator (TiNi P/N: WI-2953)
- Switch Washer (TiNi P/N: WI-3596)
- Custom Ti Bolt (REX-RC-012)
- Ti Washers (TiNi P/N: WI-2821) (x2)
- Locknut (MS21043-04)
- Braycote 601EF
- Pliers
- Calibrated Torque Wrench (able to achieve torque value of 50 in-oz)
- Frangibolt Housing (REX-RC-011)
- Bolt Head Cap (REX-RC-006)
- #4-40 thread x 3/8" , socket head cap screws (x6) (NAS1352N04-6)
- Tray (to capture loose pieces)

Once these items are collected and located at the spectrometer for installation, follow the following steps:

1. Apply a thin coat of Braycote to the threads of the bolt being used in test. A small dot of Braycote on disposable gloves works best in order to apply Braycoat into the threads.
   (a) Once the Braycote has been applied, remove the Braycote from the area to prevent its inadvertent contact with other components.
   (b) Discard and retrieve new gloves
2. Install one thermal isolation washer on the Ti bolt and insert bolt through Radiation Cover from the top (See Figure B-5).

(a) As the door will be held open by the springs, one must take care to keep pressure on the bolt head and Radiation Cover so that the bolt and washer do not fall out

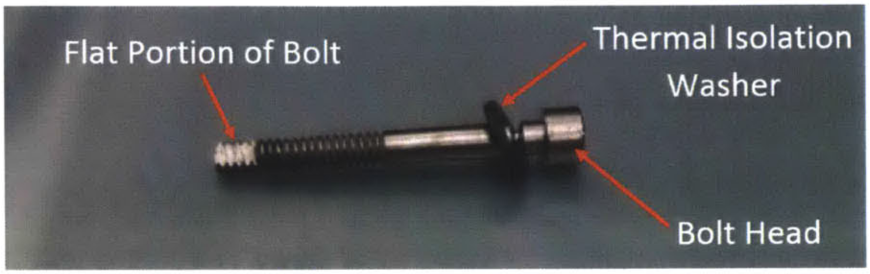


Figure B-5: Ti washer on Ti bolt

3. Close door with hand. Bolt should enter a receiving hole in the Upper Mask Frame (See Figure B-6).

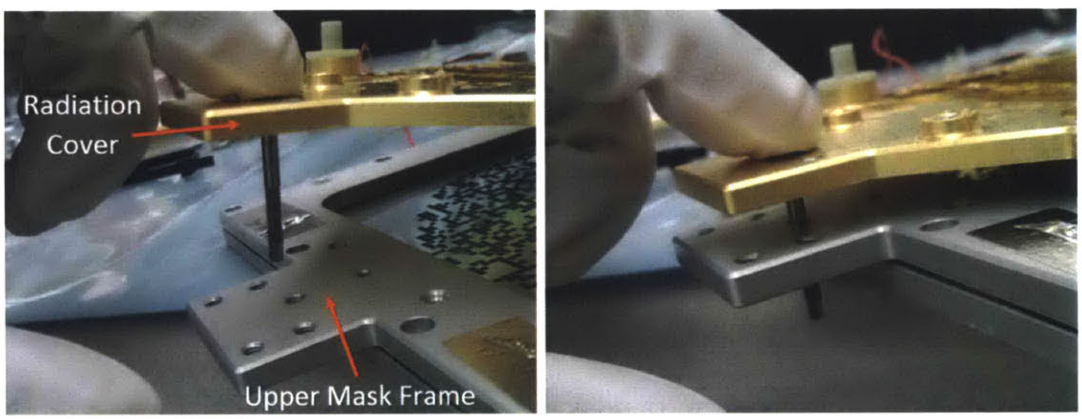


Figure B-6: Fitting Ti bolt through Radiation Cover and Upper Mask Frame

4. Install a second Ti washer on the bolt

5. Install the Frangibolt Actuator on the bolt

   (a) The Frangibolt actuator should be oriented such that the wires exiting the Frangibolt come out towards the -X direction of the REXIS axis.

6. Install the Switch Washer on the bolt

   (a) The underside of the Frangibolt actuator should be touching the compressible side of the Switch Washer

(b) Like the actuator, the wires of the Switch Washer should come out towards the -X direction of the REXIS axis.

7. Insert locknut on end of bolt and use torque wrench to secure bolt until all pieces (Ti washer, Frangibolt, Switch Washer, and Ti bolt) are barely touching. Measure and record the amount of running torque (the torque needed to move the nut down the shaft). Stackup should look similar to Figure B-7.

    (a) Note: When first getting the locknut up the Ti bolt threads, the head of the bolt will need to be held with pliers. Once the flattened portion of the bolt (See Figure B-5) is accessible with pliers, grip this area when torquing the the locknut and not the bolt head. Holding the bolt head stationary and torquing the bolt may cause excessive stress on the fracture notch in the bolt and cause the bolt to inadvertently break when using high torques. One must take care to hold the bolt steady to avoid unintentional stresses.

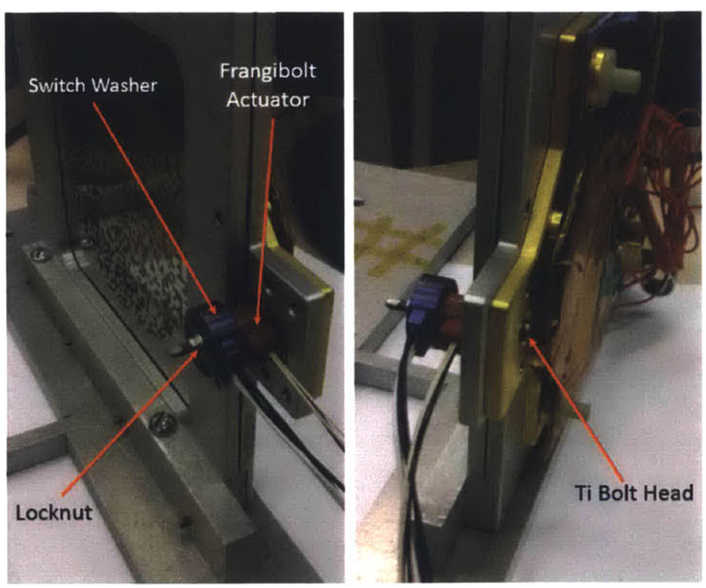


Figure B-7: Frangibolt stackup on the EM Radiation Cover subassembly. Note the Radiation Cover is oriented on its side in this photograph.

8. Once the pieces are all barely touching, use torque wrench to apply an installation torque of 50 oz-in in addition to the running torque.

(a) Use pliers to hold the flattened end of the bolt while the nut is torqued (do not hold the bold head).

(b) One individual holds the bolt with pliers while the other individual torques the nut with the torque wrench.

(c) As the nut is tightened, ensure that the actuator's orientation remains such that the wires come out towards the -X direction of the REXIS axis (wires stick away from the Radiation Cover).

9. Install the Frangibolt Housing underneath the Upper Mask Frame using four #4-40 thread x 3/8" , socket head cap screws (x6) (NAS1352N04-6)

10. Install the Bolt Head Cap on the Radiation Cover using two #4-40 thread x 3/8" , socket head cap screws (x6) (NAS1352N04-6). Result should look similar to Figure B-8.

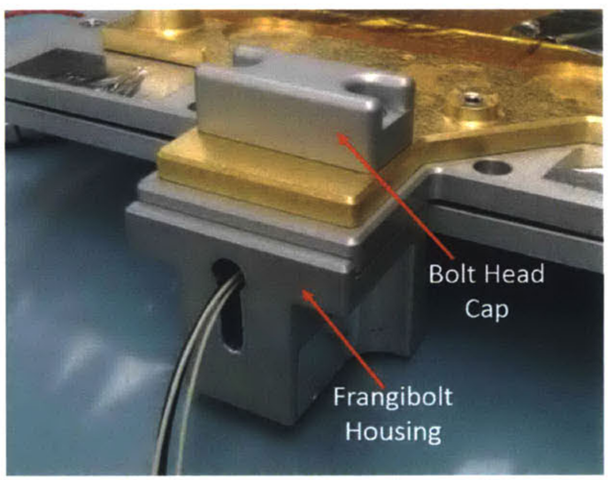


Figure B-8: Frangibolt Housing and Bolt Head Cap attached to Upper Mask Frame and Radiation Cover. Frangibolt stackup contained within.

11. Reattach the Frangibolt wires to the REXIS harness. White wires are the primary heater and black wires are the secondary heater.

12. Reattach the Switch Washer wires to the REXIS harness. White wires are the primary circuit and black wires are the secondary circuit.

At this point the Frangibolt reset and installation is complete.

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