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DESIGN, HAZARD ANALYSIS, AND SYSTEM LEVEL TESTING OF A UNIVERSITY PROPULSION SYSTEM FOR SPACECRAFT APPLICATION

by

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A THESIS

Presented to the Faculty of the Graduate School of the

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Approved by

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ABSTRACT

The Missouri Science and Technology Satellite (M-SAT) design team on the campus of the Missouri University of Science and Technology has developed a pair of satellites to perform an autonomous formation flight mission. To enable the mission, a unique cold gas propulsion system was developed which utilizes the refrigerant R-134a as propellant. This thesis details the design process and considerations which led to the propulsion system as integrated into the satellite for the Flight Competition Review of the NS4 competition. The design process described flowed from the mission requirements and program restrictions down through component-level requirements and resulted in a system capable of performing the assigned duties. The hazard analysis conducted for this thesis also expanded on previous analyses to address key issues and AFRL concerns. The analysis showed the system to be safe for personnel and equipment as designed. Finally, a propulsion test platform was developed to address the few remaining physical and theoretical performance questions remaining.

While future propulsion systems developed at Missouri S&T may face vastly different design and mission requirements, the example set forth by the NS4 system and described herein can serve as a starting point for such endeavors.

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I would be truly remiss if I failed to mention the support and guidance provided by my family. Much of what I am today can be directly linked to the efforts of my parents and for that I am grateful. I am also grateful for the support and thoughts of my two sisters; they have always been there for me.

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1. INTRODUCTION

The role satellites play in society today cannot be exaggerated as they directly impact every aspect of life, from the morning commute to evening entertainment. Such an all pervasive technology must continually adapt and improve to meet the ever expanding needs of the parent society while expending fewer resources. To meet the changing demands of the space industry, a paradigm shift in satellite design and operation is necessary. Under current design practices, satellites are large, complex systems which take a great deal of resources to launch and operate while lacking crucial flexibility in mission objectives. Small satellites offer an alternative approach to satellite operations with increased mission flexibility and smaller resource expenditure being the main attraction.

The vision that many people hold for the future sees constellations of small satellites, large and small, working together to accomplish the same goals of their much larger predecessors. Within the constellation, common tasks would be distributed among the individual satellites thus allowing the platform to have redundancy and simplicity. Also, such a design allows the entire constellation to be retasked merely by exchanging a few of the satellites rather than having to develop and launch and entirely new satellite. However, to fully realize the advantages offered by small satellites, enabling technologies such as micro-propulsion systems considered in this study must first be developed.

1.1. CLASSIFICATION OF SATELLITES

There are many objective standards by which to classify satellites: mission, cost, orbit type, size, etc. Of these, the classification based on size, i.e. wet mass of the

satellite system upon launch, is perhaps the most useful since it has a direct correlation to launch costs associated with the project. In general, the moniker of "small satellite" is given to payloads having mass less than 500 kilograms. The commonly adopted classification system, including small satellite subsets, can be found in Table 1.1 below.

Category	Mass range (kg)
Large Satellite	>1,000
Medium-Sized Satellite	500-1,000
Small Satellite	<500
Minisatellite	100-500
Microsatellite	10-100
Nanosatellite	1-10
Picosatellite	0.1-1
Femtosatellite	<0.1

 Table 1.1: Satellite Classification System [1]

Small satellite programs are also often characterized by smaller operational budgets and quicker development times. This fact makes small satellite development feasible for university level programs as well as for technology demonstration platforms.

1.2. UNIVERSITY NANOSAT PROGRAM

The University Nanosat Program (UNP) is a joint endeavor between the Air Force Research Laboratories Space Vehicle Directorate (AFRL/RV), the Air Force Office of Scientific Research (AFOSR), and the American Institute of Aeronautics and Astronautics (AIAA) with the stated purpose of encouraging and training the next generation of aerospace engineers. Participating universities design, develop, and build a proto-flight satellite with a mission that is of interest to the Department of Defense (DOD). The program is set up in a competition format between participating universities vying for a free launch through the Space Experiment Review Board (SERB) process.

The competition is a two year cycle consisting of multiple design reviews by AFRL and Industry professionals. The course of the competition is as follows [2]:

Proposal Phase – The cycle begins with the proposal phase, in which interested universities submit documents detailing the university's objectives and capabilities. These documents are reviewed by AFRL personnel and a small number (~10) of universities are accepted into the program.

System Concept Review (SCR) – SCR comes early within the two year program and is meant as a chance for each university to convey to UNP officials the mission objectives, design concepts, program feasibility, and expected schedule of their project.

Preliminary Design Review (PDR) – PDR is a review of the university's initial design with special attention paid to the implementation of all safety guidelines. Also at this time, AFRL representatives ensure teams have implemented proper program management and system engineering practices.

Critical Design Review (CDR) – CDR occurs at the end of the first year when university designs should be between 90% and 95% complete. This review is the last chance for AFRL representatives to assess the design for maturity, inherent risk, and compliance with program requirements before universities move in earnest into the build phase of the competition.

Proto-Qualification Review (PQR) – PQR occurs during the second year of the competition, and focuses on the universities implementation of their design.

Flight Competition Review (FCR) – FCR is the final review during the competition process. Universities must deliver a proto-flight satellite to the competition along with supporting documentation.

In addition to these design reviews, the UNP also provides guidance and training through a series of documents and workshops. Each team is given access to the UNP User's Guide which gives a detailed overview of the program milestones and design requirements that must be implemented in each university's spacecraft. Following the guidelines within the user's guide ensures each university spacecraft meets strict range safety criteria and will be able to survive launch. Three workshops are held during the competition; SHOT I, SHOT II, and a Satellite Fabrication Course. During both Shot I and Shot II, students from each university build a small device which is flown onboard a high-altitude weather balloon. The satellite fabrication class offered students an opportunity to observe AFRL satellite fabrication techniques as well as receive valuable information on proper procedure implementation.

1.3. M SAT OVERVIEW AND TEAM HISTORY

The M SAT program is a student design organization on the Missouri University of Science and Technology (S&T) campus. It began in 2004 with stated purpose of designing and building a satellite capable of performing technology demonstrations and furthering space systems knowledge within the community of S&T students. The conceptual satellite was to test and compare methods for maintaining Distributed Space Systems (DSS). In January of 2005, the M SAT program (then MR SAT) was accepted into the UNP Nanosat 4 competition (NS4). Though the course of the NS4 competition, the focus changed from comparing two methods of maintaining formation flight to a technology demonstration of autonomous formation flight. The M SAT team placed third out of eleven entries in the NS4 competition, a notable achievement for a team new to the program. The team was also named the Most Improved School.

1.3.1. Mission Overview. The main objective of the M-SAT program is the technological demonstration of close range autonomous formation flight utilizing two microsatellites; MR SAT (Missouri-Rolla Satellite) and MRS SAT (Missouri-Rolla Second Satellite). The formation is to be a follower/leader configuration with MR SAT maintaining a distance of 50 meters \pm 5 meters behind MRS SAT.

Achieving this objective requires the implementation of unique solutions to common satellite challenges. Inter-satellite communication, Attitude and Orbit Determination and Control, and indeed Satellite Propulsion all required new approaches if mission objectives were to be met. Technology demonstrations in these areas will provide future small satellite projects with more options to meet difficult mission objects through low-cost solutions.

The mission is organized into different mission modes based on the task required during that particular phase of the mission. The main divisions within the modes of operation are Launch, Initialization, Power-Up, Detumble, Pre-Deploy, Separation, Formation Flight, Range Test, and Extended Mission [3]. Each main mode is further divided into specific tasks that must be accomplished by the subsystems for the successful completion of that specific operation. The first five modes of operation occur while the satellites are in a docked configuration, as shown in Figure 1.1, while all other modes occur post-separation (Figure 1.2).

Figure 1.1: MR and MRS SAT in Docked Configuration

Figure 1.2: MR and MRS SAT Post-Separation

1.3.2. Current Status. After the conclusion of the NS4 competition, the team decided to continue with the construction and testing of the NS4 satellite design. The project is now entering the "Flat Sat" phase of development in which systems are to be integrated electronically to determine functionality and compatibility. The primary focus of this phase involves the C&DH and Power subsystems. As various electronic interfaces are developed, more of the satellite can be integrated into the Flat Sat until such a time as all systems are proven to work effectively together.

Independent of the Flat Sat, subsystems continue testing their components for functionality and performance. The structural strength of the satellite is currently being modeled using Finite Element Analysis.

1.4. PROPULSION REQUIREMENTS

Two sources of requirements are placed on the propulsion subsystem: NS4 design requirements and safety guidelines and M SAT mission requirements. Obviously both sets of requirements are imperative to the successful implementation of the satellite project; however, satisfying both sets of requirements is a difficult undertaking for a single propulsion system.

1.4.1. M SAT Mission Requirements. As stated previously, the main objective of the M SAT project is the demonstration of close proximity autonomous free formation flight. Any formation keeping mission requires a means to overcome the orbit perturbations inherent in space flight, hence some sort of propulsion system is necessary. Stemming from this main mission objective produces three system-level requirements:

- Provide all torques and forces required to maintain attitude and orbit control.
- Provide all torques and forces to maintain 50 meter formation flight with MRS SAT.
- Provide sufficient performance specifications and propellant mass to perform one orbit of formation flight.

Implicit within the mission requirements attached to the propulsion subsystem are other conditions and considerations which must be addressed by any successful design. Obviously a system which does not fit within the design envelope of the satellite or is excessively massive as to render the satellite unresponsive would fail to successfully accomplish the mission. Indeed, much of the system design, from the number and placement of thrusters to the necessary tank pressure, stems directly from these three simple statements. However, while adhering to these requirements ensures mission success, it by no means ensures the design of a safe, launchable system. For that, other requirements and regulations are placed upon the system.

1.4.2. NS4 Propulsion Safety Requirements. Given that the overall objective of the UNP is to develop flight-worthy spacecraft and guide such spacecraft though the launch process, safety is a foremost concern. Strict design criteria, while possibly inhibiting creative design approaches, ensure that any delivered spacecraft will be able to successfully navigate the flight approval process with a minimum of design changes. Different launch ranges and vehicles have unique regulations which must be met before launch clearance will be granted. In light of this, the only prudent course of action is to adhere to the most stringent of these standards: i.e. Space Shuttle Secondary Payload requirements.

For convenience and ease of use, the UNP has summarized the various requirements into a single limited release document: the NS4 User's Guide. As part of the NS4 competition, each team was expected to comply with guidelines and design requirements set forth in the User's Guide to ensure the safety and utility of the final satellite. In regard to a traditional propulsion system, the major requirement concerns the operation and implantation of a pressurized system. Any pressurized system must meet the definition of a sealed container as originally stated in NASA-STD-5003 *Fracture*

Control Requirements for Payloads Using the Space Shuttle. To meet the standard, the pressurized system must comply with the pertinent values highlighted in Table 1.2.

Propellant Property	Limit
P – Pressure (Absolute)	< 689.48 kPa (100 psi)
U – Internal Energy	< 19,319 kJ (14,240 ft-lbs)

 Table 1.2 Sealed Container Classification Limits [2]

On top of the sealed container requirement, the UNP provides a list of practices and design choices deemed either "discouraged" or "prohibited." Such practices that affect a propulsion system are listed below:

- The use of pyrotechnic devices and/or mechanisms is prohibited
- The use of toxic and/or volatile fluids or gases is prohibited
- The use of any material likely to undergo a phase change during launch or on orbit is discouraged
- Cast metallic or welded joints are prohibited
- It is prohibited for universities to manufacture assemblies for which safety is highly dependent upon the build or assembly process. (Composite Materials and certain deployment devices for example) If such assemblies are necessary, these processes must be completed or witnessed by aerospace professionals.

While following such guidelines will ensure the safety of the final design, it does not guarantee that the final design will be capable of meeting mission parameters. Universities are encouraged to follow User's Guide requirements wherever possible, and certain guidelines are non-negotiable; however, if need can be demonstrated a waiver process can be initiated.

1.5. PURPOSE

This thesis expands upon the knowledge previously acquired by the M SAT design team in the area of small satellite propulsion. Prior works have focused on the design and theoretical performance of the system and have laid the foundation for further development. With this work, the author attempts to discuss the design process and how the mission requirements and restrictions determine system-level requirements which in turn directly affect component-level requirements. By highlighting the process which led to the NS4 propulsion system design, in essence documenting the thoughts and motives of the design team, this thesis can serve as a guide for future system level testing plan to advance the analysis of the current system and again serve as a guide for future systems.

1.6. THESIS ORGANIZATION

This work is organized into six major sections to facilitate the understanding of the reader. A brief description of the content within each section is given below:

Literature Review – Following the introductory section, a short literature review is provided to present the proper context for this work. Within this section, an overview of small satellite history and development is first discussed with an examination of

various propulsion methods to follow. Finally, the expected future development of small satellites and the necessary technological advances are explored in detail.

System Overview – The propulsion system designed for integration into MR SAT is described in detail with an emphasis on component functionality. The integrated system and necessary design compromised and choices are explained.

Hazard Analysis – This section describes the possible hazards inherent within the system and the methods of mitigation implemented in the design of the propulsion system. It attempts to prove that the system is reasonably safe.

Testing – The testing methods and current results for the system are detailed within this section. The design and purpose of each system level test is discussed, and results are presented where applicable.

Conclusions – The final section summarizes the details previously described and lays the groundwork for future works and tests.

2. LITERATURE REVIEW

2.1. HISTORY OF SMALL SATELLITES

Over the centuries, space has captured the imagination of layman and expert alike: its vast expanse a promise of knowledge waiting to be discovered. As understanding of the physical realm advanced, so too did the methods and technologies utilized in scientific exploration. With the launch of Sputnik in October 1957, mankind's reach was finally extended beyond the atmosphere into the realm of space. While a significant achievement, Sputnik did little to further mankind's understanding of space containing only radio transmitters and no scientific payload. [4] Explorer I, launched only four months later by the United States, was a slightly more technically advanced platform incorporating basic scientific instruments to study the background radiation environment. [5] This first generation of artificial satellites were all small satellites out of necessity; however, as rocket performance increased small satellites began to give way to large, multifunctional platforms.

Throughout the next couple decades, while not entirely disbanded, small satellites were deemphasized within the space industry. Instead, satellites took advantage of the greater lifting capacity of modern rockets and ballooned in both size and mass. The mission tasks assigned to these satellites were thought too complex for their smaller counterparts and industry officials and scientists did not want to waste precious launches on inferior payloads. Satellite programs became massive undertakings with long development times and billion dollar expenditures. Failure of these projects was devastating to development programs and as a consequence conservative design practices were implemented.

During this time, small satellites programs were still active both building and launching spacecraft without much acknowledgement from the wider community. [6] Several amateur radio satellites were launched including OSCAR (Orbiting Satellite Carrying Amateur Radio) type satellites which were extremely successful. The first of these, OSCAR 1, was launched in 1961 and had a mass of a mere five kilograms. [6] By 1983, OSCAR 10 was launched with a wet mass of 90 kilograms. OSCAR 10 employed the first amateur built satellite propulsion system and many advanced systems including digital "store and forward" communication. [7] Using this technology, a single, small satellite in LEO could provide global communication coverage which is beyond the capabilities of the far larger commercial communication satellites in Geosynchronous orbit. [6]

With the development of smaller electronics the trend began to reverse and once again small satellites began to be commonplace. With the advent of the Distributed Space Systems (DSS) concept, small satellites are now performing missions previously the domain of large, complex satellites.

2.2. FUTURE OF SMALL SATELLITES

Small satellites hold the promise of a new space concept; however, the implementation and full advantage of such new methods have not yet been realized. Currently the moniker small satellite project implies not merely a satellite of significantly smaller mass, but also smaller projects in terms of budget and complexity. Future small

satellite projects will strive to keep the associated cost benefits while increasing the complexity of mission options.

The applications for small satellites appear boundless. As individual satellites the missions will remain relatively simple yet allow for important scientific knowledge to be collected. Such was the case with the Chemical Release Observation (CRO) Canister mission where simple small satellites were used to observe thrusters firings. Each of the CRO canisters was aerodynamically stabilized along its velocity vector and contained 25 kilograms of hydrazinic chemicals designed to be released under observation from both the ground and the space shuttle. [6]

The advantages of small satellites become apparent when the distributed space system concept is employed. One proposed mission calls for a cluster of a 400 identical small satellites for global communication. All the satellites within the cluster could remain unguided after insertion into low Earth orbit (LEO) and still maintain 95% global coverage. Without the need for attitude or orbit control, the base design of the satellite remains straightforward; thus reducing cost and allowing for mass production. In addition to the manufacturing savings, such a cluster has the advantage of redundancy in that the loss of one or several of the satellites would not significantly reduce the capabilities of the system [6].

Adding guidance and control to the satellites takes the distributed space system concept one step farther and allows for even more complex missions to be accomplished. For instance a constellation of satellites flying in formation could be used to create a virtual aperture, in effect a very large lens, to use in imagining missions. This virtual aperture could be more effective than traditional optical systems since it would simulate optics of much greater size than could ever be employed. However, for such a system to work each satellite within the formation must maintain strict relative position tolerances.

2.3. PROPULSION CONSIDERATIONS

Propulsion systems for satellites are chosen by a multitude of factors. The primary purpose of the system, be it attitude control or orbit adjustment, must first be considered as each mission goal places different requirements upon the system. Ideally, multiple propulsion tasks would be performed using a single propulsion system so as to reduce satellite complexity, system dry mass, and mission cost. [8] Additional factors must also be considered such as the necessary response time for maneuvers, the necessary precision of the system, and the expected mission lifetime.

Maneuver response time is an important consideration. Often times during a mission slew maneuvers, where the orientation of the satellite is drastically changed, must be performed within a narrow time window. [8] A propulsion system designed merely for attitude control may not possess the brute force capability required to enact such rapid changes. However, a system capable of rapid maneuvers often times lacks the small impulse-bit necessary for precise attitude control. In missions that require both, either a compromise must be made to arrive at the optimal solution or separate systems must be employed.

Finally, mission time line and life expectancy of the spacecraft must be considered before any propulsion system is implemented. Missions requiring vast amounts of propulsion or long mission life times will require equivalently more propellant to be stored within the spacecraft. As storing more propellant requires extra tank volume and adds mass to the satellite it is important to match system performance requirements with system efficiency. The specific impulse, I_{SP} , is often used as a means to objectively gauge the propulsion efficiency of various systems. Below; Table 2.1 gives the expected I_{SP} values for many types of propulsion systems.

Propulsion System	Expected I _{sp} (s)	
Cold Gas	30 - 70	
Liquid (bipropellant)	305 - 460	
Liquid (monopropellant)	140 - 240	
Solid	260 - 300	
Hybrid	250 - 350	
Electric	300 - 10,000	
Nuclear	800 - 6,000	

 Table 2.1: Expected Isp Ranges for Propulsion Systems [6]

2.4. PROPULSION OPTIONS

Overall, there are three major subsets of propulsion systems: cold gas, electrical, and chemical; although other types and hybrid systems do exist.

2.4.1. Cold Gas Systems. Cold gas systems are the simplest of the propulsion options available to satellite designers. Conceptually such a system is little more than a pressurized tank, a control valve, and a nozzle. Cold gas thrusters work by accelerating an inert, high-pressure gas, typically Nitrogen or Xenon, through a nozzle to produce thrust.

While the systems are valued for their relative simplicity and are often employed for attitude control, cold gas systems do have limitations. The high-pressure propellant storage often leads to system leaks causing up to 10% of the stored propellant mass to be

lost. [8] In addition to propellant loss, the systems are not nearly as efficient as other propulsion options and cannot generate the high forces necessary for certain orbital maneuvers.

2.4.2. Chemical Systems. Chemical systems have a long history of providing both access to space and propulsion for satellites. Their greatest advantage over other propulsion systems is the high thrust they are capable of producing. Working in similar fashion to Cold Gas Thrusters, Chemical systems rely on a combustion process to impart energy into the flow before it is accelerated out the nozzle.

Many differing configurations of chemical propulsion systems are available to satellite designers including liquid propellant, solid propellant, and hybrid systems. Each configuration has both advantages and disadvantages depending on the intended use of the system. For satellite propulsion, liquid propellant systems—both monopropellant and bipropellant—are used due to their ability to be throttled.

2.4.3. Electrical Systems. Over the years electrical propulsion systems have become much more prevalent in spacecraft design. Such systems utilize electromagnetic (EM) forces to impart energy into a flow and accelerate propellant; thus generating thrust. EM systems are highly valued for their I_{sp} and the efficiency it implies. Electric systems come in many configurations from electro-thermal resistojets to plasma expelling HALL thrusters. Each thruster type has different power requirements and performance characteristics; thus, the type of thruster employed for a particular satellite mission is determined by mission requirements and system resources.

2.5. SURVEY OF SMALL SATELLITE PROPULSION

Many of the first small satellites did not utilize any propulsive methods; instead relying on proper orbit insertion and spin stabilization to complete their missions. As small satellites began to require the ability to alter their orbit during the mission, propulsion systems became incorporated into the design.

For example, the 90 kg amateur radio satellite, OSCAR 10, was launched on June 16, 1983 as the first amateur built satellite to incorporate a propulsive system. [7] The propulsion system was a liquid bipropellant chemical system featuring an S400 engine designed to insert the satellite into the desired orbit and maintain the orbit once reached. [9] However, a collision with the launch vehicle coupled with a longer than expected firing time of the thruster saw the satellite fail to achieve the desired orbit. A second attempt to fire the thruster failed due to a loss of pressurization within the helium blowdown system and the subsequent loss of propellant and oxidizer pressure. [10]

Traditional cold gas thruster systems also came to be incorporated into small satellites. For instance, in 1991 the DARPA Microsat mission consisted of a constellation of small satellites each fitted with a cold gas propulsion system utilizing nitrogen as propellant. While each 22.7 kg satellite was designed with four years worth of propellant initially stored at 6000 psi, a lower than intended orbit caused the formation to deorbit after only a year of operation. [11] The European Space Agency (ESA) also employed a traditional cold gas thruster system for its original Cryosat mission launched in 2005. The propulsion system designed for both attitude and orbit control stored 36.2 kg of nitrogen in a single propellant tank at 4040 psi. [12] The mission was to last for

three years; however, the launch vehicle failed during liftoff and the satellite was lost. [13]

Electric thrusters have also been implemented into small satellites. The 300 kg Surrey Satellite Technology Ltd. (SSTL) UoSAT-12 launched in 1999 and employed both a cold gas thruster system and an electro-thermal propulsion system. The 0.125 N resistojet utilized nitrous-oxide propellant heated by a 100 W resistive heating element. The thruster was designed for orbit maintenance and could raise the 650 km orbit a full 3 km in one hour's time. The 2.5 kg of propellant allowed for 14 hours of thruster operation. [14] [15]

Finally, non-traditional cold gas thruster systems utilizing liquefied gas as propellant have been successfully flown. The University of Toronto Institute for Aerospace Studies' (UTIAS) CanX-2 nanosatellite was launched in April 2008. [16] The mission was a technology demonstration of among other systems a micropropulsion system utilizing sulfur hexafluoride (SF₆) as a propellant. As designed, the 10 mL propellant tank stored sufficient SF₆ at a MEOP of 500 psi to provide 2 m/s of ΔV . The system will also provide 50 mN of thrust and have an I_{sp} of approximately 45 s. [17] The SSTL SNAP-1 satellite launched in June 2000 also employed a cold gas propulsion system utilizing liquefied gas as propellant. The uniquely designed system used butane as propellant in a rendezvous mission between small satellites. A total of 32.6 grams of butane was stored as a liquid within a 1.1 m coiled tube with an internal volume of 65 cm³. The propellant was vaporized by a 15 ohm (4.3 W at 8 Vdc) resistive heater prior to expulsion to provide a theoretical ΔV of 3.47 m/s. Orbital data showed the initial propulsive maneuvers of the SNAP-1 satellite were both at higher thruster levels than predicted and erratic in thrust produced. This suggests that liquid propellant droplets were expelled along with the gas; thus creating higher thrust at reduced propulsive efficiency. [18]

2.6. ROLE OF UNIVERSITY PROJECTS

Universities hold a special place within the space industry. While university projects traditionally lack the resources, in terms of both experience and money, of industry projects, they more than make up for this in terms of design freedom. Whereas industry must adhere to conservative principles and above all the bottom line, university projects have the freedom to explore new methods and technologies.

Given this freedom offered by university projects, it seems only prudent for companies to form a partnership with universities to develop programs focus on areas of interest to the space community. In this way, university projects can directly benefit industry interests while at the same time developing and training a new generation for the workforce.
3. SYSTEM DESIGN OVERVIEW

3.1. INTRODUCTION

The propulsion system for the MR SAT formation flight mission was designed to meet the needs of the satellite while fitting within the guidelines and time constraints of the NS4 program. As such, certain design aspects of the system are products of necessity and not necessarily directly related to the mission requirements. This section describes the system as designed and details the choices, compromises, and iterations of the design process.

3.2. INITIAL DESIGN CONSIDERATIONS

The beginning of any design process is an important period with far reaching repercussions on the final design, particularly for projects with short durations and time tables. The MR SAT project, as part of the University Nanosat Program, had a two year concept-to-product time table with much of that time allocated to building the system. As a consequence, the initial design choices for the MR SAT propulsion system were made in the context of information available to the designers early on in the project with such choices being re-examined as new information became available.

3.2.1. Pertinent Mission Requirements. As discussed in Section 1, the propulsion system for MR SAT has three mission requirements. Stated briefly, the Propulsion subsystem is charged with providing the means for both responsive attitude control and orbital control for formation flight. Each mission statement is examined below as to its rationale and the consequences for propulsion design.

3.2.1.1 Provide means to maintain attitude and orbit control. Attitude and orbit control are vitally important to the successful completion of the M SAT mission. Attitude control is particularly essential in that without tight bounds on the orientation of the satellite while in orbit, communication with the ground would be impossible. Also, proper orientation is important for the solar panels to maintain the appropriate level of solar exposure and sustain the power levels for the satellite. The goal of the Attitude subsystem is to maintain attitude control within \pm 7 degrees of nominal satellite orientation. [19] While means other than propulsion do exist for attitude control, these devices are not as responsive and require significantly more time to slowly change the attitude of the satellite. During the formation flight mode of the mission, and particularly immediately after the deployment of MRS SAT, quick response to changing rotation rates is necessary.

To satisfy the attitude control requirements for the mission, the MR SAT propulsion system must be capable of providing full three-axis rotational control. This in turn means that a system with multiple thrusters is required. Also, as discussed in Section 2, a balance must be struck between the response time of the system and the precision of the attitude maneuvers to avoid overcompensating and propellant waste.

3.2.1.2 Provide means to maintain 50 meter formation with MRS SAT. The mission for the MR SAT project involves two satellites autonomously maintaining a follow/lead formation. Upon launch, the two satellites are coupled in a stack arrangement connected by a separation device. After separation, the formation must quickly be formed and any relative velocities overcome. Worst-case scenarios indicate

that the two satellites will reach the desired 50 meter separation distance in two minutes. Therefore, any propulsion system designed to implement formation flight for this mission must have the capacity, i.e. available thrust, to quickly mitigate relative velocities and establish the proper formation. Once the formation is formed, it must be maintained within the specified bounds by the use of the propulsion system. To achieve this as efficiently as possible, it is necessary to be able to thrust in as many translational axes as possible, thus eliminating unnecessary rotational maneuvers.

3.2.1.3 Provide sufficient performance for one orbit of formation flight. The lifetime of the mission is a major consideration and is, at least for the purposes of formation flight, defined by available propellant mass. To demonstrate that the methods utilized by the MR SAT program to conduct autonomous formation flight are valid and effective, a minimum mission duration is required to insure that adequate data are collected. Obviously longer time spans are desirable and would provide more data; however, one orbit of formation flight was chosen as the minimum mission lifetime since it was deemed effective for demonstration purposes and feasible given program requirements.

Ensuring adequate performance to achieve one orbit of formation flight is made far more difficult by the volumetric and mass constraints placed upon the system. Storage of large masses of propellant at safe pressures, as defined by the NS4 User's Guide, necessitates the use of large volume storage vessels. However, since the exact amount of propellant necessary for the mission was unknown and unknowable early in the design process, a design providing as much ΔV as possible was preferred. **3.2.2. MR SAT Propulsion Options.** Defining the mission objectives and understanding the program guidelines and requirement allowed the initial design of the MR SAT propulsion system to be determined. Due to volumetric, mass, and time considerations, the Propulsion subsystem endeavored to design a single propulsion system to encompass both attitude and orbital control during formation flight as opposed to a separate system for each need. In the sections below, the pros and cons of the three main system options are discussed.

3.2.2.1 Chemical systems for MR SAT propulsion. Chemical systems were not considered a viable option for the MR SAT mission despite performance characteristics within the bands necessary for successful completion of the mission. The issue with such systems was not complexity; indeed systems are available commercially specifically designed for small satellites, but rather the chemical reaction process inherent to their use. NS4 guidelines on propulsion systems prohibit chemical reactions and combustion as unsafe practices; however, should a satellite be constructed outside the UNP, chemical systems could be explored as a possible propulsion option. This is especially true considering that at minimum chemical systems have nearly double the I_{SP} of cold gas systems.

3.2.2.2 Electrical systems for MR SAT propulsion. Electrical systems merited some consideration. With the total required ΔV of the mission as yet undefined the relatively high I_{SP} values of electric propulsion made such systems attractive. Relatively simple electrical systems such as resistojets, arcjets, and micro pulsed plasma thrusters (µPPT) were all briefly considered for the primary propulsive means of MR SAT.

Resistojets are one step more advanced than cold gas thrusters in that they utilize small resistive heaters just prior to the nozzle to add energy to the flow. The added energy increases the efficiency of the thrust generation and thus preserves propellant mass. Arcjets work in much the same manner only utilizing an electric arc instead of resistive heaters to accomplish the heat addition. While both these devices would help extend formation flight time by increasing system efficiency; it comes at the cost of extra system mass for power conditioning units and added power draw on the satellite. The need for multiple thrusters, lack of experience with electrical propulsion, and the limited power available on the satellite made both resistojets and arcjets infeasible for implementation in MR SAT.

As an alternative, μ PPTs are traditionally used for attitude control work since they are capable of very small impulse maneuvers and work in a pulsed fashion instead of the continuous flow achieved by other systems. As such they do not truly meet the needs of the M SAT mission; however, should two systems be employed to perform attitude and orbit control separately, μ PPTs would be a possibility for the attitude control requirement. For this reason, a prototype μ PPT was to be included on MR SAT, assuming space, mass, and power for the device were available, as a technology demonstration for future missions.

3.2.2.3 Cold gas thrusters for MR SAT propulsion. Cold gas thrusters were perhaps the best option for MR SAT propulsion given their simple design and implementation requirements. The concept and laws governing the fluid flow were

familiar to the Propulsion subsystem and thus could be implemented by the student designers quickly.

The limiting factor with cold gas thrusters is the third mission requirement of producing a system capable of providing a full orbit of formation flight. While the required total ΔV for the mission was not yet known, the theoretical performance of the system using traditional propellants and tanks of reasonable volumes was not encouraging. For example, a 2.5 liter tank of nitrogen when stored under the safe conditions set by the UNP and ignoring the likely loss of 10% of the propellant mass is only capable of producing 0.47 m/s of ΔV . [20]

While cold gas thrusters offered the greatest chance of success for the Propulsion subsystem in terms of completing the system, clearly the issue of propellant choice and storage had to be carefully considered and became an integral design aspect.

3.2.2.4 Chosen system for MR SAT propulsion. To achieve the mission objectives utilizing the cold gas thruster concept, a method of low-pressure, high-density propellant storage was imperative. This is not possible with traditional gaseous propellants as density and pressure are directly related for a container at a given temperature. Employing a liquid propellant realizes the necessary storage conditions; however, the expulsion of liquid propellant greatly reduces the efficiency of the propulsive device. Therefore, a compromise system, where propellant is stored as a liquid and yet expelled through the nozzle as a gas, was sought by the Propulsion subsystem.

A saturated-liquid propellant is a good choice to attain just such a compromise. Saturated-liquids are substances that over a given temperature range can exist in both the liquid and gaseous states. Using such propellants, extra propellant mass can be stored in the tank as a higher density a liquid while the vapors are extracted and expelled to produce thrust. Identifying the specific saturated-liquid that met all the safety and performance guidelines was challenging and necessitated consultation with the Missouri S&T Chemistry Department.

In the end the selected propellant was the refrigerant R-134a due to its nonreactive, non-toxic, and performance properties. The refrigerant was to be used with the cold gas concept as the basis for MR SAT propulsion.

3.2.3. Configuration Possibilities. The placement and orientation of the thrusters within the confines of the satellite is critical to the final performance of the propulsion system; affecting both the rotation rates produced by the system and overall efficiency of maneuvers. Thruster placement also is important with regard to integrating the propulsion system into the satellite in a manner that avoids conflict with other satellite systems.

The main objective when configuring the thruster locations was to ensure the system could perform the attitude and orbit maneuvers required by the mission statements; i.e. the system had full three-axis rotational control and multiple axis translational control. However, additional considerations required placing further restrictions on thruster placement to ease system integration. The first of these requirements entailed avoiding the top and bottom panels of MR SAT since these panels are contact points for MRS SAT and the launch vehicle, respectively. Also, the

placement of thrusters in the middle of panels was discouraged due to possible interference with other satellite systems. Finally, system complexity and overall cost was to be reduced by minimizing the number of thrusters needed to accomplish the mission goals.

The configuration of thrusters for MR SAT was the product of the aforementioned reasons and time constraints; however, to exemplify the thought process necessary for designing a functional thruster pattern, the configuration used for MR SAT plus two other possible designs are analyzed below.

3.2.3.1 Twelve thruster configuration. The twelve thruster configuration is the most straightforward of the possible thruster arrangements for MR SAT. Four thrusters are placed in each translational plane of motion and arranged in such a way so the thrust vector from half the thruster group directly opposes that of the other half. To perform both translational and rotational maneuvers pairs of thrusters would fire in tandem; the specific pair of thrusters selected determining the maneuver performed. Figure 3.1 shows what this thruster configuration would look like when implemented into MR SAT as well as which thruster pairs perform which maneuvers.

This design has the benefit of providing direct maneuvering capability in all three translational and rotational axes; however, this comes at the cost of increased system complexity and cost due to the number of thrusters required. Additionally, the design requires thrusters to either be placed on the top and bottom panels of MR SAT and risk

Figure 3.1: Maneuver Pairings - Twelve Thruster Configuration

interference with satellite connection points or be placed along solar panels and risk possible solar cell contamination.

3.2.3.2 Eight thruster angled configuration. The angled nature of this configuration allows fewer thrusters to perform the same set of maneuvers as the twelve thruster configuration. In this configuration, two sets of four thrusters are arranged on

opposing panels. The thrusters are arranged in a square pattern with each thruster placed at a corner and angled 45° as seen in Figure 3.2. Four thrusters are fired simultaneously to achieve the desired thrust vector(s) for both rotational and translation maneuvers (see Figure 3.2 for maneuver groupings).

Figure 3.2: Maneuver Pairings - Eight Thrusters at 45 Degrees

While such an arrangement does indeed provide a system capable of three axis rotational and translational maneuvers, it does so at the cost of overall system efficiency. The angled nature of the thrusters means that a portion of the force produced by each thruster is canceled out by the actions of the other active thrusters. In fact, only a little over half (0.577) of the available thrust is converted into the resultant force vector. Additionally, achieving the precision in thruster placement and alignment necessary in order to ensure proper thrust vectors for such a design would drastically complicate the integration process. In the end, the inefficiency of this design and the difficulties with integration were not compatible with the needs and requirements of MR SAT.

3.2.3.3 Eight thruster straight configuration. The thruster configuration chosen for MR SAT employs eight thrusters but does away with the angle of the previous configuration. Instead of an equal number of thrusters in opposition, this method uses a single thruster directed through the CG of the satellite to offset the translational force of a thruster on the opposing panel in order to produce torque. Figure 3.3 shows the thruster configuration and the thruster pairs utilized for various maneuvers.

The design does an adequate job in meeting the requirements of MR SAT in that all rotational axes are controlled and the number of valves within the system is reduced; however, the translational axis through the top and bottom of MR SAT is left uncontrolled.

Figure 3.3: Maneuver Pairings - Eight Thrusters Straight Configuration

3.3. SYSTEM DESIGN

With the preliminary design decisions for the MR SAT propulsion system complete, the next phase of design began. Within this phase, specific component requirements were developed to ensure successful integration into a unified propulsion system. Components were then sourced to meet the necessary criteria; moving the design from a general concept to a physical model utilizing real world components integrated into a cohesive system. **3.3.1. System Components.** The components that make up a system determine the function and efficiency of that system; each component performing a particular task and adhering to specific requirements. While a cold gas propulsion system is conceptually simple, incorporating physical components in the design presented challenges and required strict selection criteria.

3.3.1.1 Propellant tank. The propellant tank was a key component for the MR SAT propulsion system given the type of propellant selected. During the development of tank requirements it was necessary to consider the unique challenges presented by propellants stored in a saturated liquid state. Specifically, the tank must be equipped with a passive means to combat and prevent propellant slosh within the tank while on orbit.

Propellant slosh occurs when the liquid propellant within the tank moves separately from the satellite structure; potentially disrupting the prescribed motion of the satellite. The problem arises due to the way liquids behave in a zero g environment. Under the influence of gravity, liquids conform to the bottom of the containment vessel; however, without gravity liquids tend to form large globules moving freely within the tank. Propellant Management Devices (PMDs) are established inside storage tanks to control slosh effects by breaking up large globules and restricting the free motion of liquids. Another function often assigned to PMDs is ensuring that the propellant extracted from the tank is in the correct state, either liquid or gas.

Therefore, the use of R-134a as a propellant set the major requirement for the propellant tank. Any tank considered for use on MR SAT would require an internal PMD

capable of working with R-134a and designed to extract the gaseous state from the tank.

This and additional requirements are listed in Table 3.1 below.

Requirement	Reason
Integrated PMD	Necessary to control propellant slosh and ensure that the proper phase is extracted from the tank.
All Metal Construction	Safety requirement imposed by UNP officials. Composite materials are deemed too great a risk without additional metal wrapping.
Fit Within the Available Volume of MR SAT	Exceeding the bounds of the satellite would violate UNP regulations. In addition, available volume is limited by not only overall satellite dimensions, but also the volume necessary for other satellite components.
Possess a Minimum Internal Volume of 2 L	This volume was deemed necessary to provide sufficient propellant mass for satellite operations.
Theoretical Burst Pressure 5X Greater than MEOP	Factor of Safety required by UNP. Ensures that pressure fluctuations will not cause a catastrophic breach of the tank.
Reasonably Priced	The M-SAT team was working with a limited budget.

 Table 3.1: Propellant Tank Requirements [21]

Two of the restrictions limited the options for commercially available tanks more than any other. With a small satellite, the tank must be correspondingly small in dimension. Many of the tanks sourced by the Propulsion Subsystem were simply too large to fit within the available volume of MR SAT. Also, most commercially available tanks were designed either without integrated PMDs or with PMDs manufactured for liquid phase extraction.

While many tanks were considered, only the Marotta BS25-001 tank fit all the design criteria set forth by the Propulsion subsystem. The 2.5 L tank had an incorporated

PMD originally designed to prevent liquid butane from being injected into propellant lines; however, it would work equally well for R-134a. An additional benefit of Marotta tank was its proven flight history and hence its space qualified nature. Further information on the selected tank can be found in Table 3.2 below.

Tuble 0.2. Thght Tunk Speemeutons [21]			
Operational Temperature	-40 °C to 65 °C	-40 °F to 150 °F	
Maximum Expected Operating Pressure (MEOP)	1.600 MPa	232 psi	
Minimum Burst Pressure (MBP)	9.7975 MPa	1421 psi	
Volume Capacity	2500 cm^3	153 in ³	
Mass	1.476 kg	3.25 lb	
Maximum Body Length	32.6 cm	12.83 in	
Outside Diameter	110.314 mm	4.24 in	
Factor of Safety (MEOP : MBP)	6 :	1	

Table 3.2: Flight Tank Specifications [21]

3.3.1.2 Isolation valves. Safety is the foremost concern of UNP officials. Pressurized systems are inherently more prone to failure and, as such, merit additional safety requirements and stipulations. As a safety measure the UNP mandates that each pressurized system must have three mechanical inhibits; one of which must be failsafe.

For the purposes of the MR SAT propulsion system, it was determined that two isolation valves would serve as the initial two inhibits with the thruster control valve serving as the final inhibit on each propellant line. For simplicity sake, the two isolation valves were to be of the same design. Therefore, the most important aspect of isolation valve selection was the failsafe nature of the chosen design. In terms of valve design, failsafe means that the valves' default position is closed and, therefore, any interruption in signal will shut off the flow and secure the propellant. The overall requirements for the isolation valves can be found in Table 3.3.

Requirement	Reason
Failsafe Design	Safety feature prevents the release of propellant in the event of a failure. Mandated by UNP.
Sealant is low outgassing	Low outgassing materials lose less matter when exposed to a vacuum. Loss of material can lead to valve leakage and material deposits on other sensitive equipment. Additionally, low outgassing is mandated by UNP.
Compatible with R- 134a	R-134a is considered chemically inert, but can dissolve certain plastics and rubber materials. Ensuring compatibility prevents seal failure.
4 x FOS over MEOP	Isolation valves will see the full pressure of the system and must be able to withstand the force.

 Table 3.3: Isolation Valve Requirements

After an extensive search and consultation with experienced industry representatives, a micro-dispense solenoid valve from Lee Valve Company was selected. The original selected valve was the INKX0512050A, however, this valve was only proof tested to 199 MPa (289 psia) which does not meet the required FOS of 4.0. Discussions with Lee yielded a derivative of the INKX0512050A valve that was slightly larger and proof tested to 5.17 MPa (750 psi). Figure 3.4 shows the MR SAT isolation valve from Lee Valve Company.

Figure 3.4: Lee Valve Company INKX0512050A Micro-Solenoid Valve

Also discussed with Lee was the possibility of changing the internal sealant used within the valve to a material compatible with R-134a. These discussions are still ongoing as a suitable material that is also low outgassing and moldable (per Lee manufacturing requirement) has yet to be found. In the mean time, the valves were ordered with EPDM seals which are compatible with R-134a but have unknown outgassing properties. Other pertinent valve characteristics are detailed in Table 3.4.

3.3.1.3 Pressure regulator. For peak performance, each thruster needs to be provided with constant and predictable flow characteristics. Without regulated pressure, the flow delivered to the nozzle would change as tank pressure falls due to propellant use. Thus, the system requires a pressure regulator downstream of the tank for optimum system performance.

Mass	7 grams
Proof Pressure (Lee Co. rating)	5.17 MPa (750 psi)
Burst Pressure (Lee Co. rating)	7.76 MPa (1125 psi)
Rated Thermal Environment	-18 °C to 70 °C
Open Response Time – 689.48 kPa (100 pisg)	0.25 ms
Close Response Time – 689.48 kPa (100 pisg)	< 3.0 ms
Actuation Voltage	24 V spike
Actuation Power (Maximum Average)	0.75 W

 Table 3.4: MR SAT Valve Specifications [22]

Pressure regulators are in essence spring loaded check valves. When the pressure downstream of the regulator exceeds a preset value, flow from upstream of the regulator is restricted; however, when the downstream pressure is below the set point, the regulator allows propellant to flow unimpeded.

Any potential pressure regulator for the MR SAT propulsion system needed to meet two key parameters for consideration: a factory set regulated pressure (i.e. non-adjustable) and be functional in vacuum. While adjustable regulators would have allowed the downstream pressure to be optimized for most efficient thrust maneuvers, a concern was that during launch the excessive vibrations could cause the set point to vary and thus negate any possible advantage. The need for vacuum functionality seems self-explanatory; however, many regulators utilize vent holes to take atmospheric pressure into account and thus it was an important issue when sourcing viable pressure regulators. Table 3.5 presents the requirements necessary of a pressure regulator for MR SAT.

Requirement	Reason
Non-adjustable Setting	Adjustability increases component complexity.
	Set point could vary due to launch vibration.
	Requirement highly suggested by AFRL.
Vacuum functionality	Avoid vent holes which may lead to propellant
	leakage.
Wetted surfaces compatible	Many regulators have internal components of
	plastic or rubber which must be compatible with
with K-15+a	the propellant
	A lower regulated pressure reduces the impulse of
	each thruster firing, and thus allows for more
Low pressure setting	precise maneuvers. Also increases the time that
	tank pressure is above regulated pressure (i.e.
	regulators functional time).
Reasonably priced	The M SAT team was working on a budget and
	space rated components often were out of the
	team's price range.

Table 3.5: Pressure Regulator Requirements

Four companies were initially considered as vendors for the MR SAT pressure regulator; Moog, Beswick, Tescom, and Swagelok. However, only the Swagelok regulator met all the requirements. The Moog 50E741 pressure regulator had the benefit of being space rated, but was also excessively massive for a small satellite and cost upwards of \$50,000. The Beswick and Tescom regulators also failed to meet the subsystem's guidelines by having a reference vent hole and an adjustment device, respectively.

The Swagelok model chosen for use on MR SAT was the HFS3B compact pressure regulator designed for use with high flow gases. The device was calibrated to a preset outlet pressure of 68.95 kPa (10 psig, 24.7 psia) and certified to work after upstream pressure falls below the preset value. The Swagelok regulator had the additional benefit of easy integration since it was an inline model and could be equipped with standard Swagelok fittings. Regulator specifications can be found in Table 3.6.

Preset outlet pressure	68.95 kPa (10 psig, 24.7 psia)
Mass (measured)	176 grams
Temperature range	-40 °C to 70 °C
Inlet pressure range	Vacuum to 6.89 MPa (1000 psig)
Operating temperature range	-23 °C to 65 °C
Orifice size	3 mm (0.12 in)
Flow capacity	100 std. L/min
Leak rate (He)	1×10^{-9} std. cm ³ /sec

 Table 3.6: MR SAT Pressure Regulator Specifications [22]

3.3.1.4 Thrusters. The thrusters for the MR SAT propulsion system were to consist of three main components; a Swagelok fitting, an actuation valve, and a nozzle. Manufacturing the nozzle to the necessary tolerances and scale was determined to be beyond the fabrication abilities of M SAT design team, and as such, the thruster assemblies were to be internally designed and externally sourced. Therefore, Micro Aerospace Solutions (MAS) a company in Melbourne, Florida with experience in micro propulsion systems was contacted by then Propulsion Lead, Carl Seubert to assist in the design and fabrication of the MR SAT thrusters.

The valve component of the thruster assembly was chosen at the same time and in the same manner as the system isolation valves; thus the inhibit requirement was satisfied by the same valve model in all three cases. The remaining design considerations for the thrusters were focused on overall thruster shape and nozzle design. The shape of the thrusters, or how the three main components are configured within the assembly, was important for integration considerations. Each thruster must be securely fixed to the satellite structure in the correct orientation which requires a method of attachment based upon the final configuration of the thruster. The requirements pertaining to thruster assembly configuration can be found in Table 3.7 below.

Requirement	Reason
Provide means to secure thruster to structure	Fixed orientation is necessary to ensure the
	system is capable of performing the required
	maneuvers correctly.
Nozzle extends beyond honeycomb panels	If the nozzle is obstructed by the honeycomb panels it will not be able to produce thrust. Also, the nozzle being merely even with the surface of the honeycomb panels could lead to
	The propellant lines must be connected to the
Allow for straightforward propellant line attachment	thruster in a manner that provides support for
	the lines.

 Table 3.7: Configuration Requirements for Thruster Assembly

An "L" shape with the bend placed between the Swagelok fitting and the valve, as seen in Figure 3.5, was chosen as the basic shape for the thruster assembly. This allowed the thruster to be attached securely to the structure at the fitting, thus preventing unnecessary stress upon the thin and relatively delicate valve tubing. With this configuration, the Swagelok fitting rests upon the inside surface of the isogrid panel while the valve and nozzle protrude through the panel and past the honeycomb solar panel.

Figure 3.5: "L" Shape Configuration for MR SAT Thruster

Figure 3.6 shows the necessary dimensions for the thruster configuration to ensure the nozzle extends sufficiently past the solar panels. Finally, this configuration allowed propellant lines to run along the inside surface of the isogrid panels, which provided a means to secure them as well. While other configuration possibilities for the thruster assemblies do exist and could have worked equally well, they were not explored given sufficiency of this design.

The nozzle portion of the thruster design was more complex as it was necessary to balance opposing performance requirements while designing a machinable part. Analysis performed by Carl Seubert demonstrated improved ΔV performance for the system given a higher nozzle Aspect Ratio (AR), the ratio between nozzle exit area (A_e) and throat area (A_T).

Figure 3.6: Thruster Schematic

However, this improvement comes at the expense of lower overall thrust produced per thruster firing which adversely affects the response times for attitude maneuvers [22]. Therefore, a compromise AR which extends mission life time, ΔV , while providing sufficient thrust for attitude control was a primary requirement for the nozzle design.

Machining issues became prominent due to the small size and the necessary tolerances of the part to be machined. The machining process greatly affected the final AR chosen for the nozzle since machining tolerances limit the minimum diameter possible for the throat. MAS is capable of machining parts accurately within 0.001 inches (0.0254 mm) meaning that a part may vary plus or minus a thousandth of an inch off specified dimensions. This is especially important for A_T since as the throat area approaches the accuracy limit the variation in machining has a correspondingly greater influence on the performance of the nozzle. The small part size also affects the complexity of the shape that can be attempted. In larger parts, complex shapes involving relatively smooth curves are possible; however, when applied to smaller parts, the accuracy limit of the machining process could cause relatively large variations in the designed curvature. Thus, simple nozzle shapes were necessary to prevent undue system losses. The requirements associated with the nozzle design can be found in Table 3.8.

Requirement	Reason
An AR that sufficiently meets all design requirements	High AR gives higher ΔV but lower thrust. A
	compromise which meets the needs and
	requirements of the mission is necessary.
Machinable A _T	The A _T must be much greater than the machining
	tolerances of MAS to reduce the influence of
	machining variability on system performance.
	Complex interior surfaces are difficult to
Simple interior shape	accurately manufacture due to the small part size.
Simple interior snape	This in turn could lead to additional system losses
	due to friction and boundary layer affects.
Stainless steel construction	The thruster is likely to experience thermal
	gradients. Using the same material in each
	component of the thruster assembly ensures
	thermal expansion rates should be similar and
	thus reduces the possibility of leaks and stress
	induced by thermal expansion.

Table 3.8: Nozzle Design Requirements

In consultation with MAS, the nozzle design was finalized and met all requirements placed upon it by the Propulsion subsystem. The design called for a stainless steel converging/diverging nozzle utilizing straight cones in both the converging and diverging sections. The straight cone shape is not as efficient as the bell-shaped section often seen in larger rocket nozzles, but is far easier to manufacture accurately. The diameter of the throat was set at 0.5 mm with the exit diameter set at 5 mm to ensure the structural strength of the outer edge. Thus, the aspect ratio is 100, which is a fine compromise between ΔV and thrust as seen in Section 3.3.3 "Expected Performance." A diagram of the nozzle design can be found in Figure 3.7.

3.3.1.5 Propellant lines and fittings. Any pressurized system is only as robust as the lines, connections, and fittings used in its assembly. They provide the means for propellant to flow from the source tank to thruster assemblies and eventually out the nozzle to produce thrust. When developing the requirements for the propellant line system restrictions and recommendations from the UNP and AFRL officials played a significant role. Many of the recommendations focused on practices known to reduce the possibility of propellant leakage within the system, a common problem with cold gas thrusters. The requirements stemming from these recommendations and restrictions are listed in Table 3.9.

Requirement	Reason
Lines and fittings must be constructed of metal	Polymer or rubber propellant lines are more likely to fail especially under the vacuum conditions of space. It is also an outgassing risk.
Avoid use of flexible tubing	This was more a suggestion as past use of flexible tubing, even of metal construction, has been shown to cause problems with connections and thus increased leak rates.
Lines and fittings made of the same material	Connections of different metals with different thermal expansion rates could lead to excess stress placed on the system or increased leak rates.
Non-welded connections	Welding performed by the team is against the policies of the UNP.
Fittings and connections with low leak rates	With the restriction on welded connections, compression fittings were the only choice left to the subsystem; however, choosing a compression fitting with a low leak rate is still prudent.
Fittings must be able to fit on the isogrid panels	Many of the panels are crowded with other system components and thus space is limited.
Maintain a FOS of at least four over MEOP	The propellant lines will experience the full pressure of the system and therefore must be able to safely contain such pressure.

Table 3.9: Propellant Line and Fitting Requirements

There were many different types of fittings available for use in sealed systems such as the MR SAT propulsion system. The majority of the connections within the system were to be tubing connections rather than threaded, and therefore compression fittings figured prominently in the product search. At first Army/Navy (AN) standard 37° flare fittings were considered for use with MR SAT propulsion. These fittings require the end of the tubing to be flared out into a trumpet shape which is then fitted over a similarly shaped cone on the fitting. A compression nut forces the cone into the flare and seals the connection. A diagram of this arrangement can be seen in Figure 3.8. After consultation with AFRL personnel, the use of AN fittings was abandoned as previous satellite teams had had difficulty attaining a proper seal with their use. Instead, AFRL officials suggested the use of Swagelok fittings which utilize a double ferrule design to both lock the tubing in place and seal the connection. A schematic of this can be found in Figure 3.9.

Figure 3.8: Schematic of an AN flare Type Fitting

Figure 3.9: Swagelok Double Ferrule [23]

Aluminum tubing and 0.25 inch aluminum Swagelok fittings were sought for use with the propulsion system; however, two problems with this intent quickly became apparent. First, after modeling the system with 0.25 inch fittings and tubing in NX3 it was clear that the fittings and tubing simply would not work within the satellite. The fittings were too large to comfortably fit upon panels containing other subsystem components and the tubing required a minimum bend radius that also interfered with other components. Secondly, many of the required fittings simply did not come with an option of aluminum construction.

The final design utilized 0.125 inch OD (outside diameter) stainless steel tubing and the corresponding stainless steel Swagelok fittings. The tubing was designed with a wall thickness of 0.02 inches making the tubing capable of handling up to 23,985.3 psia; well above the required FOS of 4.0.

3.3.1.6 Tank and line heaters. Two-phase storage of the propellant allows a greater propellant mass to be stored in an equivalent volume at a comparable pressure; however, before the liquid propellant can be effectively converted into thrust it must be transformed to the gaseous state. Also, as propellant is expelled from the tank, both tank temperature and pressure decrease causing a loss of thruster efficiency and possibly leading to an interruption in propellant flow. For these reasons, a method of adding energy into the system had to be devised in order to sustain the necessary phase change and maintain the thermodynamic conditions of the tank. Additionally, the possibility of propellant condensation within the propellant lines had to be addressed and mitigated to ensure the maximum possible efficiency of the system.

A minimum of two heaters were required by the system; one on the propellant tank to provide energy for the liquid to gas phase change, and the other situated upon the propellant line to help prevent re-condensation. More heaters would more effectively prevent propellant condensation; however, such resistive heating consumes excessive amounts of electrical power. At the time of heater selection, the power budget for MR SAT was uncertain with the exact available power unknown. As a result, it was imperative to select heaters which utilized a minimum of electrical power while still maintaining the thermal control necessary for the M SAT mission. The requirement for heater selection can be found in Table 3.10.

Requirement	Reason
Low power consumption	The power of any satellite is limited and each
	component must minimize the power consumed.
Made of low-outgassing Low-outgassing materials are mandated	
material	UNP guidelines.
Flexible material	The heaters must be fixed to round components such as the propellant tank and propellant lines. As such, they must be flexible to ensure efficient contact.
Adhesive mounting	The heater must be securely fixed to the propellant tank and lines.

Table 3.10: Propellant Tank and Line Heater Requirements

The heaters chosen for use with the MR SAT propulsion system were developed by Minco. The heaters are made of the polyimide film, Kapton, over a metallic heating element chosen to obtain the required resistance. Kapton is widely used in the space industry for its low-outgassing properties. Each heater also has an aluminum backing to ensure that the heaters conform to the curved surface of the tanks and lines. Finally, the heaters are attached using an acrylic pressure-sensitive adhesive which also meets outgassing requirements and secured using shrink bands. Heater specifications can be found in Table 3.11.

Heater Location	Dimensions cm (in)	Resistance (Ohms)	Output Wattage (W)	Voltage (V)	Lead Gauge
Tank	12.70 x 30.734 (5.00 x 12.10)	13.1	3.63	6.9	AWG 24
Propellant Line	0.864 x 8.814 (0.34 x 3.47)	33.9	1.06	6	AWG 30

 Table 3.11: Heater Specifications [21]

3.3.1.7 State sensors. Throughout the mission, it would be useful to have an indication of how effectively the system is functioning. This ensures that the propulsion system can adapt to changing situations and always operate at peak performance. Both pressure and temperature sensors were to be incorporated within the propulsion system to constantly monitor state properties. The temperature sensors fall under control of the Thermal subsystem, and as such, the input from the Propulsion subsystem was limited to number and location. Two sensors will be placed on either end of the propellant tank to monitor the temperature shift as the system is utilized with another sensor located on the main propellant line.

For the purposes of safety and thruster performance, pressure monitoring was imperative to the operation of the system. Two pressure monitoring devices were needed for complete system coverage since two distinct pressure regimes are present: tank pressure and regulated pressure. The most important aspect of pressure transducer design for the MR SAT propulsion system was the pressure range over which the transducer can accurately function. The pressure range needed to be sufficiently wide to cover the entire spectrum of expected pressures while still being fine enough to ensure that there was adequate precision in the measurements. At the time pressure transducer selection, the maximum expected operating pressure of the system was set at 100 psi and as a result the required maximum pressure was set at a mere 200 psi. This and further requirements are outlined in Table 3.12.

Requirement	Reason
Pressure range of 0-200 psia	The smaller the pressure range the more precision
	the measuring instrument has. Thus the requirement
	calls for a pressure range that easily contains the
	MEOP yet is small enough to remain precise.
Lightweight	The mass of the satellite is limited, and as such all
	components must be as light as possible.
Stainless steel connections	As explained previously, the use of similar materials
	at connection points will help alleviate the
	damaging effects of thermal expansion.

Table 3.12: Pressure Transducer Requirements

The AS17A model pressure transducer manufactured by Honeywell/Sensotec was selected for use with the MR SAT propulsion system. While not space qualified, the AS17A model was developed specifically for aerospace applications and thus is relatively compact and light. The standard model is capable of reading pressures up to 10,000 psia but can be factory set to read a portion of this range thus increasing the precision of the measurement. The two pressure transducers for MR SAT were set to an absolute range of 0 - 200 psia in accordance with the requirements in place at the time. Specifications for the MR SAT pressure transducers are found in Table 3.13.

Pressure range0 - 200 psia (0 - 1378.96 kPa)Mass140 gOperating temperature range-54 °C - 121 °CCasing materialStainless SteelConnection type7/16-20 UNFElectrical connectionPRIH-10-6P

 Table 3.13:
 Pressure Transducer Specifications [22]

3.3.2. Component Arrangement. Component arrangement encompassed two aspects of system design: the actual order of components within the propulsion system, i.e. along the propellant lines, and the layout or location of components within the satellite necessary for integration purposes. The placement of each component, both within the propulsion system and within the satellite, could not be arbitrary, but rather had to satisfy a variety of requirements from NS4 guidelines to propulsion system requirements to even structural requirements for the satellite.

3.3.2.1 Propellant line division. The function of entire propulsion system is to efficiently transport propellant from the tank to the thruster assemblies in order to produce thrust. With eight thrusters stemming from a single source tank, the main propellant line must split into eight branches. The manner in which this split is accomplished greatly affects the final layout of the system. Two methods were proposed: the utilization of a manifold design where the main line is split into eight individual lines through the use of one fitting and a fitting design which utilized a series of cross and tee fittings to split the lines to the requisite number.

The manifold design offered many advantages with regard to integration and performance. The main benefit realized would be the direct routing of propellant lines to each thruster and the corresponding reduction in connections. Direct routing would allow, with careful design, the propellant lines to be relatively equal in length and thus equalize the performance losses associated with wall friction. Uneven line lengths result in certain lines experiencing greater frictional losses and thus thrusters that could experience vastly different performance. Additionally, the propellant losses associated with connection leak rates would be reduced along with the number of connection points.

Using a series of fittings to divide the branch lines offered a commercial off the shelf (COTS) option which would meet the requirements and needs of the propulsion system. Under this plan, the main line would first be divided into three secondary lines by means of a cross fitting. Five tee fittings are then used to further divide the lines into tertiary and quaternary lines. The major benefit of this plan is the COTS nature of the components; however, this comes at the cost of ten extra connection points within the system and propellant lines of unequal length and complexity.

Time and budgetary constraints lead to the manifold option being downgraded to a long-term research project. During the NS4 competition research into manifold design determined that no COTS manifold with eight outlet ports could be sourced. Such a manifold would have to be custom designed and manufactured to meet the specifications of the MR SAT propulsion system. While this would be possible, the added time and inherent expense made this option unsuitable for implementation during the NS4 competition. Therefore, the series of Swagelok fittings was employed as seen in Figure 3.10.

3.3.2.2 Component order. Each component for the propulsion system was carefully chosen to meet the requirements set forth by the Propulsion subsystem; component placement within the propulsion system was just as important to the overall functionality of the system. With the basic propellant line structure established, the other components had to be incorporated into the system. Just as the individual specifications

of each component had to satisfy the requirements of the overall system and the UNP, the placement of each component had to contribute to the realization of system requirements. Many of these components required integration before the main line split so that they were effective for the entire propulsion system. Additionally, the position of components relative to each other was instrumental to the functionality of certain components.

Figure 3.10: Line Division Using Swagelok Fittings

The isolation valves are prime examples of components that seemingly could be placed anywhere within the system as long as program requirements are met; and yet, must be incorporated prior to the main line division point for efficient design. NS4 guidelines only stipulate that each path of a pressurized system must have three independent inhibits; however, the placement of isolation valves greatly determines the number of valves needed to attain the three inhibit status. For example, if only a single isolation valve is placed along the main line, a total of sixteen valves would have to be integrated into the branch lines to maintain the three inhibits. Thus by incorporating both isolation valves on the main line the total number of valves required for the propulsion system is reduced by seven.

With all the functional components needing to be placed along the main line, the relative location of each had to be determined. The function of each part was the determining factor for its location. For instance, the first isolation valve is intended to isolate the propellant tank from the rest of the system prior to the initiation of formation flight and as such needs to be close to the tank on the main line. However, the pressure maintained within the propellant tank needs to be constantly monitored which means one of the pressure transducers must be placed before the first isolation valve. In the same way, the final pressure transducer must be located just after the pressure regulator device or else it would be incapable of determining the regulated pressure. Finally, the line heater must be placed where the greatest possibility of propellant condensation occurs. The main concern with regard to propellant condensation was due to long term propellant storage within the lines. This is unlikely to occur post-regulator, so the line heater was
integrated just preceding the regulator. Thus combining the layout of the main line with the line division plan yields the basic order of components given in Figure 3.11.

Figure 3.11: Basic Order of Components for MR SAT Propulsion

3.3.2.3 Naming convention. Each part and connection must be individually identifiable and trackable so that torque logs and part logs can be filled out. Such logs are mandated by UNP and are a method to catalog and document pertinent information concerning the safety and usability of components throughout their lifetime. Therefore, a naming convention had to be implemented to distinguish otherwise indistinguishable parts and connections.

The easiest way to implement a naming convention in a rational and systematic manner was to base each part name on component type and location along the propellant line. The first step, then, was to systematically name each branch line. To begin the process, the line stemming directly from the propellant tank was classified as the Main Line. Each secondary line was then numbered starting with the left most line stemming from the diverging point when seen from above (see Figure 3.12) and continuing clockwise. Tertiary lines were given a letter beginning with "a" attached to the moniker of their source line and quaternary lines continued in the same manner utilizing numbers.

Figure 3.12: Example of Line Naming Convention

Parts and tubing were then named based upon the location of said part along each of the various branch lines. The final name consisted of three parts; one or two letters identifying component type, line name, and number of that particular component type along that line. For example, the tee fitting connecting the downstream pressure transducer to the main line was cataloged as TML02 where "T" denotes type of fitting, "ML" signifies that the fitting is on the main line, and "02" indicates that it is the second tee fitting on the line. Figure 3.13 depicts each component and its corresponding name within the propulsion system.

3.3.2.4 System integration. Transforming the two-dimensional basic component order into a three dimensional system integration plan required consultation with both the structures and integration subsystems to ensure that the system fit within the confines of MR SAT and met all requisite structural guidelines. Discussions focused on two key areas: the integration of the core hardware, i.e. the propellant tank and main line hardware, and the integration of the thruster assemblies and propellant lines onto the isogrid panels.

The core hardware represented the majority of the mass and volume of the MR SAT propulsions system. Its placement was also the initial task for the integration of the propulsion system into MR SAT beginning with tank placement. Due to the variable nature of propellant tank mass (i.e. the mass changes as propellant is expelled), the placement of the tank can affect the motion of the satellite CG during the mission. Ideally, the CG of the tank would be placed at the CG of the satellite to limit the change of CG throughout the mission; however, due to the dimensions of the propellant tank and the placement of other satellite components this was neither practical nor structurally feasible. Therefore, the tank was placed along the bottom panel of MR SAT with the inlet and outlet oriented towards opposing corners within the hexagon frame of the

Figure 3.13: M-SAT Propulsion System Component Names

satellite. The orientation was particularly important in terms of integration since the cross corner span of the satellite represents the greatest linear distance along the bottom panel. Thus, even with specialized fittings attached to the outlet of the propellant tank the propellant lines still remain within the interior of the satellite.

Stemming from the propellant tank is the main line of the propulsion system. As originally designed, a specially designed Swagelok elbow fitting immediately directed the main line from the propellant tank down to the base plate of MR SAT. From there the line angled in along the side of the tank to a tee fitting connected to the first pressure transducer. After the first isolation valve, the line bent 90 degrees upward where the pressure regulator and second pressure transducer were integrated into a tower. Finally, the line bent another 90 degrees to run along the top panel where the second isolation valve was incorporated. A CAD model of this set-up is shown in Figure 3.14.

The problem with this arrangement was structural in nature. The tower of components had no support structure in place to balance the mass of the components and prevent launch vibrations from tearing the components apart. Various solutions and adaptations were proposed that maintained the same basic tower structure yet attempted to provide the components added support by incorporating support rods or even tying components into special support structures added to the nearby component boxes within MR SAT. However, these options were not optimal solutions and the subsystem began considering entirely new configurations that would be structurally sound.

Figure 3.14: Early Propulsion Configuration

The challenge of developing a core hardware configuration where all components have sufficient structural support was one of limited space and attachment points within the satellite. With the propellant tank occupying most of the bottom panel and component boxes limiting the available space along the side panels, the only accessible space for the main line components is the area directly above the propellant tank. There were no natural attachment points within this region but a support structure could be incorporated into the propellant tank mounts that would allow the main line components to wrap around the tank.

This support structure consisted of two specially designed tank mounts and a mounting bridge that spans the gap between the two mounts. The tank mounts each had a contoured opening designed to fit over the hemispheric ends of propellant tank and were

bolted to the bottom plate of MR SAT. The mounting bracket on the outlet side of the tank was equipped with two lipped shelves slanted at a downward 45 degree angle. These shelves were designed to serve as mounting brackets which completely support the mass of the two pressure transducers. Each tank mount was also fitted with a raised platform serving as the integration point for the mounting bridge. The mounting bridge was a thin piece of aluminum with two sets of pronged attachment points stemming from either side of the bridge. Figure 3.15 represents the developed support structure with the tank incorporated.

Figure 3.15: Tank and Support Structure

With this support arrangement, the main line is directed upward upon leaving the tank and angled over into the run end of a tee fitting. Fitted to the branch end of the tee is the first pressure transducer angled down along the tank mount so that the mass of the

transducer is supported. From there, the line continues to the first isolation valve which is supported by two prongs of the mount bridge. The line then wraps around to the other side of the tank where the pressure regulator is also supported by the mounting bridge. Next, the line is attached to the branch end of a tee fitting which is angled so that the runs lay along the sloped supports of the tank mount. The final pressure transducer connects to the downward angled run of the tee fitting leaving the main line to continue at an upward angle to the top panel of MR SAT where the final isolation valve is connected running parallel to the tank. Figure 3.16 represents the core hardware configuration used for MR SAT with an adaptation of the propellant line between the first isolation valve and the regulator to provide the four inches of straight tubing required for line heater integration.

The integration of thruster assemblies and propellant lines into the satellite posed the same challenges of design encountered during the core hardware configuration. As discussed earlier in this section, eight thruster assemblies had to be incorporated into the satellite at specific locations to attain the performance goals of the propulsion system. Simply integrating the thrusters themselves onto the various isogrid panels would have been challenging enough given the limited available space; however, the thrusters are not self contained units and must be connected to propellant lines and fittings which both require extra space and efficient placement.

Mindful of the integration of other satellite components, the original propellant line design avoided the center of isogrid panels and limited connections on the top panel of MR SAT.

Figure 3.16: MR SAT Core Hardware

In Figure 3.17 the main line continues from the core hardware into a Swagelok cross fitting on the top panel of MR SAT. From there the three secondary lines diverge along the edges of the top panel to the second group of diverging points in the form of tee fittings located along the edges of the isogrid panels. Figure 3.18 shows a close up of Panel 1 with its four thrusters integrated.

The major difficulty with this routing of propellant lines was the unanticipated interference the lines and fittings cause in the assembly of the MR SAT structure. In attempting to avoid component boxes in the center of the panels, the routing plan inadvertently covered panel attachment points and interfered with bolt patterns. Also, particularly on Panel 1, the minimum bend radius for the tubing did not allow the propellant lines to avoid interference with component boxes. Thus a rerouting of propellant lines was required.

Figure 3.17: Original Propellant Lines Routing

To avoid component and assembly interference, the propellant lines were rerouted with more of the fittings attached to the top panel. Propellant lines were pulled away from the isogrid panels in some instances to avoid connection points and account for the minimum bend radius of the tubing. This was especially true on Panel 1 where the diverging point was moved off the panel to the top panel of MR SAT and the line division for the thrusters was changed.

Figure 3.18: Original Panel 1 Propellant Line Routing

Finally, the corner thrusters were moved from the middle of the corner to one side so they could be attached to a single panel instead of strung between panels. Figure 3.19 shows the final MR SAT propulsion system.

3.3.3. Expected Performance. Performance is the driving objective of the design process, and as such a method of objectively determining the performance of the system as designed was required. Modeling a two-phase system proved to be a difficult task since the added variables and possibility of condensation quickly complicated the mathematical equations. Therefore, assumptions were used to simplify the modeling equations yet still take into account worst-case conditions. A more detailed description of the modeling process can be found in Section 4.4 of Carl Seubert's thesis entitled

Figure 3.19: MR SAT Propulsion System Final Design

To employ the rocket flow equations, basic assumptions had to be made. These include:

- Isentropic nozzle flow
- Isothermal fluid in tank and propellant lines
- Propellant is a gas and obeys the perfect gas law

- Nozzle flow is free of discontinuities and/or shockwaves
- Flow is axially uniform with negligible boundary layer
- Steady flow with no transient effects due to valve opening/closing

While many of these assumptions are valid given the right operating conditions, others such as the negligible boundary layer are less valid and must be taken into account in the form of correction factors applied to the equations. For the final flow conditions, a pressure loss of 10 psi from regulated pressure (i.e. the nozzle is exposed to a pressure of 14.7 psi) was implemented to account for flow losses due to friction and any leaks present in the system. Additionally, it was assumed only 90% of the gas pressure could be effectively converted into thrust with the last 10% being lost to leaks and/or insufficient pressure to be expelled from the tank. Finally, the propellant temperature was set to 15 °C which gives a more conservative estimate of thruster performance and takes into account the possibility that the system heaters may not be able to maintain the propellant at the target temperature of 20 °C.

Given these conditions, the system performance was computed for three possible tank pressures. The three pressures chosen account for the sealed container requirement of NS4 and the advantages that could be realized if higher pressures could be implemented. The thrust performance is recorded in Table 3.14 and the system performance in terms of ΔV is logged in Table 3.15.

	i i m ust i ti ioi mante
I _{SP}	43.71 sec
Thrust	37.37 mN
Mass flow rate	0.0889 g/s

 Table 3.14: Predicted Thrust Performance

Table 3.15: Predicted ΔV Performance for Three Pressure Regimes

Max Tank Pressure	ΔV	Total Thrust Exhaust
at 100 °C (psi)	(m/s)	Duration (min)
100	0.935	11.34
200	2.024	24.52
300	3.345	40.46

3.4. CONCEPTUAL OPERATION

The overall performance of the propulsion system and the satellite as a whole can depend greatly on how and when various mission tasks are initiated and performed. Conceptual operations allow for mission planning to take into account multiple mission conditions and develop contingency plans to deal with suboptimal conditions. While all operating conditions have not been explored, a basic operation plan for the M SAT mission has been developed. The use of the propulsion system within this plan is discussed in the following sections.

3.4.1. Modes of Operation. The Modes of Operation were developed by the M-SAT leadership as a mission timeline to aid in planning. The Modes are a sequence of major phases within the mission that are further subdivided into general tasks to be performed by the satellite in order to accomplish the goals of that phase. The entire mission is divided into 11 major phases with additional safe modes established should unexpected situations arise. The propulsion system is featured in four of the post-launch

operation modes including Initialization, Detumble, Separation, and Formation Flight. However, under nominal conditions, the system will only fire during the Formation Flight phase of the mission. During both the Initialization and Separation modes, the propulsion system tasks are limited to monitoring pressure and temperature and ensuring that the system is prepared to function during the following phase. The propulsion system will remain on standby during the Detumble mode as a backup system in case the coils cannot adequately control the satellite; however, should the propulsion system have to be used at this early junction, the formation flight portion of the mission will be adversely affected due to the expended propellant.

3.4.2. Stand-by Operations. The major task for the propulsion subsystem when not engaged in propulsive maneuvers is to maintain the ability of the system to perform when required. This involves continually monitoring the system for pressure and temperature variations and applying active controls in the form of heaters when applicable. Maintaining the set temperature is particularly important to system function as the expulsion of propellant from the tank can quickly reduce the temperature of the propellant to the point where phase change cannot occur and propellant flow would be interrupted.

3.4.3. Mechanics of Thruster Firing. There are two ways in which the propulsion system can be configured to operate during a firing sequence. The first method has the last two inhibit levels within the propulsion system initially closed. When a thruster tasking is implemented, both valves are opened, starting with the isolation valve, in a pulsed fashion allowing propellant to flow down from the regulator and out the nozzle. The major advantage of this method is that the isolation of the second

half of the propulsion system is maintained. Thus should a small leak be experienced downstream of the second isolation valve (where the majority of the connections are), the propulsion system is not continually feeding propellant to the leaky fitting during long pauses between firings. However, this method invalidates the assumption of steady flow since transient conditions would exist in the line due to opening of the valve.

The second has both isolation valves maintained in the open position during formation flight. To execute a maneuver, therefore, would only require the opening of the specific thruster or thrusters necessary to produce the required force or torque and powering up the tank heater to ensure phase transition. Under this method, the propellant lines downstream of the regulator are kept at a constant pressure in between propulsive maneuvers and thus the steady flow assumption utilized in the model is more justifiable as long as sufficient time elapses between thruster firings. Currently, this is the method set to be used during the MR SAT mission; however, system level testing will determine the optimal arrangement.

4. HAZARD ANALYSIS

4.1. PURPOSE

Safety is of the utmost concern when developing and constructing a satellite. Hazards present serious risks to personnel and equipment, and yet are possible in all engineered systems. Identification of all such hazards within a system is the only possible way to ensure that proper mitigation efforts are in place. In a two-phase propulsion system such hazards may be caused by natural thermodynamic events (i.e. temperature changes due to ambient conditions) or component failures. The hazard analysis undertaken by the M-SAT Propulsion Subsystem sought to identify the hazards associated with the system during all phases of construction and operation in order to ensure the mitigation efforts, including component redesign and procedure implementation, were sufficient to guarantee the safety of all personnel and equipment.

4.2. PROPULSION SAFETY ASSESSMENT WHITE PAPER

The hazard assessment for the MR SAT propulsion system began during the NS4 competition in the form of the Safety Assessment White Paper (SAWP) written jointly by the three universities pursuing refrigerant based propulsion systems. The Missouri S & T-led consortium included members of the University of Texas at Austin and the Washington University in Saint Louis NS4 design teams. The stated purpose of the SAWP was to lay forth the foundations for a new type of cold gas propulsion based upon refrigerant propellants stored in a saturated-liquid state. The foundational aspect of the paper was meant to address concerns of AFRL officials by evaluating the need, design regime, and safe implementation methods of such a propulsion system.

4.2.1. Paper Specified Temperature Range. The most extreme temperature and pressure conditions the propulsion system must be designed to meet will occur on-orbit. After consultation with the UNP program managers, -50 °C to 100 °C was deemed a conservative and appropriate range of expected temperatures for nanosatellites in low Earth orbit.

The conservative nature of the specified range was confirmed in the SAWP through the analysis of telemetry data collected during various heritage satellite missions. For example, the AMSAT-OSCAR 7, a 28.6 kg satellite launched into high LEO orbit in 1974, experienced on-orbit temperatures ranging from 8.5 °C to 35.1 °C. Additionally, the range selected for use in the white paper was found to be more conservative than the thermal test range (-35 to 75 °C) currently employed by NASA for unmanned spacecraft [24].

The selection of such a conservative thermal range, particularly the high upper limit, has a direct impact on the hazard analysis of the system. Given the variable nature of propellant state within the specified temperature range, worst case scenarios, i.e. scenarios utilizing the extremes of the range, dominate the analyzed hazards.

4.2.2. Focus of SAWP Hazard Analysis. A typical hazard analysis focuses on specific physical systems; however, such was not the case with the hazard analysis associated with the NS4 Propulsion White Paper. Each member university of the consortium had designed and was in the process of implementing a unique refrigerant-based propulsion system within their specific satellite. Therefore, it was impossible to analyze a single propulsion system that would encompass the hazards present in each

system. Instead, a *general* system was analyzed for hazards associated solely with the unique propellant.

Under this guideline, hazards are not associated with a specific component failure, instead, how a change in the propellant affects the rest of the system is evaluated; e.g., an increase in propellant pressure could cause the tank to rupture. Due to the somewhat unspecific nature of the hazards, mitigation efforts described within the SAWP were presented in the form of design guidelines and suggested practices rather than specific component remedies.

4.2.3. SAWP Hazard Classification System. To begin the safety assessment, a hazard classification system was developed based on suggestions from AFRL mentors as follows:

- **Catastrophic** A Catastrophic Hazard is defined as any single or multiple system failure which has the potential to cause damage/harm not only to the spacecraft, but to surrounding equipment/personnel as well.
- **Critical** A Critical Hazard is defined as any system failure which results in damage/harm to the spacecraft and/or has the potential to negatively impact mission objectives to the point of failure.
- **Tolerable** A Tolerable Hazard is defined as any system failure which results in minimal damage to the spacecraft/mission.

Based on these definitions, hazards are classified not by the likelihood of their occurrence but rather by the ramifications of said occurrence. In this way, identified

hazards can be ranked on a relative scale, and the impact of each identified; thus enabling proper design choices to be made.

However, in discounting the probability of hazard occurrence and the possibility of mitigation efforts, the classification system makes nearly impossible to design and fly a system free of catastrophic hazards. Thus, the additional classification of Acceptable Risk for Flight, as designated below, was necessary as justification for the inclusion of catastrophic hazards within flight-ready designs.

• Acceptable Risk for Flight - Acceptable Risk for Flight is defined as operating the system with known hazards classified as Tolerable or with hazards which can be mitigated to tolerable levels by use of the appropriate safety devices and measures.

4.2.4. SAWP Hazard Analysis. The general design of any propulsion system contains many possible hazards within each classification. In most cases, propellant is initially stored in a small, pressurized vessel and from there distributed to the thrusters by means of tubing. By taking into account mission objectives, a prototype design can be developed; however, before the design can be further refined, the safety assessment must be completed to ensure selected components meet the mitigation criteria.

4.2.4.1 Catastrophic hazards. The greatest risk inherent to the system comes from uncontrolled and unexpected changes in the state of the propellant. The catastrophic hazard is directly caused by an increase in system temperature, but may have many indirect causes. As a result of this increase, the pressure of the propellant could rise to levels above the maximum design pressure mandated for the system components,

which in turn could lead to increased leak rates and/or system rupture. The use of storage tanks defined as pressure vessels greatly amplifies the effects of burst since they contain enough internal energy to seriously impact the surrounding area. Both passive and active methods of mitigation are available to combat the adverse effects of pressure increase. The first passive measure is simply designing the storage vessel with a sufficiently large factor of safety to withstand any fluctuations within the system. Also, the system should be designed to be leak-before-burst; thus alleviating dangerous over-pressurization through low energy fluid discharge rather than an explosive release of energy. The active method uses sensors to monitor system conditions and discharges the system once dangerous levels have been reached.

Another consequence of a rise in temperature is encountered within the system materials. Many materials, metallic in particular, expand and contract with changes in temperature causing increased stress at connection points. If these stresses are not accounted for in the design of the system, increased leak rates and/or rupture could occur. Additionally, if materials with dissimilar thermal expansion rates are used at connection points, the possibility of mission damaging leaks increases many fold. Two possible sources of differing thermal properties are the use of multiple materials (e.g. aluminum connected to steel) and the existence of thermal gradients between connected components. To guard against the possible consequences of thermal expansion, proper material selection must be performed with particular attention to obtaining sufficient yield and fracture stress properties, and if possible, avoiding the use of dissimilar materials.

Finally, under drastic conditions and extreme temperatures, the selected refrigerants have the added hazard of decomposition and even the possibility of autoignition. Decomposition of R-134a and R-123 occurs at temperatures above 250°C and auto ignition at or above 743°C and 770°C, respectively. All values are well above the expected temperature range; however, the seriousness of the consequences produced by this hazard merits mention. Both refrigerants decompose into highly volatile and caustic chemicals, such as hydrofluoric acid, which can cause serious burns and compromise equipment. Care should be taken during construction and storage of the satellite so propellant does not come into contact with excessive heat such as open flames.

When dealing with pressure vessels, structural strength of the selected material is of the utmost importance. However, merely designing to worst-case scenarios is no guarantee of successfully avoiding structural failure since thermal cycling has, in addition to those risks associated with the corresponding maximum and minimum temperatures, the potential to cause structural failures due to thermal fatigue. Temperature fluctuations for a two-phase propellant system can occur due to both system and environmental influences. During propulsive maneuvers the endothermic phase change lowers the overall system temperature. Environmental factors, such as leaving and entering eclipse, can also cycle system temperatures. To avoid thermal fatigue, it is first necessary to thermally insulate the system through use of MLI which will greatly reduce the effects of the spacecraft's environment. To reduce the effect of system processes, system monitoring and some method of energy addition to the system (i.e. heaters) are required. The heaters should be turned on during propulsive maneuvers to account for endothermic phase change and minimize thermal gradients. Finally, system materials should be chosen in such a way as to limit the effects of thermal cycling where possible.

4.2.4.2 Critical hazards. Catastrophic hazards may pose the greater threat to surrounding equipment and personnel; however, critical hazards are no less destructive to mission success. As with hazards classified as catastrophic, critical hazards are often products of the propellant state whereas mitigation methods normally center on proper component selection and procedures.

The effects of a temperature decrease within the system represent a critical hazard rather than catastrophic as the internal energy contained within the system is far less than that for the case of temperature increase. As such, the overall magnitude of possible consequence for any resulting failure is less. This does not mean, however, that thermal decrease can be ignored. Any substantial decrease in the temperature of the fluid will result in a phase change. If the temperature falls to the freezing point of the propellant, the fluid will solidify. The effectiveness of the propulsion system's internal mechanisms will be reduced with a potential of damage to internal mechanics of the tank if any of the solid propellant shifted. However, the system need not reach the propellant freezing point in order for a hazard to be present since there exists the potential for system materials to experience reduced structural integrity (brittleness) due to the low temperatures generated by the fluid. Also, as with thermal expansion, thermal contraction can lead to propellant leakage and eventual mission failure if different contraction rates exist between components. Mitigation efforts should include system heaters and insulation to lessen the probability of significant temperature decrease. Also,

system materials should be selected to avoid mismatched thermal contraction rates and materials which can become brittle within the expected temperature range.

Temperature and pressure are not the only propellant properties to consider during a hazard analysis; the material compatibility and potential for chemical reactivity are also a concern. While refrigerants are generally chemically inert, as previously mentioned there are certain substances with which a negative reaction can occur. Any system material should be thoroughly researched for its compatibility with the chosen propellant. System materials which have direct contact with the propellant must have a zero to very low reactivity rating to ensure continued system functionality. When determining an acceptable degradation rate, mission length should be accounted for with appropriate margins. For shorter missions, a somewhat faster reaction rate might be acceptable so long as mission goals are not negatively impacted; however, longer missions require much lower reactivity. Materials with no or limited exposure to the fluid under normal operating conditions must also be considered since any leaks could bring said material in contact with the propellant. To prevent harm to equipment and personnel, any material reactions determined to be explosive or combustible require the selection of a different material. Where material reselection is not possible, such as on board the launch vehicle, it is important to make sure the system has minimum leakage to lessen the chance of reaction with an unknown material.

4.2.4.3 Tolerable hazards. Throughout ground operations, there is the possibility of exposure to the propellant which is a tolerable hazard that can be avoided. Direct skin contact can have two results: skin irritation and/or frostbite. Skin irritation is

a symptom of chemical exposure to the refrigerants, while frostbite results from the low temperature nature of the refrigerant. Asphyxiation is possible if proper venting is not present during the discharge of any propellant. Personnel should be required to wear suitable protective clothing and eyewear. In addition approved ventilation and warnings should be instituted in the work environments where potential exposure to the propellant can occur.

4.2.4.4 Hazard classification matrix. The hazard analysis for the SAWP was put into a classification matrix in order for the identified hazards to easily be classified and associated with the required mitigation methods. The resulting catalog of hazards is shown in Table 4.1.

Hazard	Classification	Associated Risk	Methods of Mitigation	Reclassification After Mitigation
Thermal	Catastrophic	Structural failure	Temperature	Critical
Cycling		of components (Fatigue and	monitoring	
		brittle fracture)	Insulation	
			Suitable	
			selection of	
			system materials	
			Apply active	
			thermal controls	
			(i.e. heaters)	
			during	
			propellant	
	1		storage	

 Table 4.1: SAWP Hazard Classification Matrix

Hazard	Classification	Associated Risk	Methods of	Reclassification After
			Mitigation	Mitigation
Propellant	Critical	Risks of	Methods for	Tolerable
Leakage		exposure to	exposure to	
		propellant:	propellant:	
		Ground	ground	
		operations and	operations and	
		flight materials	flight materials.	
			Selection of	
			connections with	
			minimized leak	
			rates.	
			Selection of	
			system materials	
			with appropriate	
			factor of safety	
			to ensure a high	
			leak-before-	
Exposure to	Toloroblo	Skin irritation	Durst point.	Talarabla
Propellant:	TOICIADIC	and/or frosthite	exposure hazard	TUICIAUIC
Ground			exposure nazaru	
Operations		Asphyxiation	Wear suitable	
			skin protection	
			and eyewear and	
			implement	
			approved	
Matarial	Critical	Added stress at	Dramarly	Talarahla
Flongation	Critical	Added stress at	Property solocting fittings	Tolerable
Eloligation		connections	selecting fittings	
		Possible leaks		
		and/or burst		
Different	Critical	Possible leaks	Properly select	Tolerable
Material			materials	
Thermal				
Expansions				
Rates and/or				
Thermal				
Gradients	1			

Table 4.1 SAWP Hazard Classification Matrix (Cont.)

Hazard	Classification	Associated Risk	Methods of Mitigation	Reclassification After Mitigation
System Charge and Discharge	Critical	Mechanical fatigue which leads to possible rupture	Proper selection of tank materials and minimization of the number of charge and discharge cycles	Tolerable
Unexpected and Significant System Pressure Increase	Catastrophic	Increased leak rates and/or system rupture	Passive Methods: System designed with large factor of safety to withstand any pressure fluctuations. System designed to be leak before burst Active Measures: System monitoring through pressure transducers. Release of propellant to reduce pressure	Catastrophic
Substantial Temperatur e Decrease	Critical	System materials may become brittle	Proper selection of materials	Tolerable
Decomp of Propellant	Catastrophic	Production of toxic/caustic chemicals which can cause structural failures and chemical burns	Avoid temperatures above 250 C	Catastrophic

Table 4.1 SAWP Hazard Classification Matrix (Cont.)

Hazard	Classification	Associated Risk	Methods of Mitigation	Reclassification After
			Miligation	Mitigation
Thermal	Catastrophic	Risks of system	Methods for	Catastrophic
Increase		pressure increase	pressure	
			increase	
		Risks of material		
		elongation	Methods for	
		Dialra of	material	
		different thermal	elongation	
		expansion rates	Methods for	
		and/or thermal	different	
		gradient	material thermal	
		8	expansion rates	
		Risks of	and/or thermal	
		decomposition	gradient	
		Risks of fire	Methods for	
		and/or auto-	decomposition	
		ignition		
			Methods for fire	
			and/or auto-	
Dragallant	Critical	Detential damage	ignition	Talarahla
Freezing	Cinical	to internal	thermal controls	Tolerable
Treezing		mechanics of	(i e heaters)	
		system	during	
		components	propellant	
		I I I I I I	storage	
		Reduced	C	
		effectiveness of	Insulation	
		internal		
		mechanics of	Temperature	
		system	monitoring	
Fire and/or	Catastrophic	Possible fire	Avoid high	Catastrophic
Auto-		with exposure to	temperatures,	
ignition		ingli concentrations of	iligii concentration of	
		Oxygen and	Oxygen ignition	
		ignition source	sources and use	
		-Sincion Source	proper storage	
			procedures	

Table 4.1 SAWP Hazard Classification Matrix (Cont.)

4.2.4.5 SAWP hazard analysis conclusion. Ideally speaking, only systems containing no hazards classified greater than tolerable would be considered for flight; however, given the nature of spacecraft design, this is not always possible. Since the classification of a hazard is based not on the likelihood of its occurrence but on the potential harm the hazard could produce, even after mitigation some hazards cannot be reclassified. Mitigation efforts can, however, reduce the possibility of such an adverse event and even lessen the potential harm to both equipment and personnel. To represent an acceptable risk for flight, all hazards within a system must be acknowledged and addressed by implementing the proper mitigation methods. Those hazards which cannot be reclassified do not preclude a system from flight if ground and launch personnel are aware of the potential danger and can execute the necessary procedures to prevent the occurrence.

4.2.5. AFRL Approval for the SAWP. After completion, the SAWP was presented to AFRL officials for final approval of the document and thus their tacit approval of the foundations and guidelines within the paper. Two separate levels of approval were sought by the consortium; approval of concept and approval of design constraints. Approval of concept covers the idea that refrigerant based cold gas propulsion systems are not inherently unsafe and can be implemented under the UNP. AFRL approval of the design constraints developed in the SAWP would imply that systems designed within the specifications of the SAWP would meet safety guidelines and be permitted to fly.

Top level analysis of the SAWP by AFRL officials found the paper to be well written and reasoned. Thus, AFRL acknowledged the necessity of using two-phase cold gas thrusters and that such thruster systems were not innately in violation of UNP policies. However, final approval for the document was not granted due to lack of specifics within the design and hazard analysis portions. AFRL safety officials were looking for assurances within the paper that each propulsion system had been designed and implemented in a safe manner. Due to the general nature of the paper such assurances were impossible. Additionally, safety officials took exception to the "Acceptable Risk for Flight" definition; stating that catastrophic hazards are generally not acceptable flight risks and that mitigation efforts or design changes are necessary to remove said hazards from the system.

4.3. SCOPE OF HAZARD ANALYSIS

Addressing the concerns of AFRL officials in terms of the M SAT propulsion system required a shift in focus away from the previous consortium of universities and toward a system tailored hazard analysis. The analysis must strive to discover, classify, and correct all potential hazards to personnel and equipment. As such, the analysis cannot merely be based upon hazards present in the final product, but also must take into account hazards present during all phases of construction and operation.

Therefore, the second hazard analysis undertaken by the M SAT Propulsion subsystem sought to identify and mitigate hazardous situations during all phases of design, construction, and operation with particular attention to possible situations which could lead to catastrophic hazards later on in the mission timeline.

4.4. TYPES OF HAZARD ANALYSIS

Multiple hazard analysis methodologies were explored for possible adaptation to the needs of the M SAT Propulsion hazard analysis. The methods researched basically fell into one of two categories: a "What if?" method where the analysis is performed by determining the consequence of the realization of component failure modes and a more quantitative analysis based upon the given rate of component failure and the effect of said failure upon system operation.

The quantitative analysis has the benefit of being a far more thorough analysis method that utilizes manufacturer's component failure rates to determine the probability of hazard occurrence. Additionally, the consequences of the hazard on the system are quantitatively described through simulation; thus, allowing for the quantitative assignment of severity levels. The major drawback of such an analysis is its time and labor intensive nature. While not as thorough as the more quantitative analysis, the "What if" type of analysis has the major benefit of low personnel cost. As both time and personnel are legitimate concerns for the M SAT team, a "What if" style hazard analysis was deemed adequate for the purposes of the M SAT Propulsion subsystem.

4.5. DEFINING A HAZARD CLASSIFICATION SYSTEM

The shortfall of the previous classification system was that it failed to take into account the probability of hazard occurrence and thus limited the manners in which catastrophic hazards could be addressed. Therefore, a new system of classification that still accounted for hazard severity yet also incorporated hazard probability was required. At the suggestion from SAWP reviewers, inspiration for the new classification system was drawn from NASA and DOD documents concerning hazard analysis implementation.

Under the new system, the measure of severity definitions remain relatively unchanged. Four severity classifications are defined in Table 4.2.

	Table 1.2. Hazard Severity Classifications [25]				
	Description	Category	ory Environmental, Safety, and Health Result Criteria		
	Catastrophic	Ι	Could result in death, permanent total disability, loss exceeding \$1M, or irreversible severe environmental damage that violates law or regulation.		
CriticalIICould result in permanent partial disability, injuri occupational illness that may result in hospitalization least three personnel, loss exceeding \$200K but less \$1M, or reversible environmental damage causi violation of law or regulation.		Could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding \$200K but less than \$1M, or reversible environmental damage causing a violation of law or regulation.			
	Marginal III Negligible IV		Could result in injury or occupational illness resulting in one or more lost work days(s), loss exceeding \$10K but less than \$200K, or mitigatible environmental damage without violation of law or regulation where restoration activities can be accomplished.		
			Could result in injury or illness not resulting in a lost work day, loss exceeding \$2K but less than \$10K, or minimal environmental damage not violating law or regulation.		

 Table 4.2. Hazard Severity Classifications [25]

Probability of occurrence was taken into account by implementing a secondary set of classifications indicating the frequency the hazardous situation is likely to occur. These definitions are given in Table 4.3.

The two classifications are then combined within a Risk Assessment Matrix (RAM) to yield the Risk Assessment Code (RAC) associated with each hazard. The RAM used for the MR SAT Propulsion hazard analysis is detailed in Table 4.4.

Description	Category	Applicable Criteria		
Frequent	А	Likely to occur often during the operational lifetime of the system, with a probability of occurrence greater than 10^{-1} in that life.		
Probable	В	B Will occur several times during the operational lifetime of the system, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} in that life.		
Occasional	С	Likely to occur sometime during the operational lifetime of the system, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life.		
Remote D		Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life.		

 Table 4.3: Probability Estimate Classification [25]

 Table 4.4: Risk Assessment Matrix

	Frequent	Probable	Occasional	Remote
Catastrophic	1	1	2	3
Critical	1	2	3	3
Marginal	2	3	4	4
Negligible	3	3	4	4

The different RACs attached to each identified hazard speak to the flight acceptability of said hazard. The definitions for RACs 1-4 are as follows:

 RAC 1 – The hazard presents an imminent danger and unacceptable risk for flight. Mitigation efforts must be implemented (preferably in the form of a redesign) to reduce hazard severity and probability.

- RAC 2 The hazard presents a serious danger to surrounding equipment and personnel. The hazard is an unacceptable risk for flight and mitigation efforts must be implemented.
- RAC 3 The hazard is an acceptable flight risk yet should be addressed with applicable mitigation procedures if possible.
- RAC 4 The hazard is an acceptable flight risk with current controls.

4.6. HAZARD IDENTIFICATION

Hazard identification is an important step in the analysis process. To begin the process of hazard identification, the failure modes of each component within the system were delineated. Any event, defect, or deviation from nominal component performance which has the potential to adversely affect mission goals or cause dangerous situations is deemed a failure mode of said component. For example, the elbow fitting attached to the propellant tank has two identified failure modes: component leak and component burst. However, to account for hazards not associated merely with component failure, the identification process was extended to the different phases of the propulsion project beginning with the construction phase. Within the various phases of the project, the hazards present are mainly procedural in nature rather than component related. To identify these hazards, the procedures were analyzed for hazardous situations and potential errors in implementation which could result in future hazards.

4.7. HAZARD ANALYSIS

With hazards present within the system identified, the analysis portion of the process begins. Each identified failure mode was examined as to the circumstances

which could lead to the occurrence of said failure mode. The probability of hazard occurrence was then assessed by analyzing the pertinent data such as Factors of Safety and available data on component failure rates. Finally, the consequences of occurrence were evaluated and described in order to judge the severity classification necessary for the failure mode.

The next step in the analysis process was the assignment of the initial Risk Assessment Code for each identified hazard based on the method described in Section 4.5. Finally, controls and mitigation efforts were considered and the RAC adjusted to correspond with the new severity and probability classifications. The resulting hazard analysis can be found in the appendix.

4.8. MITIGATION: DESIGN VS. PROCEDURE

When confronting a possible hazard, the primary goal of the system designer should be to eliminate the hazard through a redesign process or implement automatic controls within the system that remove the probability of hazard occurrence. This provides the safest means for continued operation of the system; however, under certain circumstances the hazard cannot be wholly removed from the system and in such instances procedures must be implemented to mitigate the risk.

4.9. HAZARD ANALYSIS CONCLUSIONS

The completed hazard analysis for the M SAT propulsion system demonstrates the inherent safety of the system. As designed, or with the implementation of proper handling procedures, all identified possible hazards within the system merit risk assessment codes deemed acceptable for flight.

5. SYSTEM-LEVEL TESTING

5.1. INTRODUCTION

Complex systems must undergo a multitude of tests in order to be certified ready for flight. Testing begins at the component level; with each component undergoing extensive evaluations to ensure that the expected performance characteristics are achieved. At the same time, small conceptual tests are performed at the subsystem level to explore the pertinent theory utilized by the system. However, the system cannot be certified as ready without full system-level testing that confirms the expected performance. Such testing must be conducted in a manner as close as possible to the conditions in which the system will normally operate so as to identify performance deviations and to verify system function.

5.2. SYSTEM-LEVEL TEST GOALS

The MR SAT propulsion system embodies an innovative approach to small satellite propulsion, and as such the theoretical work performed for the design process must be confirmed. The key performance parameters still in need of physical demonstration for the refrigerant based system include the performance of the integrated PMD, the ability of the system to maintain the necessary tank temperature, and the overall thruster performance of the system. These three physical traits of the system are interconnected in such a manner that they must be explored in unison for useful information to be determined. The goal then, for system-level testing, is to develop a testing platform capable of monitoring and testing each of these functions.
5.3. REDUCED GRAVITY STUDENT FLIGHT OPPORTUNITY PROGRAM

Under normal laboratory conditions it is difficult and perhaps impossible to accurately determine the successful operation of the integrated PMD since slosh effects occur only in micro gravity conditions. Therefore, it was necessary to secure laboratory facilities that could mimic the micro gravity environment in which the propulsion system would normally operate.

The Reduced Gravity Student Flight Opportunity Program (RGSFOP) is a NASA program in which university-presented research projects can secure flight time on NASA aircraft used to simulate micro gravity conditions. The program begins in late September or early October with the submission of a research proposal by university group or design team seeking a flight berth. In December, approximately 40 university teams are selected for flights during the first half of the following year.

The C-9 aircraft used for the program flies a series of parabolas between 20,000 and 35,000 feet. As the aircraft flies over the crest of the flight pattern, approximately 30 seconds of micro gravity occur during which experiments can be run. As the aircraft pulls out of the dive, a period of twice normal gravity is experienced. Each experiment receives two flights per flight week with approximately 30 parabolas of micro gravity encountered per flight.

5.4. TEST APPARATUS

With regard to the design of the testing apparatus, the intent was to develop a platform capable of supporting and conducting the proposed RGSFOP experiment and also supporting any future expanded testing plans. With this in mind, the platform was

designed as a freestanding workstation incorporating the safety and measuring equipment necessary to perform the testing operations within the various experiment environments.

5.4.1. Measuring Equipment. The propulsion system developed for the satellite inherently incorporates two pressure transducers in order to monitor the tank pressure and regulated pressure of the system during spaceflight. In order to augment the information gathering capabilities, two thermal-couples were added to the propulsion system: one placed directly at the tank outlet and one within the propellant lines just prior to the thruster. Rounding out the measuring equipment is a single force transducer capable of measuring forces from 0 to 50 millinewtons positioned on the air bearing slide to directly measure thruster performance.

5.4.2. Testing Platform Structural Design. As the experiment was to be flown on board NASA's "Weightless Wonder" aircraft, the experiment structure had to be constructed to the specifications outlined by the RGSFO program. The experiment must be able to withstand the g-loading requirements found in Table 5.1.

Direction	Loading Requirement
Forward	9 g
Aft	3 g
Upward	2 g
Downward	6 g
Lateral	2 g

 Table 5.1: Experiment Loading Requirements

The structural design of the experiment was kept very simple. A base cart was constructed out of 2 inch by 1/8th inch thick aluminum angle welded into a rectangular frame. Aluminum plate 1/8th inch thick was then welded to the frame to form the top and bottom shelf and work area. While in Houston, significant concerns were discovered with the quality of the structural welds. Therefore, to add greater strength to the structure, triangular gussets were bolted to the corners of the base cart.

To contain the expelled propellant and prevent any leaks into the aircraft cabin, a containment box was developed. The upper frame of the box was constructed from 1 inch aluminum angle with 1 inch square tubing used as cross bracing. The bottom rim of the containment box was fabricated from 2 inch aluminum angle and fitted with 12 bolts to allow for the attachment of the containment box to the base cart. The sides and top of the containment box were enclosed using 3/8 inch thick Lexan bolted to the upper frame and sealed with silicone. With this configuration, the propulsion system is bolted directly to the base cart with the containment box fitting over the top of it. Testing Apparatus shows a diagram of the experimental set-up.

5.4.3. Experiment Electronics Design. Controlling the experiment and monitoring the various sensing devices required the development of a computer interface for the experiment. The interface between the control/monitoring equipment and the computer was handled by means of a Data Acquisition (DAQ) board. The DAQ board allowed the computer, using a custom designed LabVIEW program, to operate the two solenoid valves as well as the two resistive heaters within the system. Utilizing the same program and DAQ system, the computer is also able to monitor and record the data from both temperature and pressure sensors as well as the force transducer.

The power for the system is isolated from the aircraft by means of a Universal Power Supply (UPS). The isolation is necessary to prevent aircraft power fluctuations from interfering with the experiment or computer operations. The UPS battery will charge off aircraft power and in turn power the computer and experiment. Small power supplies housed in the same box as the DAQ board provide the various voltages necessary for experiment operation. A diagram of the testing platform can be found in Figure 5.1.

5.5. TEST DESCRIPTION

Accomplishing the testing goals set forth in Section 5.2 required a testing platform and experiment design capable of monitoring all aspects of system performance. Toward that end, a two-phase testing plan was developed that utilized a slightly modified propulsion system in both ground and microgravity environments.

The modifications to the propulsion system were implemented both to expand the information gathering capabilities of the experiment and simplify the overall testing procedures. In addition to the two thermal couples discussed above, other modifications include the removal of one isolation valve and the use of a single thruster as opposed to the full complement of eight. Also, a length of flexible tubing was inserted into system to prevent the stiffness of the metallic tubing from distorting the force data collection.

Figure 5.1: Testing Apparatus

The basic goal of the ground-based testing is to assess the thermodynamic properties of the system as well as provide a base-reading of system performance to compare to later testing data. For this test, a single thruster is fitted into an aluminum slide on the air bearing and in contact with the sensing lever of a force transducer. The system is pressurized with R-134a propellant to the level equivalent which would used on orbit for the satellite. The thruster will be fired in a variety of patterns to simulate situations which could occur on orbit. This testing will determine the validity of the theoretical analysis performed on the system as well as allow for the optimal running conditions and equipment settings for the system to be determined. Of particular interest is the recovery time necessary for the heater to overcome the temperature drop associated with the release of propellant. The target temperature for the heating system and the pattern of heater use can be varied to determine the best settings for use.

The flight testing is an extension of ground testing merely changing the apparent gravity on the system. The flight will be used to verify the functionality of the PMD device within the tank and thus complete the final goal of system level testing. The testing procedure utilized during flight will be exactly the same as on the ground to provide an equivalent comparison for performance. Flight data will be compared to ground data to determine whether or not a detrimental effect on system performance is present during the microgravity testing. Such a detrimental effect would indicate the failure of the internal PMD.

5.6. TEST RESULTS

Unfortunately, the test conducted in June of 2008 failed to produce results due to equipment failure. Prior to the microgravity flights, a design flaw within the DAQ box caused a continuous 24 volts of electricity to be delivered to both the isolation valve and the thruster valve. Consequently, both solenoids failed within the isolation valve and were damaged beyond repair. At the time, the specific flaw within the electronic system could not be ascertained; therefore, all electronics within the system were suspect and could not be used within the experiment.

Given the situation, the experiment was quickly reworked to test the functionality of the experiment platform itself; specifically the air bearing system. Testing on the aircraft confirmed that the air bearing system did not noticeably reduce friction along the slide. Therefore, it is unlikely that useful force data would have been obtained even without the electrical failure. Possible suggested causes for the inadequate performance of the air bearing include material galling and insufficient manufacturing methods. Galling is a form of surface damage that can occur when two like metals contact in a sliding manner. Such surface damage increases friction and can prevent smooth sliding. While both the slide and guide tubing were made of aluminum 6061, and thus susceptible to galling, the nitrogen expelled by the air bearing should have prevented material contact and thus surface damage. The more likely cause stems from the design and manufacture of the air bearing itself. For an air bearing to be effective, the gas flow along the length of the track must be constant and even over the entire length. Such was not the case with the MIS air bearing due to an uneven distribution of the holes and their diameter. The uneven gas flow prevented the slide from moving freely along the guide tubing and thus prevent accurate force data from being collected.

5.7. FUTURE TEST REQUIREMENTS

The testing platform developed for the RGSFOP experiment is the foundation on which future system level testing can be conducted. However, minor modifications must first be made to the design in order to improve functionality. Specifically, the problems with the air bearing system need to be addressed.

Air bearings are precision devices; dependant on a multitude of design details such as hole pattern, slide weight, gas pressure, hole size, etc. to garner the expected performance. While an in-house design is certainly still an option, given the complex nature of such a design and the difficulties inherent in manufacturing to the necessary tolerances, a better use of time and team resources might be to procure a commercial air bearing system. Alternatively, research into other methods of friction reduction, such as a magnetic track system, or methods of force measuring which do not rely on the thruster moving could be conducted in order to address the issue and implement a functional device.

With the minor modifications discussed above, the initial experiment can be run on future RGSFOP flights. Afterword, the experiment can be modified and the testing platform updated to control and monitor multiple thrusters in order to determine the change in system performance as multiple thrusters are fired. The effect of different propellant line configurations on thruster performance and different firing patterns can also be tested.

6. CONCLUSION

6.1. SUMMARY

As the M-SAT team transitions from the NS4 competition into NS6 and beyond, it is more important than ever to document not only the intricacies of design associated with the current system, but also the design and thought processes that directly and indirectly led to the final propulsion system. The research described in this thesis expands upon prior works while focusing on the design process used to develop the M-SAT propulsion system. The design process described flowed from the mission requirements and program restrictions down through component-level requirements and resulted in a system capable of performing the assigned duties. While future systems may face vastly different design and mission requirements, the example set forth by the NS4 system and the design process used can serve as a starting point for such endeavors.

The hazard analysis conducted for this paper also expanded on previous analyses to address key issues and AFRL concerns. The analysis showed the system to be safe for personnel and equipment as designed. Since the design may change and future systems will be developed, the methodology behind the analysis was also included to serve as a reference for future hazard analyses.

Finally, a propulsion test platform was developed to address the few remaining physical and theoretical performance questions remaining. While the platform has yet to produce the necessary results, minor modifications are being implemented to ensure that the testing platform is operational and producing results in the near future. The research conducted with this platform will focus on confirming the theoretical model for thruster performance. Additional testing will focus on the thermodynamic aspect of the system to determine how thruster firing affects the system properties and at what frequency the thrusters can be cycled while maintaining heater effectiveness. Testing can then be expanded to include multiple thrusters in order to determine the effect such situations have on overall system performance.

6.2. FUTURE WORK

While the propulsion design for the NS4 Satellite met the mission requirements, it was a first-generation design with much room for further improvement. Design compromises due to time and other constraints plus overall inexperience with satellite propulsion design has left several areas within the design where modifications could potentially improve performance.

The first major design change which could significantly improve mission performance involves attaining control along the final translational axis. As discussed previously, a design constraint on thruster placement within the satellite was the desire to minimize the complexity and cost of the design by minimizing the number of thrusters used. However, the additional control axis would allow the satellite to avoid the necessity of the ninety degree attitude rotation at the onset of formation flight and thus preserve propellant and extend the formation flight duration. Therefore, a new thruster configuration that offers control of all translational and rotational axes should be researched and implemented. A traditional 12 thruster pattern could be implemented assuming the configuration avoids interference with both the Lightband on bottom of MR SAT and the docking interface of MRS SAT on top and limits propellant contamination along the solar panels.

Another area of possible modification, particularly considering the likely changes in MR SAT structure and configuration due to NS6 requirements, is the running and division of propellant lines within the satellite. Currently, the main line is divided into the various sub-lines by means of standard fittings; however, it has been suggested that a manifold design could simplify the running of propellant lines and reduce the number of connection points within the system. This last point is particularly important given that leaks are a common cause of losses within cold gas propulsion systems. Integration could also be simplified as fittings would no longer need to be attached to the side panels for support and propellant lines could be routed directly to the thruster. A trade study should be conducted utilizing both theoretical and experimental loss data as well as integration considerations to determine the possible benefits associated with such a design change.

These modifications should improve propulsion system performance and allow the current system to be adapted into any NS6 satellite design.

APPENDIX

Hazard Numb	e i Prop-001			Final RAC	3	
Hazard Name	Propellant Tank Ruptu	ıre		Part Name	Tk	01
Pre-mitigation Class	ification					
Severity Classification	Catastrophic	Probability Classificatio	Remote		RAC	3
Hazard Analysis						
Causes	Propellant tank rupture such an occurrence is th	is caused by the ne propellant pre	e structur essure exc	ral failure of t ceeding the yi	he tank. The tank feld point of	e most like the tank m
Consequences	The rupture of the prop spontaneous and sudder a release could severely equipment) and cause ir	ellant tank would n release all prop damage nearby njury or death to	d be an ex ellant sto equipme personn	xtremely dang pred within the nt (including el.	gerous situat e propellant t satellite and	ion. It invo tank. The i launch veł
Probability	The probability of proper remote. This is mainly of the 100 psi equivalent p Pressure (1421 psi) for pressure (235 psi). At greater than 4 is still ac	ellant tank ruptu due to the limite point, a FOS grea the Marrotta ta the maximum o chieved.	re within d propella ater than nk and a perationa	the MR SAT ant mass whic 14 is achieve FOS greater al pressure be	propulsion s h is to be st d with regar than 2 exists ing consider	ystem is c ored withir d to the th s with rega ed (307 ps
Physical Mitigation	Physical mitigation is no risk down to acceptable	t necessary in th levels for flight	iis case a:	s the factors	of safety are	e sufficient
Procedural Mitigation	Maintaining the factors mass be added to the ta measuring equipment to implemented each time procedure will be signed ensure the procedure is appropriate authorities	of safety within nk. Filling proced ensure the corr the propellant ta l off by the perfor followed correc	the prop dures have ect prope ank is cha orming te tly. All d	ellant tank re e been develo ellant mass is arged with pro echnician and eviations and	quires that t ped that inco added. Thes opellant. Eac a quality ass problems wi	he specifie orporate ma se procedu ch step of t urance tec ill be repor
Prost-mitigation Cla	ssification					

Severity Classification	Probability Strophic Classificatio	Remote	RAC	3
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Hazard Numb	elProp-002			Final RAC	3	}
Hazard Name	Propellant Tank	Leak		Part Name	Tk	01
Pre-mitigation Class	ification					
Severity Classification	Critical	Probability Classificatio	Remote		RAC	3
Hazard Analysis						
Causes	A leak from the the yielding of the pressurized tank. and outlet end of	propellant tank could b te tank material in a m The second failure in the tank.	be caused anner that volves the	by two possi t allows prope inadequate t	ble failures. ellant to slow ightening of	The first f /ly be expe the fittings
Consequences	A leak of the pro completion of mi maneuvers. Add said materials. F exposed to R-13	pellant from the tank ssion objectives in jeo itionally, leaked prope inally, should the leak 4a which can cause s	during fligl pardy due llant could occur dur kin irritatio	nt would imm to lack of suf interact with ing testing of on, frost-bite	ediately put ficient prope n nearby mat r loading, ne , or asphyxia	the succes ellant to co erials to th arby perso ation in end
Probability	The first failure r (leak test perform within the syster procedures and c	node is considered unl ned using He and proof n. The second failure juality assurance polici	ikely due t tested to mode is co es are not	to the factory 16 bar) and c onsidered mo implemented	/ testing per due to the hig re likely to o l.	formed by gh factors c ccur if suff
Physical Mitigation	Physical mitigatic risk down to acc	n is not necessary in t eptable levels for fligh	his case a: t.	s the factors	of safety are	sufficient
Procedural Mitigation	Maintaining the f mass be added to measuring equipr implemented eac procedure will be ensure the proce appropriate auth	actors of safety within the tank. Filling proce nent to ensure the con h time the propellant signed off by the per dure is followed corre norities.	n the prop edures hav rect prope tank is cha forming te ctly. All d	ellant tank re e been develo ellant mass is arged with pro chnician and eviations and	quires that t pped that inco added. Thes opellant. Eac a quality ass problems w	the specific proprate manual se proceduin ch step of t urance tec ill be repor
Prost-mitigation Cla	ssification					

	Severity Classification	Critical	Probability Classificatio	Remote	RAC	3
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Hazard Number	prop-003				Final RAC	3	
Hazard Name	Special Elbow	/ Fitting M	laterial Yield		Part Name	ESM	L01
Pre-mitigation Classifi	ication						
Severity Classification	Critical		Probability Classificatio	Remote		RAC	3
Hazard Analysis							
Causes	For the materi would have to	al of the s greatly exc	pecial elbow f ceed the spec	fitting to ex cified ranges	perience yiel s for this miss	d, the pressu sion.	ire seen by
Consequences	Should the ma would put the occur to surro flying parts.	iterial of th successful unding equ	ne special elb completion o uipment and p	ow fitting y f mission ol personnel s	vield, at minir ojectives in do hould the rele	num the rest oubt. Additic ease of prope	ulting prope onally, dama ellant result
Probability	The Swagelok Therefore, the	fittings are chance fo	e rated to evo r material yie	en higher pi Id leading t	ressures than to leaks and p	the propella propellant los	nt tank.(‹ s is remote
Physical Mitigation	Physical mitiga risk down to a	tion is not cceptable	necessary in levels for flig	this case a ht.	s the factors	of safety are	e sufficient
Procedural Mitigation	Procedural mit within the sys of the procedu to ensure the appropriate an	igation cor tem and th Ire will be s procedure Ithorities.	mes in the fo nat all proced signed off by is followed co	rm of ensur ures (asser the perforr prrectly. Al	ing that the o mbly, filling, e ning technicia Il deviations a	correct prope etc.) are perf an and a qual nd problems	ellant mass formed corr ity assuran will be rep
Prost-mitigation Class	sification						

SeverityProbabilityClassificationCriticalClassificationRemoteRemoteRemote	Severity Classification	Critical	Probability Classificatio	RAC	3
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Hazard Numb	eprop-004		Final RAC	4
Hazard Name	Special Elbow Fitting L	_eak	Part Name	ESML01
Pre-mitigation Classi	fication			
Severity Classification	Marginal	Probability Classificatio Occasio	nal	RAC 4
Hazard Analysis				
Causes	The most obvious cause tightening at the connec	for a loss of propellant tion points of the fitting	stemming from th	e special elbow is tł
Consequences	Leaks both small and larg performance of system of nature of a rupture and increase risk of asphyxia	ge at this point of the s objectives. Leaks stemn as such are less likely to ation and propellant rea	ystem will have de ning from such a ca o cause damage. H actions with nearb	trimental effects on ause would not have łowever, leaking pro y materials.
Probability	When assembling a syste followed exactly and ste situations can occur.	em, human error has to ps are not taken to ensi	be taken into acco ure their correct in	unt. If procedures a applementation, haza
Physical Mitigation	Physical mitigation is no	ot possible for this haza	ard.	
Procedural Mitigation	The prevention of leaks tightening procedures ar step by step manner the assembly procedure will technician to ensure the reported to the appropr controlled manner to en-	stemming from improper re followed. Assembly p proper method of tighte be signed off by the per procedure is followed iate authorities. Additi sure any potential leak	er connections req rocedures have be ening each connecti erforming technicia correctly. All devi onally, the final as is addressed prior	uires that the manu en developed which ion point. Each step in and a quality assu ations and problems sembly will be press to launch.
Prost-mitigation Clas	ssification			
Soverity		Probability		

Classification Marginal Classificatio Remote RAC 4	RAC 4	Remote	Probability Classificatio	Marginal	Severity Classification
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Hazard Numb	eProp-005		Final RAC	4
Hazard Name	TML01 leak		Part Name	TML01
Pre-mitigation Class	ification			
Severity Classification	Marginal	Probability Classificatio Occas	ional	RAC 4
Hazard Analysis				
Causes	The most probable cause improper tightening at tubing connection also of the tubing needs to have	se for a loss of propella the connection points can have an effect on t e a smooth, flat end.	ant stemming fron of the fitting. Add he connection poir	n the first Swagelok Te ditionally, the manufac nt since for a proper sea
Consequences	A leak at this point in the transducer and thus ha reduces the chances of	ne system, even a sma mper the monitoring c mission success.	ll one, could alter f If propellant tank	the reading of the attain pressure. Also, any los
Probability	When assembling a syst followed exactly and sto situations can occur.	tem, human error has t eps are not taken to ei	o be taken into ac nsure their correct	count. If procedures a implementation, haza
Physical Mitigation	Ensuring the tubing con ends.	nected to the Tee fitti	ng is correctly ma	nufactured with flat an
Procedural Mitigation	The prevention of leaks tightening procedures a step by step manner the assembly procedure wil technician to ensure th reported to the approp controlled manner to en-	s stemming from impro- ine followed. Assembly e proper method of tigh I be signed off by the e procedure is followe riate authorities. Add insure any potential lea	pper connections r procedures have ntening each conne performing techni d correctly. All d itionally, the final k is addressed pri	requires that the manu been developed which ection point. Each step ician and a quality assu eviations and problems assembly will be press or to launch.
Severity	ssincation	Probability	<u>٦</u>	PAC
Classification	Marginal	Classificatio Remo	ote	KAC 4

Hazard NumberProp-006	Final RAC	3
Hazard Name TML01 Rupture	Part Name	TML01

Severity Classification	Critical	Probability Classificatio Remote	RAC	3
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Hazard Analysis

Causes	The material yields due to excessive stress caused by over-pressurization
Consequences	A leak at this point in the system, even a small one, could alter the reading of the atta transducer and thus hamper the monitoring of propellant tank pressure. Additionally could damage surrounding equipment such as the pressure transducer and lead to furt Finally, the loss of propellant would end the mission.

Probability	The Swagelok fittings are rated to even higher pressures than the propellant tank. (
	Therefore, the chance for material yield leading to leaks and propellant loss is remote

Physical Mitigation	Physical mitigation is not necessary in this case as the factors of safety are sufficient risk down to acceptable levels for flight.
Droodural	Depend well within the server is the form of encuring that the correct examplest more
Procedural	Procedural mitigation comes in the form of ensuring that the correct propeliant mass
Mitigation	within the system and that all procedures (assembly, filling, etc.) are performed cor
	of the procedure will be signed off by the performing technician and a quality assurant a second problems will be rep

Mitigation	within the system and that all procedures (assembly, filling, etc.) are performed co
	of the procedure will be signed off by the performing technician and a quality assura
	to ensure the procedure is followed correctly. All deviations and problems will be re
	appropriate authorities.

Prost-mitigation Classification

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Severity Classification Critical	Probability Classificatio	RAC 3
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Hazard NumberProp-007	Final RAC	4
Hazard Name CpML01 Leak	Part Name	CpML01
Pre-mitigation Classification		
Severity Classification Marginal Probability Classificatio Occ	casional	RAC 4
Hazard Analysis		
Causes As with all fittings the most likely cause of	a leak is an imprope	er connection.
Consequences Leaks both small and large at this point of the performance of system objectives. Addition asphyxiation and propellant reactions with	he system will have o onally, leaking prope nearby materials.	detrimental effects on llant could increase ris
Probability When assembling a system, human error has followed exactly and steps are not taken to situations can occur.	s to be taken into ac ensure their correct	count. If procedures a implementation, haza
Physical No physical mitigation is possible for this h Mitigation	nazard.	

Procedural Mitigation The prevention of leaks stemming from improper connections requires that the manu tightening procedures are followed. Assembly procedures have been developed which step by step manner the proper method of tightening each connection point. Each step assembly procedure will be signed off by the performing technician and a quality assu technician to ensure the procedure is followed correctly. All deviations and problems reported to the appropriate authorities. Additionally, the final assembly will be press controlled manner to ensure any potential leak is addressed prior to launch.

Classification Marginal Classificatio Occasional 4	Severity Classification	Marginal	Probability Classificatio	RAC	4
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Hazard NumbeProp-008	Final RAC	3
Hazard Name CpML01 Rupture	Part Name	CpML01

Severity	Critical	Probability	RAC	2
Classification	Critical	Classificatio Remote	1010	3

Hazard Analysis

Causes	The material yields due to excessive stress caused by over-pressurization
Consequences	A leak at this point in the system even a small one, could alter the reading of the atta-
Consequences	transducer and thus hamper the monitoring of propellant tank pressure. Additionally
	could damage surrounding equipment such as the pressure transducer and lead to furt

Probability	The Swagelok fittings are rated to even higher pressures than the propellant tank. (
	Therefore, the chance for material yield leading to leaks and propellant loss is remote

Physical Mitigation	Physical mitigation is not necessary in this case as the factors of safety are sufficient risk down to acceptable levels for flight.
Procedural	Procedural mitigation comes in the form of ensuring that the correct propellant mass
Mitigation	within the system and that all procedures (assembly, filling, etc.) are performed con
	of the procedure will be signed off by the performing technician and a quality assuran to ensure the procedure is followed correctly. All deviations and problems will be rep

Procedural	Procedural mitigation comes in the form of ensuring that the correct propellant ma
Mitigation	within the system and that all procedures (assembly, filling, etc.) are performed co
	of the procedure will be signed off by the performing technician and a quality assure
	to ensure the procedure is followed correctly. All deviations and problems will be re-
	appropriate authorities.

Severity Classification Critical	Probability Classificatio Remote	RAC 3
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Hazard Numb	Prop-009				Final RAC	4	ŀ
Hazard Name	CpML01 Ben	ding/Crimping]		Part Name	СрМ	IL01
Pre-mitigation Classi	fication						
Severity Classification	Marginal	Pr Cla	robability assificatio	Frequent		RAC	2
Hazard Analysis							
Causes	The two secti be bent if exc	ons of the cou essive stress is	pling are co s placed up	nnected b on it durin	y a very narr g assembly (ow (1/16" C (tightening o	D) tubing (f fittings)
Consequences	A bending of t transducer fro monitored wh	he tubing could m the system. ch could increa	d cause the . Without t ase the sub	tubing to o he pressur sequent ris	crimp which w e transducer sk of hazards	would cut off reading tank 3.	the attach conditions
Probability	The delicate n much stress is crimp.	ature of the co applied to the	onnecting tu e tubing du	bing mean ring the as	s that it is ve sembly proce	ery susceptib ess the tubin	le to being Ig will bend
Physical Mitigation	Should a bend part.	occur during t	he assembl	y process a	a new part w	ill be substitu	ited for the
Procedural	The assembly	procedures for	this conne	ction are d	esigned to m	ninimize the f	orce placed
mitidation	procedure will ensure the pro appropriate a	be signed off becedure is follo uthorities.	by the perf	orming teo stly. All de	process wit chnician and eviations and	a quality ass problems wi	urance tecl
Prost-mitigation Clas	sification						

Severity Classification Marginal Probability Classificatio Occasional RAC	Severity Classification	Marginal	Probability Classificatio Occasional	RAC	4
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Hazard NumberProp-010	Final RAC	4
Hazard Name PtML01 electrical failure	Part Name	PtML01
Pre-mitigation Classification		
SeverityProbabilityClassificationMarginalClassificationRemote		RAC 4
Hazard Analysis		
Causes The pressure transducers require specific voltage The electrical conditioning could be altered by f wires.	les and power laws in the cir	levels to maintain prop cuitry or problems with
Consequences Should the electronics of the first pressure tran unmonitored for the duration of the mission. Th go unnoticed and have detrimental effects on the	sducer fail, th is could allow a mission.	e tank pressure would a potentially hazardous
Probability The possibility of an electrical failure cannot be detected during testing in a safe manner. There dangerous situation is considered remote.	entirely discou efore, the prob	nted; however, such de pability of electrical failu
Physical <u>Mitigation</u> The boards will be designed in such a way that t they need to accurately record the tank pressure	he pressure tra	ansducers receive the p
Procedural Mitigation In order to prevent a possible hazard, the electron thoroughly tested prior to charging the tank. An and reported to the proper authorities.	onics connecte ny and all defe	ed to the pressure trans cts or discrepancies will
Prost-mitigation Classification		

Severity Classification Marginal Pro	ssificatio Remote RAC	4
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Hazard Name PtML01 Burst Part Name PtML01 Pre-mitigation Classification Severity Marginal Probability ? ? RAC ? ? Hazard Analysis Causes For the pressure transducer to burst, the material (stainless steel) of the outer casin yield. Over pressurization could trigger material yield. Consequences A rupture of the first pressure transducer would release most of the stored propellan nuin any chance of mission success. Also, such a release of energy could cause damage equipment and injuries to nearby personnel. Probability The pressure transducers (both first and second) used for the MR SAT propulsion syst type rated to pressures up to 10000 psig. However, due to the restrictions on tark pressures and present a hazardous situation. Therefore, the current probability randucers and present a hazardous situation. Therefore, the current probability randucers and present a hazardous situation. Therefore, the current probability randucers and present a hazardous situation. Therefore, the Current probability randucers and present a hazardous situation. Therefore, the Current probability randucers and present a hazardous situation. Therefore, the current probability randucers and presest respected to pressure situation. Physical If tank pressure greater than 100 psi are to be used for the MR SAT propulsion syste pressure. Mitigation Currently, the system is only safe at the 100 psi level. Therefore, proper filling pro adhered to in order to ensure the safety of surrounding personnel and equipment. Su procedures have been developed and will be implemented in a step by step manner. Ea the proce	Hazard Numb	Prop-011	Final RAC	4 (for 100 psi)
Pre-mitigation Classification Marginal Probability Classification ? ? RAC ? ? Hazard Analysis Causes For the pressure transducer to burst, the material (stainless steel) of the outer casin yield. Over pressurization could trigger material yield. Consequences A rupture of the first pressure transducer would release most of the stored propellan ruin any chance of mission success. Also, such a release of energy could cause damage equipment and injuries to nearby personnel. Probability The pressure transducers (both first and second) used for the MR SAT propulsion syst type rated to pressures up to 10000 psig. However, due to the restrictions on tank p transducers were calibrated for a maximum pressure of 200 psi to give better precis instrument. It is unknown at this time if pressures greater than 200 psi would destr for pressures greater than 200 psi. For the 100 psi operating pressure the FOS of 2 possibility of burst remote. Physical If tank pressure greater than 100 psi are to be used for the MR SAT propulsion syste pressure transducer may need to be procured to monitor tank pressure. Procedural Currently, the system is only safe at the 100 psi level. Therefore, proper filling pro adhered to in order to ensure the safety of surrounding personnel and equipment. Su procedures have been developed and will be implemented in a step by step manner. Ea the procedures will be signed off by the performing technician and a quality assuranc Any deviations will be reported to the appropriate authorities.	Hazard Name	PtML01 Burst	Part Name	PtML01
Severity Classification Marginal Probability Classification RAC ? ? Hazard Analysis Causes For the pressure transducer to burst, the material (stainless steel) of the outer casin yield. Over pressurization could trigger material yield. Consequences A rupture of the first pressure transducer would release most of the stored propellan ruin any chance of mission success. Also, such a release of energy could cause damage equipment and injuries to nearby personnel. Probability The pressure transducers (both first and second) used for the MR SAT propulsion syst type rated to pressures up to 10000 psig. However, due to the restrictions on tank p transducers were calibrated for a maximum pressure of 200 psi to give better precis instrument. It is unknown at this time if pressures greater than 200 psi op givould destr transducers and present a hazardous situation. Therefore, the current probability r for pressures greater than 200 psi. For the 100 psi operating pressure the FOS of 2 possibility of burst remote. Physical Mitigation If tank pressure greater than 100 psi are to be used for the MR SAT propulsion syste pressure transducer may need to be procured to monitor tank pressure. Procedural Mitigation Currently, the system is only safe at the 100 psi level. Therefore, proper filling pro adhered to in order to ensure the safety of surrounding personnel and equipment. Su procedures have been developed and will be implemented in a step by step manner. Ea the procedures will be signed off by the performing technician and a quality assuranc Any deviations will be reported to the appropriate authorities. <td>Pre-mitigation Classi</td> <td>fication</td> <td></td> <td></td>	Pre-mitigation Classi	fication		
Hazard Analysis Causes For the pressure transducer to burst, the material (stainless steel) of the outer casin yield. Over pressurization could trigger material yield. Consequences A rupture of the first pressure transducer would release most of the stored propellan nuin any chance of mission success. Also, such a release of energy could cause damage equipment and injuries to nearby personnel. Probability The pressure transducers (both first and second) used for the MR SAT propulsion syst type rated to pressures up to 10000 psig. However, due to the restrictions on tank p transducers were calibrated for a maximum pressure of 200 psi to give better precisi instrument. It is unknown at this time if pressures greater than 200 psi would destruct transducers and present a hazardous situation. Therefore, the current probability ra for pressures greater than 200 psi. For the 100 psi operating pressure the FOS of 2 possibility of burst remote. Physical If tank pressure greater than 100 psi are to be used for the MR SAT propulsion syster metsure transducer may need to be procured to monitor tank pressure. Procedural Currently, the system is only safe at the 100 psi level. Therefore, proper filling produced may need to be procured to monitor tank pressure. Ea the procedures will be signed off by the performing technician and a quality assuranc Any deviations will be reported to the appropriate authorities. Prost-mitigation Currently. The system is only safe at the 100 psi level. Therefore, proper filling productions will be signed off by the performing technician and a quality assuranc Any deviations will be reported to the appropriate authorities.	Severity Classification	Probability Marginal Classificatio ??		RAC ??
Causes For the pressure transducer to burst, the material (stainless steel) of the outer casin yield. Over pressurization could trigger material yield. Consequences A rupture of the first pressure transducer would release most of the stored propellan ruin any chance of mission success. Also, such a release of energy could cause damage equipment and injuries to nearby personnel. Probability The pressure transducers (both first and second) used for the MR SAT propulsion syst type rated to pressures up to 10000 psig. However, due to the restrictions on tank p transducers were calibrated for a maximum pressure of 200 psi to give better precisi instrument. It is unknown at this time if pressures greater than 200 psi would destr transducers and present a hazardous situation. Therefore, the current probability ra for pressures greater than 200 psi. For the 100 psi operating pressure the FOS of 2 possibility of burst remote. Physical If tank pressure greater than 100 psi are to be used for the MR SAT propulsion syste pressure transducer may need to be procured to monitor tank pressure. Procedural Currently, the system is only safe at the 100 psi level. Therefore, proper filling provadhered to in order to ensure the safety of surrounding personnel and equipment. Su procedures have been developed and will be implemented in a step by step manner. Ea the procedures will be signed off by the performing technician and a quality assuranc Any deviations will be reported to the appropriate authorities. Prost-mitigation Cassification	Hazard Analysis			
Consequences A rupture of the first pressure transducer would release most of the stored propellan ruin any chance of mission success. Also, such a release of energy could cause damage equipment and injuries to nearby personnel. Probability The pressure transducers (both first and second) used for the MR SAT propulsion syst type rated to pressures up to 10000 psig. However, due to the restrictions on tank p transducers were calibrated for a maximum pressure of 200 psi to give better precise instrument. It is unknown at this time if pressures greater than 200 psi would destruct transducers and present a hazardous situation. Therefore, the current probability ra for pressures greater than 200 psi. For the 100 psi operating pressure the FOS of 2 possibility of burst remote. Physical If tank pressure greater than 100 psi are to be used for the MR SAT propulsion syster metsure transducer may need to be procured to monitor tank pressure. Procedural Currently, the system is only safe at the 100 psi level. Therefore, proper filling proved adhered to in order to ensure the safety of surrounding personnel and equipment. Su procedures will be signed off by the performing technician and a quality assuranc Any deviations will be reported to the appropriate authorities. Prost-mitigation Classification	Causes	For the pressure transducer to burst, the mater yield. Over pressurization could trigger mater	ial (stainless stee ial yield.	el) of the outer casin
Probability The pressure transducers (both first and second) used for the MR SAT propulsion syst type rated to pressures up to 10000 psig. However, due to the restrictions on tank p transducers were calibrated for a maximum pressure of 200 psi to give better precis instrument. It is unknown at this time if pressures greater than 200 psi would destruct transducers and present a hazardous situation. Therefore, the current probability ra for pressures greater than 200 psi. For the 100 psi operating pressure the FOS of 2 possibility of burst remote. Physical If tank pressure greater than 100 psi are to be used for the MR SAT propulsion system pressure transducer may need to be procured to monitor tank pressure. Procedural Currently, the system is only safe at the 100 psi level. Therefore, proper filling provadhered to in order to ensure the safety of surrounding personnel and equipment. Su procedures have been developed and will be implemented in a step by step manner. Ea the procedures will be signed off by the performing technician and a quality assurance Any deviations will be reported to the appropriate authorities. Prost-mitigation Classification	Consequences	A rupture of the first pressure transducer would ruin any chance of mission success. Also, such a equipment and injuries to nearby personnel.	I release most of release of energ	the stored propellan y could cause damage
Physical Mitigation If tank pressure greater than 100 psi are to be used for the MR SAT propulsion system pressure transducer may need to be procured to monitor tank pressure. Procedural Mitigation Currently, the system is only safe at the 100 psi level. Therefore, proper filling pro- adhered to in order to ensure the safety of surrounding personnel and equipment. Su procedures have been developed and will be implemented in a step by step manner. Ea the procedures will be signed off by the performing technician and a quality assurance Any deviations will be reported to the appropriate authorities. Prost-mitigation Classification	Probability	The pressure transducers (both first and second type rated to pressures up to 10000 psig. How transducers were calibrated for a maximum pre instrument. It is unknown at this time if pressu transducers and present a hazardous situation. for pressures greater than 200 psi. For the 100 possibility of burst remote.	d) used for the M rever, due to the ssure of 200 psi ures greater than Therefore, the 0 psi operating p	R SAT propulsion syst restrictions on tank p to give better precis 200 psi would destri current probability ra ressure the FOS of 2
Procedural Mitiaation	Physical Mitigation	If tank pressure greater than 100 psi are to be pressure transducer may need to be procured to	used for the MR S o monitor tank pr	SAT propulsion system ressure.
Prost-mitigation Classification	Procedural Mitigation	Currently, the system is only safe at the 100 p adhered to in order to ensure the safety of surr procedures have been developed and will be impl the procedures will be signed off by the perform Any deviations will be reported to the appropria	osi level. Therefo ounding personne emented in a step ning technician a ate authorities.	ore, proper filling prod el and equipment. Su o by step manner. Ea nd a quality assurance
	Prost-mitigation Clas	ssification		

Severity	Probability	RAC (1	4
Classification Margina	Classificatio		00 ps

Hazard NumberProp-012	Final RAC 4
Hazard Name VML01 stuck closed	Part Name VML01
Pre-mitigation Classification	
Severity Classification Negligible Classificatio	Probable RAC 3
Hazard Analysis	
Causes The most likely cause for an isolation of problem preventing the opening of the 24 volt pulse required for opening, or	/alve being locked in the closed position is an e valve. This could be the electrical board never physical damage to the internal solenoid of the
Consequences With the first isolation valve stuck in there is not a potential risk of injury o	the closed position, formation flight is unachiev r further equipment damage associated with th
Probability The design of the electrical boards whi the propulsion subsystem. However, a system. Due to the dependence on as currently rated as probable.	ch control the isolation valves are not under the working design is necessary for the proper fur yet untested electronics the probability of proble
Physical Mitigation Change out non working valves.	
Procedural Mitigation Thorough testing of all electronics for functional testing of the board electror valves integrated into a 'flat sat' confi recorded and reported to the proper a process will be addressed and then ret	proper operation is necessary. Such testing w ics and end with system level testing of the elec- guration. Any deviations from nominal operation uthorities. Electrical problems documented in the ested until nominal operation is achieved.
Prost-mitigation Classification	

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard NumberProp-013	Final RAC 4
Hazard Name VML01 Locked Open	Part Name VML01
Pre-mitigation Classification	
Severity Classification Negligible Probability Classificatio Remote	RAC 4
Hazard Analysis	
Causes The Lee Valve designed is a 'fail safe' design in th continually supplied to the solenoid. Therefore, r position is a defective part.	nat the valve is designed to close if pov most likely cause of a valve stuck in t
Consequences With the valve stuck in the open position, the tar along with one of the three system inhibits. This the first isolation valve is to remain open throug however, the lack of isolation of the tank prior to probability of propellant loss due to connection le	nk's isolation from the rest of the sys s is not directly detrimental to missio hout the period of formation flight ar o the start of formation flight increas eakage (as the propellant is exposed t
Probability Due to the fail safe nature of the design, it is cor will be stuck in the open position.	nsidered a remote possibility that the
Physical All defective valves discovered in the testing pro Mitigation	ocess will be replaced.
Procedural Mitigation Thorough testing of all valves will be conducted. recorded and reported to the proper authorities be replace.	Any deviations from nominal operat All valves failing to achieve nomina

Severity Probability Remote RAC Classification Negligible Classification Remote RAC	RAC 4	atio Remote RAC	Probability Classificatio	Negligible	Severity Classification
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Hazard NumberProp-014	Final RAC	4
Hazard Name VML01 Clogged	Part Name	VML01

Severity Classificatior	Negligible	Probability Classificatio Frequent	RAC	3
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Hazard Analysis	
Causes	The inner mechanisms of the isolation valves are extremely narrow and easily clogged material present within the propellant lines. (Left over material from the constructi as metallic shavings)
Consequences	Foreign material lodged within the valve can interfere with the workings of the intern lock the valve in either the open or closed position.
Probability	Since all parts of the propulsion system are machined, the possibility of foreign debr the propellant lines can not be discounted. Without mitigation a clog of the valve is lik frequent occurrence.
Physical Mitigation	Fine mesh filters added before each valve within the system will capture any debris b interfere with the internal workings of the valve.

Pr	rocedural	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys
М	itigation	should limit the remaining debris.

Severity Classification Negligible	Probability Classificatio Remote	RAC 4
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Hazard NumbeProp-015	Final RAC	3
Hazard Name VML01 Burst	Part Name	VML01

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3
Hazard Analysis					
Causes	For the isolation valve yield pressure. Additio rupture.	to burst, it would nally, over heating	I have to experience a g of the valve could ca	a propellant p ause the oute	ressure gre r casing of
Consequences	A rupture of the first is any chance of mission s equipment and injuries	solation valve wo success. Also, suc to nearby perso	uld release most of th h a release of energy o nnel.	e stored prop could cause da	bellant and amage to no
Probability	Valve rupture due to o associated with the val greater than 11. For t over heating is also cor the mission. The valve function properly at ter	ver pressurization ve. The valve is he 307 psi settin isidered a remote is rated to 70 C a mperatures great	n is a remote possibilit rated to 1125 psi; the g, the FOS is still a re- possibility based upor and has been observed er than 100 C.	y due to the refore, at the spectable 3.6 n the expecte I during funct	high factor e 100 psi se i6. Valve r d temperat ional testir
Physical Mitigation	Physical mitigation is norisk down to acceptabl	ot necessary in th e levels for flight	nis case as the factors	of safety are	e sufficient
Procedural Mitigation	Procedural mitigation of within the system and of the procedure will be to ensure the procedur appropriate authoritie	comes in the form that all procedur e signed off by th re is followed corn s.	n of ensuring that the res (assembly, filling, on ne performing technici rectly. All deviations a	correct prope etc.) are perf an and a qual and problems	ellant mass ormed cori ity assuran will be rep
Prost-mitigation Clas	sification				

Severity Classification Critical Probability Classificatio Remote RAC 3

Hazard NumberProp-016	Final RAC	4
Hazard Name VML01 leak	Part Name	VML01

Classification Marginal Classificatio	Occasional RAC	4

Hazard Analysis	

Causes	The most likely cause of a noticeable leak stemming from the first isolation valve is i tightening of the Swagelok connections.
Consequences	A leak from the first isolation valve would cause a serious loss of propellant and could detrimental to mission goals.
Probability	When assembling a system, human error has to be taken into account. If procedures a followed exactly and steps are not taken to ensure their correct implementation, haza situations can occur.

Physical	No physical mitigation is possible for this hazard.
Mitigation	

Procedural	The prevention of leaks stemming from improper connections requires that the manu
Mitigation	tightening procedures are followed. Assembly procedures have been developed which
	step by step manner the proper method of tightening each connection point. Each step
	assembly procedure will be signed off by the performing technician and a quality assu
	technician to ensure the procedure is followed correctly. All deviations and problem
	reported to the appropriate authorities. Additionally, the final assembly will be press
	controlled manner to ensure any potential leak is addressed prior to launch.

Prost-mitigation Classification

Severity Classification Marginal	Probability Classificatio	RAC 4
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Hazard Numb	elProp-017		Final RAC	4
Hazard Name	Voltage step-down ma	alfunction	Part Name	VML01
Pre-mitigation Class	ification			
Severity Classification	Marginal	Probability Classificatio Prob	able	RAC 3
Hazard Analysis				
Causes	The voltage step-down is cause of the failure of vo electronics board either	s accomplished by the oltage step-down for due to component m	e propulsion electro the isolation valve v alfunction or improj	nics board. The most would be the failure of per design.
Consequences	The Lee valves used for then stepped down to 5 within the time specified heat and possibly ruptur	the MR SAT propulsion volts to maintain the c , the excess voltage c re.	n system rely on a 2 open state. If the st ould destroy the so	24 V pulse to open. T ep-down process does lenoid and cause the v
Probability	The design of the electri the propulsion subsyster system. Due to the depe currently rated as proba	ical boards which cont m. However, a workir endence on as yet unt able.	trol the isolation va ng design is necess ested electronics th	lves are not under the ary for the proper fur ne probability of proble
Physical Mitigation	A properly designed elec remote.	ctronics board control	ling the system cou	uld reduce the probab
Procedural Mitigation	Thorough testing of all of functional testing of the valves integrated into a recorded and reported to process will be addresse	electronics for proper board electronics and 'flat sat' configuratio o the proper authoriti d and then retested u	r operation is neces I end with system le on. Any deviations es. Electrical proble until nominal operat	essary. Such testing w evel testing of the elect from nominal operation ems documented in the ion is achieved.
Prost-mitigation Cla	ssification			
Severity Classification	Marginal	Probability Classificatio	ote	RAC 4

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Hazard NumberProp-018	Final RAC	3
Hazard Name RML01 burst	Part Name	RML01

Severity Classification	Critical	Probability Classificatio		RAC	3
Hazard Analysis					
Causes	The rupture of the pre which results in mate	ssure regulator would be orial yield.	caused by an o	over pressuri:	zation of th
Consequences	Should the material of put the successful com surrounding equipmen parts.	the pressure regulator y hpletion of mission objection t and personnel should th	ield, at minimi ves in doubt. 7 ne release of p	um the resul Additionally, o propellant res	ting propel damage cou sult in shraț
Probability	The inlet portion of th mark a FOS of 10 exist of 3.25 is maintained.	e pressure regulator is rat ts. At the maximum press Therefore, material yield	ted to 1000 p sure being con d is considered	si. Therefore sidered for t d a remote p	e at the 10 he system possibility.
Physical Mitigation	Physical mitigation is n risk down to acceptab	ot necessary in this case le levels for flight.	as the factors	of safety are	e sufficient
Procedural Mitigation	Procedural mitigation of within the system and of the procedure will b to ensure the procedu appropriate authoritie	comes in the form of ensu that all procedures (asse signed off by the perfor re is followed correctly. A ss.	uring that the embly, filling, e ming technicia All deviations a	correct prop etc.) are perf an and a qual and problems	ellant mass formed cori lity assuran s will be rep

Severity	Critical	Probability Classificatio	RAC	3
Classification	Citical	Classificatio		

Hazard Name	RML01 leak	Part Name	RML01
Pre-mitigation Classi	fication		
Severity Classification	Marginal Probability Classificatio	Occasional	RAC 4
Hazard Analysis			
Causes	The most likely cause of a noticeable lea tightening of the Swagelok connections.	ak stemming from the	pressure regulator is ir
Consequences	Assuming the first isolation valve remain flight, a small leak at this point of the sy flight, but could drastically reduce the d would prevent formation flight being ma	ns closed (and holds se stem would not prever uration which formatic intained for any mean	eal) until the beginning It the implementation o In flight can be held. <i>A</i> Ingful duration.
Probability	When assembling a system, human error followed exactly and steps are not taken situations can occur.	has to be taken into a to ensure their correc	ccount. If procedures a t implementation, hazai
Physical Mitigation	No physical mitigation is possible for th	is hazard.	
Procedural Mitigation	The prevention of leaks stemming from tightening procedures are followed. Asses step by step manner the proper method of assembly procedure will be signed off by technician to ensure the procedure is for reported to the appropriate authorities.	improper connections embly procedures have of tightening each connect the performing techn llowed correctly. All c Additionally, the final	requires that the manu been developed which ection point. Each step ician and a quality assu leviations and problems I assembly will be press

Hazard NumberProp-019

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote		RAC	4
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controlled manner to ensure any potential leak is addressed prior to launch.

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Final RAC

Hazard Numb	eProp-020		Final RAC	4
Hazard Name	RML01 Failure to Reg	ulate Pressure	Part Name	RML01
Pre-mitigation Classi	fication			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4
Hazard Analysis				
Causes	The pressure regulator i to reduce outlet pressu	is preset at the factory t re, the internal mechanisi	o a specific out m of the regula	let pressure. For the tor would have to fail.
Consequences	With out the benefit of pressure remaining in the components are rated to have a detrimental effect continually be changing	pressure regulation, the re he tank. The exposure w o withstand the full syste of on system performance as the tank pressure is re	emainder of the vould not likely m pressure. Ho as the thrust p educed.	system would be expo result in problems as owever, the loss of reg roduced by the nozzle
Probability	The possibility of a facto	ory defect is considered r	emote.	
Physical Mitigation	No physical mitigation i	s possible in this case.		
Procedural Mitigation	Thorough testing of the operation will be record	e pressure regulator will b ed and reported to the p	e conducted. A roper authoritie	ny deviations from no
Prost-mitigation Clas	ssification			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4

Hazard Numb	Prop-021				Final RAC	4	ŀ
Hazard Name	TML02 leak				Part Name	TM	L02
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	al	RAC	4
Hazard Analysis							
Causes	The most prol the improper tubing connec the tubing nee	bable cause tightening tion also c eds to have	e for a loss of p at the connecti an have an effec a smooth, flat e	ropellant s on points ct on the c end.	temming fron of the fitting onnection poi	n the second . Additionall <u>i</u> int since for a	Swagelok y, the manu a proper sea
Consequences	With the tee propellant los However, any pressure loss and affect the	placed afte s before the loss of pro- associated e monitorin	er the first isola he beginning of opellant reduces I with the leak w Ig of the regulat	tion valve formation the possi yould disru ed pressur	, a leak stem flight (assur ble duration o pt the readin re.	ming from it ning the valv of the forma gs of the see	: will not ca /e seal is m tion flight p cond pressi
Probability	When assemb followed exac situations can	ling a syst tly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	iccount. If p t implement	rocedures a ation, haza
Physical Mitigation	No physical m	nitigation i	s possible for t	his hazard			
Procedural Mitigation	The preventic tightening pro step by step r assembly prod technician to reported to th controlled ma	on of leaks ocedures an manner the cedure will ensure the he appropri nner to en	stemming from re followed. Ass proper method be signed off b e procedure is f riate authorities asure any poten	i improper sembly pro of tighten by the perf ollowed co . Additior tial leak is	connections ocedures have ing each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha e been develo ection point. nician and a o deviations ar I assembly v rior to launch	t the manu oped which Each step quality assund problems vill be press
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-022		Final RA	AC 3	}
Hazard Name	TML02 Rupture		Part Nar	ne TM	L02
Pre-mitigation Classi	fication				
Severity Classification	Critical	Probability Classificatio	emote	RAC	3
Hazard Analysis					
Causes	The material yields due	e to excessive stres	s caused by over	-pressurization	
Consequences	A rupture could damag hazards. Additionally, ⁻	e surrounding equipi the loss of propellan	ment such as the It would end the	pressure trans mission.	ducer and l
Probability	The fitting in question experience at most 24 the regulator should fa propellant tank. (~400 propellant loss is remo	is after the pressure .7 psi of pressure w il, the Swagelok fitti 00 psig) Therefore, te.	e regulation devic /hich is well with ngs are rated to the chance for n	ce within the sy in the capabiliti even higher pre naterial yield lea	vstem. The es of the fi essures tha ading to lea
Physical Mitigation	Physical mitigation is no risk down to acceptabl	ot necessary in this e levels for flight.	case as the facto	ors of safety are	e sufficient
Procedural	Procedural mitigation c	omes in the form of	f ensuring that th	ne correct prop	ellant mass
Mitigation	within the system and of the procedure will be to ensure the procedur appropriate authoritie:	that all procedures e signed off by the p re is followed correc s.	(assembly, filling performing techn tly. All deviation	g, etc.) are peri ician and a qua is and problems	formed cori lity assuran s will be rep
Prost-mitigation Clas	sification				
Severity		Probability		DAC	

Hazard Numb	Prop-023				Final RAC	4	-
Hazard Name	CpML02 Lea	k			Part Name	СрМ	IL02
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona		RAC	4
Hazard Analysis							
Causes	The most like could be caus	ly cause of se by eithe	f a leak regardir er improper tigh	ng a Swage tening or i	elok fitting is mproper tub	an improper ing construc	connectior tion.
Consequences	Given that the leak at this pc a leak would I would reduce	e fitting in bint of the imit the ak the time a	question is aft system would n bility of the sec available for for	er the first ot occur u ond pressu mation flig	t isolation va ntil formation Ire transduce Jht.	lve, propellan n flight had be er to monitor	nt loss ster een engage regulated
Probability	When assemb followed exac situations can	ling a syst tly and ste i occur.	em, human erro eps are not take	r has to be n to ensur	e taken into a e their correc	account. If p ct implement	rocedures a ation, haza
Dhusiaal	No. who wind w			h:- h			
Physical Mitigation	No physical m	nitigation i	s possible for t	his hazard			
Procedural Mitigation	The preventic tightening pro step by step r assembly prod technician to reported to th controlled ma	on of leaks ocedures an nanner the cedure will ensure the he appropr nner to en	stemming from re followed. As proper method be signed off the procedure is f riate authorities isure any poten	n improper sembly pro of tighteni by the perf followed co s. Additior tial leak is	connections ocedures have ng each conn forming tech prrectly. All nally, the fina addressed p	requires that been develor nection point. nician and a or deviations ar al assembly v rior to launch	t the manu oped which Each step quality assu d problems vill be press
Prost-mitigation Clas	ssification						
Severity	Marginal		Probability Classificatio	Remote		RAC	4

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Hazard Numb	elProp-024		Final RAC	3				
Hazard Name	CpML02 Rupture		Part Name	СрМ	L02			
Pre-mitigation Class	ification							
Severity Classification	P Critical Cla	robability assificatio Remote	[[RAC	3			
Hazard Analysis								
Causes	The material yields due to e	excessive stress caus	ed by over-pre	essurization				
Consequences	A rupture could damage sur hazards. Additionally, the lo	rounding equipment s oss of propellant woul	uch as the pre d end the miss	essure transo sion.	ducer and li			
Probability	The fitting in question is aft experience at most 24.7 ps the regulator should fail, the propellant tank. (~4000 ps propellant loss is remote.	er the pressure regul i of pressure which is e Swagelok fittings ar ig) Therefore, the ch	ation device w s well within th e rated to eve ance for mate	vithin the sy ne capabilitio n higher pre rial yield lea	stem. The es of the fi ssures tha iding to lea			
Physical Mitigation	Physical mitigation is not ne risk down to acceptable lev	cessary in this case a els for flight.	s the factors o	of safety are	sufficient			
Procedural Mitigation	Procedural mitigation comes within the system and that of the procedure will be sigr to ensure the procedure is f appropriate authorities.	s in the form of ensur all procedures (asser ned off by the perforr followed correctly. Al	ing that the c nbly, filling, et ning technicia Il deviations ar	orrect prope cc.) are perf n and a quali nd problems	ellant mass ormed cori ity assuran will be rep			
Prost-mitigation Classification								
Severity	Р	robability	ſ	DAG				

Severity
ClassificationProbability
ClassificatioRAC3

Hazard Numb	eProp-025		Final RAC	4				
Hazard Name	CpML02 Bending/Crim	nping	Part Name	CpML02				
Pre-mitigation Classification								
Severity Classification	Marginal	Probability Classificatio Frequen	it	RAC 2				
Hazard Analysis								
Causes	The two sections of the be bent if excessive stro	coupling are connected ess is placed upon it duri	by a very narrov ing assembly (ti	w (1/16" OD) tubing v ightening of fittings)				
Consequences	A bending of the tubing transducer from the sys monitored which could in	could cause the tubing to tem. Without the pressunce ncrease the subsequent i	o crimp which wo ure transducer re risk of hazards.	ould cut off the attach eading tank conditions				
Probability	The delicate nature of th much stress is applied t crimp.	ne connecting tubing mea o the tubing during the a	ans that it is very assembly proces	y susceptible to being is the tubing will bend				
Physical Mitigation	Should a bend occur dur part.	ing the assembly process	s a new part will	be substituted for the				
Procedural Mitigation	The assembly procedure tubing by isolating the t procedure will be signed ensure the procedure is appropriate authorities.	s for this connection are ubing during the tightenin l off by the performing to followed correctly. All o	designed to mir ng process with echnician and a deviations and p	nimize the force placed the aid of a vice. Eacl quality assurance tech problems will be report				
Prost-mitigation Classification								
Coverity		Drobobility	— г					
Hazard Numb	elProp-026		Final RAC	4				
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Hazard Name	PtML02 electrical failu	lre	Part Name	PtML02				
Pre-mitigation Class	ification							
Severity Classification	Marginal	Probability Classificatio Remo	te	RAC 4				
Hazard Analysis								
Causes	The pressure transduce The electrical condition wires.	ers require specific volt ing could be altered by	ages and power / flaws in the circ	levels to maintain prop cuitry or problems with				
Consequences	Should the electronics of unmonitored for the du go unnoticed and have of	of the second pressure ration of the mission. ⁻ detrimental effects on tl	transducer fail, t This could allow a he mission.	the regulated pressure potentially hazardous				
Probability	The possibility of an ele detected during testing dangerous situation is c	ectrical failure cannot b i in a safe manner. The onsidered remote.	e entirely discour erefore, the prob	nted; however, such de ability of electrical failı				
Physical	The boards will be desig	aned in such a way that	t the pressure tra	ansducers receive the p				
Mitigation	they need to accurately	record the tank pressu	ire.					
Procedural	In order to prevent a po	ssible hazard, the elec	tronics connecte	d to the pressure trans				
Mitigation	and reported to the pro	to charging the tank.	Any and all detec	ts or discrepancies will				
Prost-mitigation Cla	ssification							

Hazard Numb	Prop-027	Final RAC	3
Hazard Name	PtML02 Burst	Part Name	PtML02
Pre-mitigation Class	ification		
Severity Classification	Probability Critical Classificatio Remote		RAC 3
Hazard Analysis			
Causes	For the pressure transducer to burst, the mater yield. Over pressurization could trigger mater	ial (stainless st ial yield.	teel) of the outer casin
Consequences	A rupture of the first pressure transducer would ruin any chance of mission success. Also, such a equipment and injuries to nearby personnel.	release most release of ener	of the stored propellan gy could cause damage
Probability	The pressure transducers (both first and second type rated to pressures up to 10000 psig. How transducers were calibrated for a maximum pres instrument. As this pressure transducer is afte low pressures; therefore, the possibility of rupt) used for the ever, due to th ssure of 200 p er the regulato ure is conside	MR SAT propulsion syst le restrictions on tank p si to give better precis or, it should experience red remote.
Physical Mitigation	To entirely prevent this hazard from occurring, greater than the tank pressure is required. How occurrence is such than no physical mitigation i	a new pressur vever, as curre s necessary.	e transducer rated to a ntly designed the prob
Due ee duwel	The second ship do is shown is an also second		
Procedural Mitigation	system testing is imperative. Any and all deviation proper authorities.	on of the press ions with syste	ure regulation device. m components will be r
Prost-mitigation Cla	ssification		
Severity	Probability		PAC

Hazard Numb	Prop-028		Final RAC	4
Hazard Name	VML02 stuck closed		Part Name	VML02
Pre-mitigation Classi	fication			
Severity Classification	Negligible	Probability Classificatio Probable	e	RAC 3
Hazard Analysis				
Causes	The most likely cause fo problem preventing the o 24 volt pulse required fo	r an isolation valve being opening of the valve. Th or opening, or physical da	g locked in the c is could be the e amage to the int	losed position is an e electrical board never ernal solenoid of the
Consequences	With the second isolation However, there is not a failure mode.	n valve stuck in the clos potential risk of injury o	ed position, forn r further equipm	nation flight is unachi Ient damage associat
Probability	The design of the electri the propulsion subsyster system. Due to the depe currently rated as proba	cal boards which control m. However, a working c endence on as yet untest able.	the isolation val design is necessa ed electronics th	ves are not under the ary for the proper fur e probability of proble
Physical Mitigation	Change out non working	valves.		
Procedural Mitigation	Thorough testing of all effunctional testing of the valves integrated into a recorded and reported to process will be addressed	electronics for proper op board electronics and en 'flat sat' configuration. o the proper authorities. d and then retested unti	peration is neces d with system le Any deviations f Electrical proble I nominal operati	sary. Such testing w evel testing of the elect from nominal operation ems documented in the ion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4

Hazard Numb	elProp-029		Final RAC	4
Hazard Name	VML02 Locked Open		Part Name	VML02
Pre-mitigation Class	ification		-	
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4
Hazard Analysis				
Causes	The Lee Valve designed continually supplied to t position is a defective p	is a 'fail safe' design in th he solenoid. Therefore, r art.	at the valve is d most likely cause	esigned to close if pov e of a valve stuck in t
Consequences	With the valve stuck in t directly detrimental to second isolation valve is	the open position, the ser mission objectives as the s to remain open through	cond of the thre e first isolation v out the period o	e system inhibits is lo valve maintains tank i f formation flight any
Probability	Due to the fail safe natu will be stuck in the oper	ure of the design, it is cor n position.	nsidered a remot	te possibility that the
Physical Mitigation	All defective valves disc	covered in the testing pro	ocess will be rep	laced.
Procedural Mitigation	Thorough testing of all recorded and reported be replace.	valves will be conducted. to the proper authorities	Any deviations All valves faili	from nominal operat ng to achieve nomina
Prost-mitigation Cla	ssification			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4

Hazard Numb	Prop-030	Final RAC	4
Hazard Name	VML02 Clogged	Part Name	VML02
Pre-mitigation Classi	fication		
Severity Classification	Negligible Probability Classificati	o Frequent	RAC 3
Hazard Analysis			
Causes	The inner mechanisms of the isolatio material present within the propellar as metallic shavings)	n valves are extremely nan valves are extremely nant lines. (Left over mate	arrow and easily clogged rial from the constructi
Consequences	Foreign material lodged within the va lock the valve in either the open or c	alve can interfere with the losed position.	e workings of the intern
Probability	Since all parts of the propulsion syst the propellant lines can not be discou frequent occurrence.	em are machined, the po inted. Without mitigation	ssibility of foreign debr a clog of the valve is lik
Physical Mitigation	Fine mesh filters added before each interfere with the internal workings	valve within the system v of the valve.	vill capture any debris b
Procedural Mitigation	Each part will be cleaned with isopro should limit the remaining debris.	ppyl alcohol prior to incor	poration within the sys
Prost-mitigation Clas	sification		

Hazard Numb	Prop-031	Final RAC	3
Hazard Name	VML02 Burst	Part Name	VML02
Pre-mitigation Class	fication		
Severity Classification	Critical Probability Classificatio	emote	RAC 3
Hazard Analysis			
Causes	For the isolation valve to burst, it would hyield pressure. Additionally, over heating or rupture.	have to experience a of the valve could cau	propellant pressure gre se the outer casing of
Consequences	A rupture of the second isolation valve we assemblies, and thus end the formation flip could cause damage to nearby equipment	ould prevent propellar ght portion of the mis and injuries to nearby	nt from reaching the the sion. Also, such a rele personnel.
Probability	Valve rupture due to over pressurization is associated with the valve. The valve is rat the pressure regulator, at the 100 psi set FOS is still a respectable 3.66. Valve rupt possibility based upon the expected tempe and has been observed during functional greater than 100 C.	s a remote possibility ed to 1125 psi; there ting, the FOS is great ure due to over heati erature range for the testing by MAS to fun	due to the high factor fore even discounting er than 11. For the 30 ng is also considered a mission. The valve is ra ction properly at temp
Physical Mitigation	Physical mitigation is not necessary in this risk down to acceptable levels for flight.	case as the factors of	f safety are sufficient
Procedural Mitigation	Procedural mitigation comes in the form of within the system and that all procedures of the procedure will be signed off by the to ensure the procedure is followed correct appropriate authorities.	of ensuring that the c (assembly, filling, et performing technician ctly. All deviations ar	orrect propellant mass ic.) are performed corn n and a quality assuran nd problems will be rep
Prost-mitigation Cla	ssification		
Severity Classification	Critical Probability Classificatio	emote	RAC 3

Hazard Numb	Prop-032		Final RA	AC 4	
Hazard Name	VML02 leak		Part Nar	ne VML(02
Pre-mitigation Classi	fication				
Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4
Hazard Analysis					
Causes	The most likely ca tightening of the S	use of a noticeable le wagelok connections.	ak stemming from t	he second isolati	on valve i
Consequences	A leak in the secor first isolation valve leaking propellant	nd isolation valve wou e is functioning prop would limit the durat	ld not immediately o erly). However, ono ion of the formatior	cause a loss of pr ce formation fligh n flight mission p	opellant (; nt operati hase.
Probability	When assembling a followed exactly ar situations can occu	a system, human erro nd steps are not take ur.	r has to be taken int n to ensure their cor	o account. If pro	ocedures a tion, hazai
Physical Mitigation	No physical mitiga	ation is possible for t	nis hazard.		
Procedural Mitigation	The prevention of tightening procedu step by step manna assembly procedu technician to ensu reported to the ap controlled manner	leaks stemming from ures are followed. Ass er the proper method re will be signed off b ure the procedure is fo ppropriate authorities to ensure any poten	improper connection sembly procedures h of tightening each co y the performing te ollowed correctly. A . Additionally, the f cial leak is addressed	ons requires that ave been develop onnection point. I chnician and a qu All deviations and final assembly wil d prior to launch.	the manu bed which Each step Jality assu I problems II be press
Prost-mitigation Clas	sification				
Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numb	eProp-033		Final RAC	4
Hazard Name	Voltage step-down m	alfunction	Part Name	VML02
Pre-mitigation Classi	fication			
Severity Classification	Marginal	Probability Classificatio Probab	le	RAC 3
Hazard Analysis				
Causes	The voltage step-down i cause of the failure of vo electronics board either	is accomplished by the p oltage step-down for the due to component malf	propulsion electro e isolation valve function or impro	onics board. The most would be the failure of oper design.
Consequences	The Lee valves used for then stepped down to 5 within the time specified heat and possibly ruptur	the MR SAT propulsion s volts to maintain the ope , the excess voltage cou re.	system rely on a en state. If the s Id destroy the so	24 V pulse to open. T tep-down process does olenoid and cause the v
Probability	The design of the electr the propulsion subsyste system. Due to the dep currently rated as prob	ical boards which contro m. However, a working endence on as yet untes able.	ol the isolation va design is neces ted electronics t	alves are not under the sary for the proper fur he probability of proble
Physical Mitigation	A properly designed elec remote.	ctronics board controllin	g the system co	ould reduce the probab
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper o board electronics and en 'flat sat' configuration. to the proper authorities ad and then retested unt	peration is nece nd with system Any deviations . Electrical prob il nominal opera	essary. Such testing w level testing of the elect from nominal operation lems documented in the tion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Marginal	Probability Classificatio Remote		RAC 4

Hazard Numb	Prop-034				Final RAC	4	
Hazard Name	Swagelok Cros	s (CML01) Le	eak		Part Name	CML	_01
Pre-mitigation Classi	fication						
Severity Classification	Marginal	Prob Class	ability ificatio	Occasiona	l	RAC	4
Hazard Analysis							
Causes	The most likely o could be cause l	cause of a leak by either impro	regarding oper tight	g a Swage ening or i	lok fitting is mproper tub	an improper ing construc	connectior tion.
Consequences	A leak stemming flight phase of th goals may not be prevent propella	from the Swag ne mission. Thu e met. There is nt from reachir	gelok cros us that pl i little to ng the cro	ss would c nase of th no danger oss fitting	ause a loss o e mission wor to personnel except durin	f propellant uld be reduce as the two i g controlled	during the sed in time a solation val testing of
Probability	When assembling followed exactly situations can or	g a system, hur and steps are i ccur.	man error not taker	has to be	e taken into a e their correc	ccount. If pr	ocedures a ation, hazai
Physical Mitigation	No physical miti	gation is possil	ble for th	iis hazard			
Procedural Mitigation	The prevention of tightening processes by step mar assembly processes by processes by processes by processes by processes by processes by the	of leaks stemm dures are follow oner the proper lure will be sigr sure the proce appropriate au er to ensure an	ing from wed. Ass method on hed off b dure is fo thorities. ny potent	improper embly pro of tighteni y the perf ollowed co Additior ial leak is	connections cedures have ng each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha been develo ection point. nician and a o deviations an I assembly w rior to launch	t the manu pped which Each step quality assu d problems ill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal	Prob	ability	Remote		RAC	4

Hazard Numb	Prop-035		Final RAC	3	
Hazard Name	Swagelok Cross (CML0	1) Rupture	Part Name	CMI	_01
Pre-mitigation Classi	fication				
Severity Classification	Critical	Probability Classificatio Remote		RAC	3
Hazard Analysis					
Causes	The material yields due to	o excessive stress caus	ed by over-pr	ressurization	
Consequences	A rupture at this point win mission and seriously jeop to other near by satellite	thin the system would i ardize extended mission equipment; thus, furthe	mmediately e n operations. er reducing the	nd the forma A rupture co e chances of	ntion flight buld also ca mission su
Probability	The fitting in question is a experience at most 24.7 the regulator should fail, t propellant tank. (~4000 propellant loss is remote.	after the pressure regu psi of pressure which is the Swagelok fittings ar psig) Therefore, the ch	lation device s well within t re rated to ev nance for mat	within the sy :he capabiliti en higher pre erial yield lea	rstem. The es of the fi essures tha ading to lea
Physical Mitigation	Physical mitigation is not in risk down to acceptable le	necessary in this case a evels for flight.	s the factors	of safety are	sufficient
Procedural Mitigation	Procedural mitigation com within the system and the of the procedure will be s to ensure the procedure i appropriate authorities.	nes in the form of ensur at all procedures (asser igned off by the perforr s followed correctly. A	ring that the o mbly, filling, e ming technicia Il deviations a	correct prop etc.) are perf an and a qual nd problems	ellant mass formed corn ity assuran will be rep
Prost-mitigation Clas	sification				
Severity Classification	Critical	Probability Classificatio Remote		RAC	3

Hazard Numb	elProp-036		Fi	inal RAC	4	-
Hazard Name	TL101 leak		Pai	rt Name	TL	101
Pre-mitigation Classi	fication			_		
Severity Classification	Marginal	Probability Classificatio	Occasional		RAC	4
Hazard Analysis						
Causes	The most likely cause of could be cause by eith	of a leak regardir er improper tigh	ng a Swagelok tening or imp	fitting is a roper tubi	an improper ng construc	connectior tion.
Consequences	A leak stemming from t flight phase of the miss goals may not be met. prevent propellant from	the Swagelok tee sion. Thus that p There is little to n reaching the fi	ETL101 would whase of the m no danger to tting except d	l cause a le nission wou personnel uring cont	oss of prope Ild be reduce as the two i rolled testin	llant during ed in time a solation val g of the sy
Probability	When assembling a sys followed exactly and st situations can occur.	tem, human erro eps are not take	r has to be ta n to ensure th	ken into a neir correc	ccount. If pi t implement	rocedures a ation, hazai
Physical Mitigation	No physical mitigation	is possible for t	his hazard.			
Procedural Mitigation	The prevention of leaks tightening procedures a step by step manner the assembly procedure wi technician to ensure the reported to the approprise controlled manner to e	s stemming from are followed. As e proper method II be signed off h ne procedure is f priate authorities nsure any poten	a improper con sembly proced of tightening by the perform collowed corre collowed corre	nnections dures have each conno- ning techn ctly. All c v, the final dressed pr	requires tha been develo ection point. ician and a o leviations ar assembly w ior to launch	t the manu oped which Each step quality assu d problems <i>i</i> ill be press
Prost-mitigation Clas	ssification					
Severity Classification	Marginal	Probability Classificatio	Remote		RAC	4

Hazard Numb	eProp-037	Final RAC	3	
Hazard Name	TL101 Rupture	Part Name	TL1	01
Pre-mitigation Class	ification			
Severity Classification	Probability Critical Classificatio Remote		RAC	3
Hazard Analysis				
Causes	The material yields due to excessive stress caus	ed by over-pr	ressurization	
Consequences	A rupture at this point within the system would in mission and seriously jeopardize extended missio to other near by satellite equipment; thus, furthe	immediately e n operations. er reducing th	nd the forma A rupture co e chances of	tion flight uld also ca mission su
Probability	The fitting in question is after the pressure regulexperience at most 24.7 psi of pressure which i the regulator should fail, the Swagelok fittings as propellant tank. (~4000 psig) Therefore, the ch propellant loss is remote.	llation device is well within t re rated to ev hance for mat	within the sy che capabilition en higher pre erial yield lea	stem. The es of the fi ssures tha ding to lea
Physical Mitigation	Physical mitigation is not necessary in this case a risk down to acceptable levels for flight.	as the factors	of safety are	sufficient
Procedural	Procedural mitigation comes in the form of ensu	ring that the o	correct prope	ellant mass
Mitigation	within the system and that all procedures (asse of the procedure will be signed off by the perfor to ensure the procedure is followed correctly. A appropriate authorities.	mbly, filling, є ming technicia Il deviations a	etc.) are perf an and a quali and problems	ormed cori ty assuran will be rep
Prost-mitigation Cla	ssification			
Severity	Probability		DAG	

Hazard Numb	Prop-038				Final RAC	4	ł
Hazard Name	TL201 leak				Part Name	TL	201
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	l	RAC	4
Hazard Analysis							
Causes	The most like could be caus	ly cause of e by eithe	f a leak regardir er improper tigh	ig a Swage tening or i	lok fitting is mproper tub	an improper ing construc	connectior tion.
Consequences	A leak stemm flight phase o goals may not prevent prope	ing from th f the missi be met ellant from	ne Swagelok tee on. Thus that p There is little to reaching the fi	TL201 wo hase of th no danger ting excep	ould cause a l e mission wo to personnel ot during con	loss of prope uld be reduce as the two i trolled testin	Ilant during ed in time a solation val Ig of the sy
Probability	When assemb followed exac situations can	ling a systa tly and ste occur.	em, human erro eps are not take	r has to be n to ensur	e taken into a e their correc	ccount. If pr	rocedures a ation, hazai
Physical Mitigation	No physical m	nitigation i	s possible for t	his hazard	-		
Procedural Mitigation	The preventic tightening pro- step by step r assembly pro- technician to reported to the controlled ma	on of leaks ocedures an nanner the cedure will ensure the he appropr nner to en	stemming from re followed. As: proper method be signed off k e procedure is f riate authorities nsure any poten	i improper sembly pro of tighteni by the perf ollowed co . Additior tial leak is	connections cedures have ng each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha been develo ection point. nician and a o deviations ar l assembly w rior to launch	t the manu oped which Each step quality assu nd problems vill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-039	Final RAC	3
Hazard Name	TL201 Rupture	Part Name	TL201
Pre-mitigation Class	fication		
Severity Classification	Critical Probability Classificatio	Remote	RAC 3
Hazard Analysis			
Causes	The material yields due to excessive s	tress caused by over-pi	ressurization
Consequences	A rupture at this point within the systemission and seriously jeopardize extend to other near by satellite equipment; the	em would immediately e ded mission operations. hus, further reducing th	nd the formation flight A rupture could also ca e chances of mission su
Probability	The fitting in question is after the presexperience at most 24.7 psi of pressu the regulator should fail, the Swagelok propellant tank. (~4000 psig) Therefor propellant loss is remote.	ssure regulation device are which is well within t fittings are rated to ev ore, the chance for mat	within the system. The the capabilities of the fi en higher pressures tha erial yield leading to lea
Physical Mitigation	Physical mitigation is not necessary in risk down to acceptable levels for fligh	this case as the factors it.	of safety are sufficient
Procedural Mitigation	Procedural mitigation comes in the for within the system and that all procedu of the procedure will be signed off by to to ensure the procedure is followed co appropriate authorities.	m of ensuring that the ures (assembly, filling, e the performing technicia rrectly. All deviations a	correct propellant mass etc.) are performed corr an and a quality assuran and problems will be rep
Prost-mitigation Cla	ssification		
Severity Classification	Critical Probability Classificatio	Remote	RAC 3

Hazard Numb	Prop-040				Final RAC	4	ŀ
Hazard Name	TL301 leak				Part Name	TL	301
Pre-mitigation Classi	fication				-		
Severity Classification	Marginal		Probability Classificatio	Occasiona	I	RAC	4
Hazard Analysis							
Causes	The most like could be caus	ly cause of e by eithe	f a leak regardir r improper tigh	ng a Swage tening or i	elok fitting is Improper tub	an improper ing construc	connectior tion.
Consequences	A leak stemm flight phase o goals may not prevent prope	ing from the mission the mission be met. allant from	ne Swagelok tee on. Thus that p There is little to reaching the fir	e TL301 wo hase of th no danger tting excep	ould cause a l e mission wo to personnel ot during con	oss of prope uld be reduce as the two i trolled testin	llant during ed in time a solation val Ig of the sy
Probability	When assemb followed exac situations can	ling a systo tly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	ccount. If pi	rocedures a ation, hazai
Physical Mitigation	No physical m	nitigation is	s possible for t	his hazard			
Procedural Mitigation	The prevention tightening pro- step by step r assembly pro- technician to reported to the controlled ma	on of leaks ocedures ar nanner the cedure will ensure the he appropr nner to en	stemming from re followed. As: proper method be signed off to procedure is f riate authorities isure any poten	n improper sembly pro of tighteni by the perf collowed co c. Additior tial leak is	connections ocedures have ng each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha been develo ection point. nician and a o deviations ar l assembly w rior to launch	t the manu sped which Each step quality assund problems vill be press
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	eProp-041	Final RAC	3	
Hazard Name	TL301 Rupture	Part Name	TL3	301
Pre-mitigation Class	ification			
Severity Classification	Critical Probability Classificatio Remote		RAC	3
Hazard Analysis				
Causes	The material yields due to excessive stress caus	ed by over-pr	ressurization	
Consequences	A rupture at this point within the system would i mission and seriously jeopardize extended mission to other near by satellite equipment; thus, furthe	immediately e n operations. er reducing the	nd the forma A rupture co e chances of	tion flight ould also ca mission su
Probability	The fitting in question is after the pressure regu experience at most 24.7 psi of pressure which i the regulator should fail, the Swagelok fittings ar propellant tank. (~4000 psig) Therefore, the ch propellant loss is remote.	lation device s well within t re rated to even nance for mat	within the sy he capabilition en higher pre erial yield lea	stem. The es of the fi essures tha ading to lea
Physical Mitigation	Physical mitigation is not necessary in this case a risk down to acceptable levels for flight.	as the factors	of safety are	sufficient
Procedural	Procedural mitigation comes in the form of ensu	ring that the	correct prope	ellant mass
Mitigation	within the system and that all procedures (asse of the procedure will be signed off by the perform to ensure the procedure is followed correctly. A appropriate authorities.	mbly, filling, e ming technicia Il deviations a	etc.) are perf an and a quali nd problems	ormed cori ity assuran will be rep
Prost-mitigation Cla	ssification			
Severity	Probability		DAC	

Severity
ClassificationProbability
ClassificationRAC3

Hazard Numb	Prop-042				Final RAC	4	ł
Hazard Name	TL2a01 leak				Part Name	TL2	2a01
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	I	RAC	4
Hazard Analysis							
Causes	The most like could be caus	ly cause of se by eithe	f a leak regardir er improper tigh	ng a Swage tening or i	elok fitting is mproper tub	an improper ing construc	connectior tion.
Consequences	A leak stemm formation fligh mission goals should preven	ing from th nt phase o may not b nt propellar	ne Swagelok tee f the mission. T e met. There is nt from reaching	TL2a01 w hus that p little to no the fittin	vould cause a hase of the n o danger to p g except duri	loss of proponission would personnel as t ang controlled	ellant during I be reduce the two isol d testing of
Probability	When assemb followed exac situations can	ling a syst tly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	ccount. If pr	rocedures a ation, hazai
Physical Mitigation	No physical m	nitigation i	s possible for t	his hazard			
Procedural Mitigation	The preventic tightening pro- step by step r assembly pro- technician to reported to the controlled ma	on of leaks ocedures an nanner the cedure will ensure the he appropri- nner to en	stemming from re followed. As: proper method be signed off k e procedure is f riate authorities isure any poten	n improper sembly pro of tighteni by the perf followed co a. Addition tial leak is	connections ocedures have ng each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha been develo ection point. nician and a o deviations ar I assembly w rior to launch	t the manu oped which Each step quality assu ad problems vill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	eProp-043	Final RAC	3
Hazard Name	TL2a01 Rupture	Part Name	TL2a01
Pre-mitigation Class	ification		
Severity Classification	Critical Probability Classificatio Remot	te	RAC 3
Hazard Analysis			
Causes	The material yields due to excessive stress ca	used by over-pr	essurization
Consequences	A rupture at this point within the system would mission and seriously jeopardize extended miss to other near by satellite equipment; thus, furt	d immediately e ion operations. her reducing th	nd the formation flight A rupture could also ca e chances of mission su
Probability	The fitting in question is after the pressure regexperience at most 24.7 psi of pressure which the regulator should fail, the Swagelok fittings propellant tank. (~4000 psig) Therefore, the propellant loss is remote.	gulation device n is well within t are rated to ev chance for mat	within the system. The he capabilities of the fi en higher pressures tha erial yield leading to lea
Physical Mitigation	Physical mitigation is not necessary in this case risk down to acceptable levels for flight.	e as the factors	of safety are sufficient
Procedural Mitigation	Procedural mitigation comes in the form of ensitivity within the system and that all procedures (assof the procedure will be signed off by the perfect of ensure the procedure is followed correctly. appropriate authorities.	suring that the o sembly, filling, e orming technicia All deviations a	correct propellant mass etc.) are performed corr in and a quality assuran ind problems will be rep
Prost-mitigation Cla	ssification		
Severity	Probability		DAG.

Severity
ClassificationProbability
CriticalRAC3

Hazard Numb	Prop-044				Final RAC	4	ŀ
Hazard Name	TL2b01 leak				Part Name	TL2	2b01
Pre-mitigation Classi	fication				-		
Severity Classification	Marginal	[Probability Classificatio	Occasiona	al	RAC	4
Hazard Analysis							
Causes	The most likel could be cause	y cause of e by either	a leak regardin r improper tigh	g a Swage tening or	elok fitting is improper tub	an improper ing construc	connectior tion.
Consequences	A leak stemmi formation fligh mission goals should preven	ng from the It phase of may not be t propellan	e Swagelok tee the mission. T e met. There is t from reaching	TL2b01 v hus that p little to n the fittin	would cause a bhase of the n o danger to p g except duri	loss of prop nission would ersonnel as t ing controlled	ellant durin I be reduce the two isol d testing of
Probability	When assembl followed exact situations can	ing a syste ly and step occur.	em, human erro os are not take	r has to be n to ensur	e taken into a e their correc	ccount. If pr	rocedures a ation, hazai
Physical Mitigation	No physical m	itigation is	possible for t	his hazard			
Procedural Mitigation	The prevention tightening pro- step by step m assembly pro- technician to o reported to th controlled man	n of leaks a cedures are nanner the cedure will ensure the ne appropri nner to ens	stemming from e followed. Ass proper method be signed off b procedure is f iate authorities sure any poten	improper sembly pro of tighten by the perf ollowed co . Addition tial leak is	connections ocedures have ing each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha been develo ection point. nician and a o deviations ar I assembly w rior to launch	t the manu oped which Each step quality assu nd problems vill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal	[Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-045	Final RAC	3
Hazard Name	TL2b01 Rupture	Part Name	TL2b01
Pre-mitigation Class	ification		
Severity Classification	Critical Probability Classificatio Remot	e	RAC 3
Hazard Analysis			
Causes	The material yields due to excessive stress cat	used by over-pr	essurization
Consequences	A rupture at this point within the system would mission and seriously jeopardize extended missi to other near by satellite equipment; thus, furt	d immediately e ion operations. her reducing th	nd the formation flight A rupture could also ca e chances of mission su
Probability	The fitting in question is after the pressure regentience at most 24.7 psi of pressure which the regulator should fail, the Swagelok fittings propellant tank. (~4000 psig) Therefore, the propellant loss is remote.	gulation device n is well within t are rated to ev chance for mat	within the system. The the capabilities of the fi en higher pressures tha erial yield leading to lea
Physical Mitigation	Physical mitigation is not necessary in this case risk down to acceptable levels for flight.	e as the factors	of safety are sufficient
Procedural Mitigation	Procedural mitigation comes in the form of ensitivity within the system and that all procedures (assof the procedure will be signed off by the perfort o ensure the procedure is followed correctly. appropriate authorities.	suring that the o sembly, filling, e orming technicia All deviations a	correct propellant mass etc.) are performed corr an and a quality assuran and problems will be rep
Prost-mitigation Cla	ssification		
Severity	Probability		DAG.

Severity
ClassificationProbability
CriticalRAC3

Hazard Numb	Prop-046		Final RAC	4	
Hazard Name	Tr05 stuck closed		Part Name	Tr05 (TrL	1a01)
Pre-mitigation Classi	fication				
Severity Classification	Negligible	Probability Classificatio Probable	e	RAC	3
Hazard Analysis					
Causes	The most likely cause for preventing the opening pulse required for opening	or a thruster valve being of the valve. This could k ng, or physical damage to	locked in the o be the electrica o the internal s	closed position i al board never se solenoid of the v	s an ele ending f /alve.
Consequences	Thruster Tr05 is respon (assuming positive x ax rotation maneuvers arounegatively impact format would be impaired. This	nsible for providing count is runs through panel 4), und the x axis would be li ation flight goals. Also, hazard presents no dang	terclockwise ro . With this th imited to the c translational n ger to equipme	otation around t ruster stuck in t lockwise direction naneuvers in the nt or testing per	he x ax the clos on whic positi rsonnel
Probability	The design of the electr propulsion subsystem. system. Due to the dep currently rated as prob	ical boards which control However, a working desig endence on as yet untest able.	the thrusters gn is necessary ed electronics	are not under th / for the proper the probability o	e conti functic f proble
Physical Mitigation	Change out non working	valves.			
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and en 'flat sat' configuration. to the proper authorities. ad and then retested unti	peration is neco Id with system Any deviation: Electrical prol I nominal opera	essary. Such te level testing of s from nominal o blems document ation is achieved	sting w the elec operatio ed in th l.
Prost-mitigation Clas	ssification				
Severity Classification	Negligible	Probability Classificatio Remote		RAC	4

Hazard Numb	Prop-047		F	inal RAC	4	
Hazard Name	Tr05 Locked Open		Pa	rt Name	Tr05 (T	rL1a01)
Pre-mitigation Classi	fication					
Severity Classification	Negligible	Probability Classificatio	Remote		RAC	4
Hazard Analysis						
Causes	The Lee Valve designed continually supplied to position is a defective p	l is a 'fail safe' de the solenoid. Th part.	sign in that tl erefore, mos	he valve is de t likely cause	signed to c of a valve	lose if pov stuck in t
Consequences	The consequences of suvalves. The thruster ware from the nozzle; thus comode would release procession of the second secon	uch a failure would yould be activated causing the satell opellant into the t	d be felt imm d and a contin ite to careen esting area in	nediately upor nuous stream out of contro n amounts po	opening the of propella of propella ol. During ossibly grea	ne two isc int would testing, 1 ter than e
Probability	Due to the fail safe nat will be stuck in the ope	ure of the design en position.	, it is conside	ered a remote	e possibility	[,] that the
Physical	All defective values dis	covered in the to	cting proces	c will be real	and	
Mitigation			sting proces	s will be repla	4Ce0.	
Procedural	Thorough testing of all	valves will be co	nducted. Al	I testing will	occur in we	ell ventilat
Mitigation	as the fume hood prese from nominal operatior achieve nominal operat	ent in the SSE lab n will be recorded tion will be repla) to mitigate I and reporte ce.	the risk of protect the protect of t	ropellant ex per authori	(posure.) ties. All v
Prost-mitigation Clas	ssification					

Hazard Numb	eIProp-048		Final RA	AC 4	
Hazard Name	Tr05 Clogged		Part Nar	me Tr05 (1	[rL1a01)
Pre-mitigation Class	ification				
Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3
Hazard Analysis					
Causes	The inner mechanisms easily clogged with fo construction process	of the valves as v reign material pre such as metallic sl	vell as the throat of sent within the pro navings)	^E the nozzle are e opellant lines. (L	extremely .eft over r
Consequences	Foreign material lodge lock the valve in either would prevent propella	ed within the valve r the open or close ant flow and end t	can interfere with ed position. Foreign ne usefulness of the	the workings of n material lodged e thruster.	the intern I within the
Probability	Since all parts of the p the propellant lines car likely to be a frequent	propulsion system n not be discounte occurrence.	are machined, the d. Without mitigati	possibility of for ion a clog of the	reign debr valve and <i>i</i>
Physical	Fine mesh filters adde	d before each val	e within the system	n will capture an	v debris b
Mitigation	interfere with the inte	ernal workings of	the valve.		
Procedural	Each part will be clear	ned with isopropy	alcohol prior to in	corporation with	in the sys
Mitigation	should limit the rema	ining debris.			
Prost-mitigation Cla	ssification				

Severity
ClassificationProbability
ClassificatioRAC4

Hazard Numb	eProp-049		Final RAC	3	
Hazard Name	Tr05 Burst		Part Name	Tr05 (TrL1	a01)
Pre-mitigation Class	ification				
Severity Classification	Critical	Probability Classificatio Remote		RAC	3
Hazard Analysis					
Causes	For the thruster to bur pressure. Additionally, rupture.	rst, it would have to expe over heating of the valve	erience a prope could cause th	llant pressure gre e outer casing of	eater f the va
Consequences	If Thruster Tr05 was to trigger a safe mode wit ended prematurely and happen during testing, and increase the risk o	o burst, the resulting pro thin the satellite. Thus, t l extended mission operat the resulting propellant l f exposure.	pellant loss wou he formation fli ions would be ir oss could releas	uld send the sate ght portion of th n jeopardy. Shoul se unexpected an	llite o e miss Id the nounts
Probability	Valve rupture due to or associated with the val the pressure regulator, FOS is still a respectabl possibility based upon and has been observed greater than 100 C.	ver pressurization is a rer ve. The valve is rated to , at the 100 psi setting, t le 3.66. Valve rupture du the expected temperature I during functional testing	note possibility 1125 psi; there he FOS is great ue to over heati e range for the by MAS to fund	due to the high f fore even discour er than 11. For ng is also conside mission. The valv ction properly at	factor nting f the 30 ered a ve is ra tempe
Physical Mitigation	Physical mitigation is no risk down to acceptabl	ot necessary in this case le levels for flight.	as the factors o	of safety are suffi	cient
Procedural Mitigation	Procedural mitigation of within the system and of the procedure will be to ensure the procedur appropriate authorities such as the fume hood	comes in the form of ensu that all procedures (asse e signed off by the perfor re is followed correctly. / s. Additionally, all system in the SSE lab.	uring that the c embly, filling, et rming technician All deviations ar n testing will be	orrect propellant tc.) are performe n and a quality as nd problems will b e conducted in a v	mass d cori ssuran be rep well v
Prost-mitigation Cla	ssification				
Severity		Probability	Г (DAG.	

Hazard Numb	Prop-050				Final RAC	4	-
Hazard Name	Tr05 leak				Part Name	Tr05 (TrL1a01)
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	al	RAC	4
Hazard Analysis							
Causes	The most like the Swagelok	ly cause o connection	f a noticeable le I.	ak stemm	ing from the	thruster TrC	5 is improp
Consequences	A leak at this activated and which would le pressure just propulsive ma	point in th formation essen the before the aneuvers.	e system would flight implemen amount of time nozzle would r	not pose ted. At th available educe the	a problem un nat point the for formation thrust produ	til the propu leak would ca flight. Addi ced by this t	lsion syster ause propel tionally, th hruster and
Probability	When assemb followed exac situations can	ling a systo tly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	ccount. If pr t implement:	ocedures a ation, haza
Physical Mitigation	No physical m	nitigation i	s possible for t	his hazard			
Procedural Mitigation	The preventic tightening pro step by step r assembly prod technician to reported to th controlled ma	on of leaks ocedures an nanner the cedure will ensure the he approprinner to en	stemming from re followed. Ass proper method be signed off b e procedure is f riate authorities isure any poten	improper sembly pro of tighteni y the perf ollowed co . Additior tial leak is	connections ocedures have ing each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha e been develo ection point. nician and a o deviations an I assembly w rior to launch	t the manu pped which Each step quality assu d problems <i>i</i> ill be press
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-051		Final RAC	4
Hazard Name	Voltage step-down m	alfunction	Part Name	Tr05 (TrL1a01)
Pre-mitigation Classi	fication		-	
Severity Classification	Marginal	Probability Classificatio Probabl	e	RAC 3
Hazard Analysis				
Causes	The voltage step-down cause of the failure of v electronics board either	is accomplished by the pr roltage step-down for the due to component malfu	ropulsion electro i isolation valve v unction or improj	nics board. The most would be the failure of per design.
Consequences	The Lee valves used for then stepped down to 5 within the time specified heat and possibly ruptu	the MR SAT propulsion sy volts to maintain the oper d, the excess voltage could ire.	ystem rely on a 2 n state. If the st d destroy the so	24 V pulse to open. T ep-down process does lenoid and cause the v
Probability	The design of the electric the propulsion subsyster system. Due to the dep currently rated as prob	rical boards which control em. However, a working o endence on as yet untest pable.	the isolation va design is necess ed electronics th	Ives are not under the ary for the proper fur ne probability of proble
Physical Mitigation	A properly designed ele remote.	ctronics board controlling	g the system cou	uld reduce the probab
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported to process will be addresse	electronics for proper op board electronics and en 'flat sat' configuration. to the proper authorities. ed and then retested unti	peration is neces ad with system le Any deviations Electrical proble I nominal operat	essary. Such testing we evel testing of the elect from nominal operation ems documented in the ion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Marginal	Probability Classificatio Remote		RAC 4

Hazard Numb	eProp-052		Final RAC	4
Hazard Name	Tr06 stuck closed		Part Name	Tr06 (TrL1b01)
Pre-mitigation Classi	fication			
Severity Classification	Negligible	Probability Classificatio Probable	e	RAC 3
Hazard Analysis				
Causes	The most likely cause for preventing the opening pulse required for openi	or a thruster valve being of the valve. This could k ng, or physical damage to	locked in the clo be the electrical b the internal sc	osed position is an el board never sending t lenoid of the valve.
Consequences	Thruster Tr06 is respor (assuming positive x ax rotation maneuvers arou could negatively impact direction would be impa	nsible for providing clock tis runs through panel 4). und the x axis would be li t formation flight goals. ired. This hazard present	wise rotation ar . With this thru imited to the co Also, translation as no danger to	round the x axis of th ister stuck in the clos ounterclockwise direct hal maneuvers in the p equipment or testing
Probability	The design of the electr propulsion subsystem. system. Due to the dep currently rated as prob	ical boards which control However, a working desig endence on as yet untest able.	the thrusters ar gn is necessary ed electronics th	re not under the conti for the proper function ne probability of proble
Physical Mitigation	Change out non working	ı valves.		
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and en 'flat sat' configuration. to the proper authorities. ad and then retested until	eration is neces d with system le Any deviations Electrical proble I nominal operat	essary. Such testing we evel testing of the elect from nominal operation ems documented in the ion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4

Hazard Numb	Prop-053		Fina	al RAC	4
Hazard Name	Tr06 Locked Op	en	Part	Name	Tr06 (TrL1b01)
Pre-mitigation Classi	fication				
Severity Classification	Negligible	Probability Classificatio	Remote	F	RAC 4
Hazard Analysis					
Causes	The Lee Valve des continually supplie position is a defec	igned is a 'fail safe' de ed to the solenoid. Th tive part.	sign in that the erefore, most lil	valve is desig kely cause of	ned to close if po a valve stuck in
Consequences	The consequences valves. The thrus from the nozzle; t mode would releas	of such a failure wou ster would be activate hus causing the satel se propellant into the	ld be felt immed d and a continuc lite to careen ou testing area in a	iately upon o ous stream of ut of control. mounts poss	pening the two is ⁵ propellant would During testing, ibly greater than
Probability	Due to the fail saf will be stuck in th	e nature of the desigr e open position.	n, it is considere	d a remote p	ossibility that the
Physical	All defective value	a discovered in the t	osting process w	ill be replace	² d
Mitigation					-u.
Procedural Mitigation	Thorough testing as the fume hood from nominal oper achieve nominal c	of all valves will be co present in the SSE lab ration will be recorded operation will be repla	onducted. All te b) to mitigate th d and reported t ice.	esting will oc e risk of prop to the proper	cur in well ventila pellant exposure. r authorities. All
Prost-mitigation Clas	ssification				

Hazard Numb	eProp-054		Final RAC	4
Hazard Name	Tr06 Clogged		Part Name	Tr06 (TrL1b01)
Pre-mitigation Classi	ification			
Severity Classification	Negligible	Probability Classificatio Frequen	t	RAC 3
Hazard Analysis				
Causes	The inner mechanisms of easily clogged with fore construction process su	of the valves as well as th eign material present wit uch as metallic shavings)	e throat of the n hin the propellan	ozzle are extremely It lines. (Left over r
Consequences	Foreign material lodged lock the valve in either would prevent propellan	within the valve can inte the open or closed position It flow and end the useful	erfere with the w on. Foreign mate Iness of the thrus	orkings of the intern erial lodged within the ster.
Probability	Since all parts of the pr the propellant lines can likely to be a frequent c	opulsion system are mac not be discounted. Witho occurrence.	hined, the possil out mitigation a c	bility of foreign debr log of the valve and/
Physical	Fine mesh filters added	before each valve within	the system will	capture any debris b
Mitigation	interfere with the inter	nal workings of the valve	e	
Procedural	Each part will be cleane	ed with isopropyl alcohol	prior to incorpo	ration within the sys
Mitigation	should limit the remain	ing debris.		
Prost-mitigation Clas	ssification			

Severity
ClassificationProbability
ClassificatioRAC4

Hazard Numb	Prop-055	Final RAC	3
Hazard Name	TrO6 Burst	Part Name	Tr06 (TrL1b01)
Pre-mitigation Classi	fication		
Severity Classification	Critical Probability Classificatio Remote	e	RAC 3
Hazard Analysis			
Causes	For the thruster to burst, it would have to exponent pressure. Additionally, over heating of the value rupture.	erience a prope e could cause th	llant pressure greater t e outer casing of the va
Consequences	If Thruster Tr06 was to burst, the resulting pro trigger a safe mode within the satellite. Thus, t ended prematurely and extended mission operat happen during testing, the resulting propellant and increase the risk of exposure.	pellant loss wo the formation fl tions would be i loss could releas	uld send the satellite o ight portion of the miss n jeopardy. Should the se unexpected amounts
Probability	Valve rupture due to over pressurization is a reassociated with the valve. The valve is rated to the pressure regulator, at the 100 psi setting, FOS is still a respectable 3.66. Valve rupture du possibility based upon the expected temperatur and has been observed during functional testing greater than 100 C.	mote possibility 1125 psi; there the FOS is great ue to over heat re range for the g by MAS to fun	due to the high factor efore even discounting ter than 11. For the 30 ing is also considered a mission. The valve is ra ction properly at tempe
Physical Mitigation	Physical mitigation is not necessary in this case risk down to acceptable levels for flight.	as the factors of	of safety are sufficient
Procedural Mitigation	Procedural mitigation comes in the form of ens within the system and that all procedures (ass of the procedure will be signed off by the perfo to ensure the procedure is followed correctly. appropriate authorities. Additionally, all syster such as the fume hood in the SSE lab.	uring that the c embly, filling, e orming technicia All deviations a n testing will be	correct propellant mass tc.) are performed corr n and a quality assuran nd problems will be rep e conducted in a well v
Prost-mitigation Clas	ssification		
Severity Classification	Critical Probability Classificatio Remote	e	RAC 3

Hazard Numb	Prop-056				Final RAC	4	ł
Hazard Name	Tr06 leak				Part Name	Tr06 (TrL1b01)
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	al	RAC	4
Hazard Analysis							
Causes	The most like the Swagelok	ly cause o connection	f a noticeable le	eak stemm	ing from the	thruster TrC)6 is improp
Consequences	A leak at this activated and which would lo pressure just propulsive ma	point in th formation essen the before the aneuvers.	e system would flight implemen amount of time nozzle would r	I not pose ited. At th available educe the	a problem un nat point the for formation thrust produ	til the propu leak would ca flight. Addi ced by this t	lsion syster ause propel tionally, th hruster and
Probability	When assemb followed exac situations can	ling a syste tly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	ccount. If pr	rocedures a ation, hazai
Physical Mitigation	No physical m	nitigation i	s possible for t	his hazard			
Procedural Mitigation	The preventic tightening pro- step by step r assembly pro- technician to reported to the controlled ma	on of leaks ocedures an nanner the cedure will ensure the he appropr nner to en	stemming from re followed. Ass proper method be signed off k e procedure is f riate authorities sure any poten	n improper sembly pro of tighteni by the perf followed co a. Additior tial leak is	connections ocedures have ing each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha been develo ection point. nician and a o deviations ar I assembly w rior to launch	t the manu oped which Each step quality assu ad problems vill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-057		Final RAC	4	
Hazard Name	Voltage step-down m	alfunction	Part Name	Tr06 (1	[rL1b01]
Pre-mitigation Classi	fication		-		
Severity Classification	Marginal	Probability Classificatio Probab	ole	RAC	3
Hazard Analysis					
Causes	The voltage step-down i cause of the failure of vo electronics board either	s accomplished by the p oltage step-down for th due to component mal	propulsion electro le isolation valve function or impro	onics board. would be th oper design.	The most e failure of
Consequences	The Lee valves used for then stepped down to 5 within the time specified heat and possibly ruptur	the MR SAT propulsion s volts to maintain the op , the excess voltage cou re.	system rely on a en state. If the s uld destroy the s	24 V pulse t tep-down pro olenoid and d	to open. T ocess does cause the v
Probability	The design of the electr the propulsion subsyste system. Due to the dep currently rated as prob	ical boards which contro m. However, a working endence on as yet untes able.	ol the isolation v design is neces sted electronics t	alves are no sary for the the probabilit	t under the proper fur cy of proble
Physical Mitigation	A properly designed elec remote.	ctronics board controllir	ng the system co	ould reduce t	the probab
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper of board electronics and e 'flat sat' configuration. o the proper authorities ed and then retested un	operation is nece and with system . Any deviations s. Electrical prob til nominal opera	essary. Such level testing s from nomir blems docum ation is achie	n testing w of the elec nal operatio ented in th ved.
Prost-mitigation Clas	ssification				
Severity Classification	Marginal	Probability Classificatio Remot	e	RAC	4

Hazard Numb	Prop-058		Final RAC	4
Hazard Name	Tr01 stuck closed		Part Name	Tr01 (TrL2a101)
Pre-mitigation Classi	fication			
Severity Classification	Negligible Clas	bability sificatio Probable		RAC 3
Hazard Analysis				
Causes	The most likely cause for a the preventing the opening of the pulse required for opening, or	nruster valve being valve. This could b physical damage to	locked in the clo be the electrical k the internal sol	esed position is an ele poard never sending enoid of the valve.
Consequences	Thruster Tr01 is responsible (assuming positive x axis run rotation maneuvers around th could negatively impact form direction would be impaired.	for providing clocky s through panel 4). he y axis would be li ation flight goals. A This hazard present	wise rotation arc With this thrus mited to the cou Also, translationa s no danger to e	bund the y axis of th ster stuck in the closunterclockwise direct al maneuvers in the p equipment or testing
Probability	The design of the electrical bo propulsion subsystem. Howe system. Due to the dependen currently rated as probable.	bards which control ver, a working desig ce on as yet unteste	the thrusters are in is necessary f ed electronics the	e not under the contr or the proper functic e probability of proble
Physical Mitigation	Change out non working valve	S.		
Procedural Mitigation	Thorough testing of all electric functional testing of the board valves integrated into a 'flat s recorded and reported to the process will be addressed and	onics for proper op d electronics and en sat' configuration. proper authorities. then retested until	eration is necess d with system lev Any deviations f Electrical proble nominal operation	sary. Such testing w vel testing of the electrom nominal operations most documented in the on is achieved.
Prost-mitigation Clas	sification			
Severity Classification	Negligible Pro	bability sificatio Remote		RAC 4

Hazard Numb	elProp-059		Final RA	C 4	
Hazard Name	Tr01 Locked Oper	1	Part Nam	ne Tr01 (Tr	L2a101)
Pre-mitigation Classi	fication				
Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4
Hazard Analysis					
Causes	The Lee Valve design continually supplied position is a defective	ned is a 'fail safe' de to the solenoid. Th ve part.	sign in that the valve erefore, most likely o	e is designed to c cause of a valve	lose if pov stuck in t
Consequences	The consequences o valves. The thruste from the nozzle; thu mode would release	f such a failure woul er would be activated us causing the satell propellant into the t	d be felt immediately d and a continuous s ite to careen out of cesting area in amou	v upon opening th tream of propella control. During nts possibly grea	ne two isc int would testing, 1 ter than e
Probability	Due to the fail safe will be stuck in the	nature of the desigr open position.	n, it is considered a r	emote possibility	[,] that the
Physical	All defective values	discovered in the te	esting process will be	replaced	
Mitigation					
Procedural Mitigation	Thorough testing of as the fume hood pr from nominal opera achieve nominal ope	all valves will be co resent in the SSE lab tion will be recorded eration will be repla	onducted. All testing) to mitigate the risi I and reported to th ce.	g will occur in we < of propellant ex e proper authori	ell ventilat (posure.) ties. All v
Prost-mitigation Clas	ssification				

Hazard Numb	Prop-060	Final RAG	C 4
Hazard Name	Tr01 Clogged	Part Nam	e Tr01 (TrL2a101)
Pre-mitigation Classi	fication		
Severity Classification	ProbabilitNegligibleClassificat	io Frequent	RAC 3
Hazard Analysis			
Causes	The inner mechanisms of the valves easily clogged with foreign material construction process such as metal	as well as the throat of t present within the prop lic shavings)	the nozzle are extremely cellant lines. (Left over r
Consequences	Foreign material lodged within the v lock the valve in either the open or o would prevent propellant flow and e	alve can interfere with t closed position. Foreign nd the usefulness of the	he workings of the intern material lodged within the thruster.
Probability	Since all parts of the propulsion sys the propellant lines can not be disco likely to be a frequent occurrence.	tem are machined, the p unted. Without mitigatio	ossibility of foreign debr n a clog of the valve and/
Physical	Fine mesh filters added before each	valve within the system	will capture any debris b
Mitigation	interfere with the internal workings	of the valve.	
Procedural	Each part will be cleaned with isopr	opyl alcohol prior to inc	orporation within the sys
Mitigation	should limit the remaining debris.		
Prost-mitigation Clas	ssification		

Severity
ClassificationProbability
RemoteRAC4

Hazard Numb	eProp-061	Final RAC	3				
Hazard Name	Tr01 Burst	Part Name	Tr01 (TrL2a101)				
Pre-mitigation Classi	fication						
Severity Classification	Critical Probability Classificatio Remo	te	RAC 3				
Hazard Analysis							
Causes	For the thruster to burst, it would have to expressure. Additionally, over heating of the valv rupture.	perience a prope re could cause th	llant pressure greater t e outer casing of the va				
Consequences	If Thruster Tr01 was to burst, the resulting pr trigger a safe mode within the satellite. Thus, ended prematurely and extended mission opera happen during testing, the resulting propellant and increase the risk of exposure.	opellant loss wor the formation fli ations would be in loss could releas	uld send the satellite o ght portion of the miss n jeopardy. Should the se unexpected amounts				
Probability	Valve rupture due to over pressurization is a reassociated with the valve. The valve is rated to the pressure regulator, at the 100 psi setting, FOS is still a respectable 3.66. Valve rupture of possibility based upon the expected temperature and has been observed during functional testing greater than 100 C.	emote possibility o 1125 psi; there the FOS is great due to over heati re range for the g by MAS to fund	due to the high factor fore even discounting ter than 11. For the 30 ng is also considered a mission. The valve is ra ction properly at tempe				
Physical Mitigation	Physical mitigation is not necessary in this case risk down to acceptable levels for flight.	e as the factors o	of safety are sufficient				
Procedural Mitigation	Procedural mitigation comes in the form of en- within the system and that all procedures (as of the procedure will be signed off by the perf to ensure the procedure is followed correctly. appropriate authorities. Additionally, all syste such as the fume hood in the SSE lab.	suring that the c sembly, filling, et orming technicia All deviations ar m testing will be	orrect propellant mass tc.) are performed corn n and a quality assuran nd problems will be rep e conducted in a well v				
Prost-mitigation Clas	ssification						
Severity Classification	Probability Critical Classificatio Remo	te	RAC 3				
Hazard Numb	Prop-062				Final RAC	4	ŀ
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Hazard Name	Tr01 leak				Part Name	Tr01 (TrL2a101)
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	l	RAC	4
Hazard Analysis							
Causes	The most like the Swagelok (ly cause o connection	f a noticeable le I.	eak stemm	ing from the	thruster TrC)1 is improț
Consequences	A leak at this activated and which would le pressure just propulsive ma	point in th formation essen the before the aneuvers.	e system would flight implemen amount of time nozzle would r	l not pose ited. At th available t educe the	a problem un nat point the for formation thrust produ	til the propu leak would ca flight. Addi ced by this 1	lsion syster ause propel tionally, th hruster and
Probability	When assemb followed exac situations can	ling a systo tly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	ccount. If p t implement	rocedures a ation, hazai
Physical Mitigation	No physical m	nitigation i	s possible for t	his hazard			
Procedural Mitigation	The prevention tightening pro- step by step no assembly pro- technician to reported to the controlled ma	n of leaks ocedures an nanner the cedure will ensure the ne appropr nner to en	stemming from re followed. Ass proper method be signed off k e procedure is f riate authorities isure any poten	a improper sembly pro of tighteni by the perf ollowed co a. Additior tial leak is	connections cedures have ng each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha been develor ection point. nician and a or deviations ar I assembly v rior to launch	t the manu oped which Each step quality assu ad problems vill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-063		Final RAC	4
Hazard Name	Voltage step-down m	alfunction	Part Name	Tr01 (TrL2a1-01
Pre-mitigation Classi	fication			
Severity Classification	Marginal	Probability Classificatio Probab	le	RAC 3
Hazard Analysis				
Causes	The voltage step-down i cause of the failure of v electronics board either	is accomplished by the p oltage step-down for the due to component malfu	ropulsion electro e isolation valve v unction or improj	nics board. The most vould be the failure of per design.
Consequences	The Lee valves used for then stepped down to 5 within the time specified heat and possibly ruptu	the MR SAT propulsion s volts to maintain the ope I, the excess voltage coul re.	ystem rely on a 2 n state. If the st ld destroy the so	24 V pulse to open. T ep-down process does lenoid and cause the v
Probability	The design of the electr the propulsion subsyste system. Due to the dep currently rated as prob	rical boards which contro em. However, a working endence on as yet untest able.	l the isolation va design is necess ted electronics th	lves are not under the ary for the proper fur ne probability of proble
Physical Mitigation	A properly designed elec remote.	ctronics board controlling	g the system cou	uld reduce the probab
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and er 'flat sat' configuration. to the proper authorities. ad and then retested unt	peration is neces nd with system le Any deviations Electrical proble il nominal operat	esary. Such testing we evel testing of the elect from nominal operation ems documented in the ion is achieved.
Prost-mitigation Clas	sification			
Severity Classification	Marginal	Probability Classificatio Remote		RAC 4

Hazard Numb	Prop-064		Final RAC	4
Hazard Name	Tr02 stuck closed		Part Name	Tr02 (TrL2a2-01
Pre-mitigation Classi	fication			
Severity Classification	Negligible	Probability Classificatio Probable	e	RAC 3
Hazard Analysis				
Causes	The most likely cause for preventing the opening pulse required for openi	or a thruster valve being of the valve. This could k ng, or physical damage to	locked in the clo be the electrical b the internal sc	osed position is an el board never sending t lenoid of the valve.
Consequences	Thruster Tr02 is respor (assuming positive x ax rotation maneuvers arou negatively impact forma would be impaired. This	nsible for providing count tis runs through panel 4), und the z axis would be li ation flight goals. Also, t hazard presents no dang	erclockwise rot. With this thru mited to the clo translational ma ger to equipmen	ation around the z ax ister stuck in the clos ockwise direction whic neuvers in the positiv t or testing personnel
Probability	The design of the electr propulsion subsystem. system. Due to the dep currently rated as prob	ical boards which control However, a working desig endence on as yet untest able.	the thrusters ar gn is necessary ed electronics th	re not under the conti for the proper function ne probability of proble
Physical Mitigation	Change out non working	valves.		
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and en 'flat sat' configuration. to the proper authorities. ad and then retested until	eration is neces d with system le Any deviations Electrical proble I nominal operat	ssary. Such testing we evel testing of the elect from nominal operation ems documented in the ion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4

Hazard Numb	eProp-065		Fin	al RAC	4	
Hazard Name	Tr02 Locked Open		Part	Name	Tr02 (Tr	L2a2-01
Pre-mitigation Classi	fication					
Severity Classification	Negligible	Probability Classificatio	Remote		RAC	4
Hazard Analysis						
Causes	The Lee Valve designed continually supplied to t position is a defective p	is a 'fail safe' de he solenoid. Th art.	sign in that the erefore, most l	valve is des ikely cause	signed to c of a valve	lose if pov stuck in t
Consequences	The consequences of su valves. The thruster we from the nozzle; thus ca mode would release pro	ch a failure woul ould be activated ausing the satell pellant into the t	d be felt immed and a continu ite to careen o esting area in a	diately upon ous stream ut of contro amounts po	opening th of propella bl. During ssibly grea	ne two isc nt would testing, 1 ter than e
Probability	Due to the fail safe natu will be stuck in the ope	ure of the desigr n position.	, it is considere	ed a remote	possibility	that the
Physical	All defective values disc	overed in the te	sting process	will be repla	ced	
Mitigation			sting process		ueu.	
Procedural Mitigation	Thorough testing of all as the fume hood prese from nominal operation achieve nominal operat	valves will be co nt in the SSE lab will be recordeo ion will be repla	onducted. All t) to mitigate th l and reported ce.	esting will one risk of proton to the prop	occur in we opellant ex per authori	ell ventilat posure. , ties. All v
Prost-mitigation Clas	ssification					

Hazard Numb	eProp-066		Final RAC	4
Hazard Name	Tr02 Clogged		Part Name	Tr02 (TrL2a2-01
Pre-mitigation Classi	fication			
Severity Classification	Negligible	Probability Classificatio Frequen	t	RAC 3
Hazard Analysis				
Causes	The inner mechanisms of easily clogged with fore construction process su	f the valves as well as th ign material present witl ch as metallic shavings)	e throat of the hin the propella	nozzle are extremely nt lines. (Left over r
Consequences	Foreign material lodged lock the valve in either t would prevent propellant	within the valve can inte he open or closed position t flow and end the useful	rfere with the v on. Foreign mat ness of the thru	vorkings of the intern erial lodged within the uster.
Probability	Since all parts of the pro the propellant lines can r likely to be a frequent o	opulsion system are mac not be discounted. Witho ccurrence.	hined, the poss out mitigation a	ibility of foreign debr clog of the valve and/
Physical	Fine mesh filters added	before each valve within	the system will	capture any debris b
Mitigation	interfere with the interr	al workings of the valve	eno oyocom m 9.	
Procedural	Each part will be cleane	d with isopropyl alcohol	prior to incorpo	pration within the sys
<u>Mitigation</u>	should limit the remaini	ng debris.		
Prost-mitigation Clas	ssification			

Severity
ClassificationProbability
ClassificatioRAC4

Hazard Numb	eProp-067	Final RAC	3
Hazard Name	Tr02 Burst	Part Name	Tr02 (TrL2a2-01
Pre-mitigation Classi	fication		
Severity Classification	Critical Probability Classificatio Remo	te	RAC 3
Hazard Analysis			
Causes	For the thruster to burst, it would have to exp pressure. Additionally, over heating of the valv rupture.	perience a propel e could cause the	lant pressure greater t e outer casing of the va
Consequences	If Thruster TrO2 was to burst, the resulting pr trigger a safe mode within the satellite. Thus, ended prematurely and extended mission opera happen during testing, the resulting propellant and increase the risk of exposure.	opellant loss wou the formation fli ations would be ir loss could releas	uld send the satellite o ght portion of the miss n jeopardy. Should the se unexpected amounts
Probability	Valve rupture due to over pressurization is a reassociated with the valve. The valve is rated to the pressure regulator, at the 100 psi setting, FOS is still a respectable 3.66. Valve rupture of possibility based upon the expected temperature and has been observed during functional testing greater than 100 C.	emote possibility o 1125 psi; there the FOS is great due to over heati re range for the g by MAS to fund	due to the high factor fore even discounting er than 11. For the 30 ng is also considered a mission. The valve is ra ction properly at tempe
Physical Mitigation	Physical mitigation is not necessary in this case risk down to acceptable levels for flight.	e as the factors o	of safety are sufficient
Procedural Mitigation	Procedural mitigation comes in the form of en- within the system and that all procedures (as of the procedure will be signed off by the perfi- to ensure the procedure is followed correctly. appropriate authorities. Additionally, all syste such as the fume hood in the SSE lab.	suring that the c sembly, filling, et orming technician All deviations ar m testing will be	orrect propellant mass c.) are performed corn n and a quality assuran nd problems will be rep conducted in a well v
Prost-mitigation Clas	ssification		
Severity Classification	Probability Critical Classificatio Remo	te	RAC 3

Hazard Numb	Prop-068				Final RAC	4	ŀ
Hazard Name	Tr02 leak				Part Name	Tr02 (1	rL2a2-01
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	I	RAC	4
Hazard Analysis							
Causes	The most like the Swagelok	ly cause o connection	f a noticeable le I.	ak stemm	ing from the	thruster TrC)2 is improp
Consequences	A leak at this activated and which would lo pressure just propulsive ma	point in th formation essen the before the aneuvers.	e system would flight implemen amount of time nozzle would r	not pose ted. At th available educe the	a problem un hat point the for formation thrust produ	til the propu leak would ca flight. Addi ced by this t	lsion syster ause propel itionally, th chruster and
Probability	When assemb followed exac situations can	ling a systo tly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	ccount. If pr	rocedures a ation, hazai
Physical Mitigation	No physical m	nitigation i	s possible for t	his hazard			
Procedural Mitigation	The preventic tightening pro- step by step r assembly pro- technician to reported to the controlled ma	n of leaks ocedures an nanner the cedure will ensure the ne appropr nner to en	stemming from re followed. Ass proper method be signed off k e procedure is f riate authorities isure any poten	improper sembly pro of tighteni y the perf ollowed co . Additior tial leak is	connections ocedures have ng each conn forming techr prrectly. All o nally, the fina addressed pr	requires tha been develo ection point. nician and a o deviations ar I assembly w rior to launch	t the manu oped which Each step quality assu nd problems vill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	elProp-069		Final RAC	4
Hazard Name	Voltage step-down m	nalfunction	Part Name	Tr02 (TrL2a2-01
Pre-mitigation Classi	fication			
Severity Classification	Marginal	Probability Classificatio Probab	le	RAC 3
Hazard Analysis				
Causes	The voltage step-down cause of the failure of v electronics board either	is accomplished by the p voltage step-down for the r due to component malf	ropulsion electro e isolation valve v unction or improj	nics board. The most would be the failure of per design.
Consequences	The Lee valves used for then stepped down to 5 within the time specified heat and possibly ruptu	the MR SAT propulsion s volts to maintain the ope d, the excess voltage coul ire.	ystem rely on a 2 m state. If the st ld destroy the so	24 V pulse to open. T ep-down process does lenoid and cause the v
Probability	The design of the elect the propulsion subsyste system. Due to the dep currently rated as prob	rical boards which contro em. However, a working pendence on as yet untes pable.	l the isolation va design is necess ted electronics th	lves are not under the ary for the proper fur ne probability of proble
Physical Mitigation	A properly designed ele remote.	ectronics board controlling	g the system cou	uld reduce the probab
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported process will be address	electronics for proper of e board electronics and en a 'flat sat' configuration. to the proper authorities. ed and then retested unt	peration is neces nd with system le Any deviations Electrical proble il nominal operat	ssary. Such testing we evel testing of the elect from nominal operation ems documented in the ion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Marginal	Probability Classificatio Remote		RAC 4

Hazard Numb	eProp-070		Final RAC	4
Hazard Name	Tr03 stuck closed		Part Name	Tr03 (TrL2b1-01
Pre-mitigation Classi	fication			
Severity Classification	Negligible	Probability Classificatio Probable	e	RAC 3
Hazard Analysis				
Causes	The most likely cause for preventing the opening pulse required for openi	or a thruster valve being of the valve. This could k ng, or physical damage to	locked in the clo be the electrical b the internal so	osed position is an ele board never sending a lenoid of the valve.
Consequences	Thruster Tr03 is respor (assuming positive x ax rotation maneuvers arou could negatively impact direction would be impa	nsible for providing clocky tis runs through panel 4). und the z axis would be li t formation flight goals. ired. This hazard present	wise rotation and With this thru mited to the co Also, translation as no danger to o	ound the z axis of th ister stuck in the clos unterclockwise direct ial maneuvers in the p equipment or testing
Probability	The design of the electr propulsion subsystem. system. Due to the dep currently rated as prob	ical boards which control However, a working desig endence on as yet untest able.	the thrusters ar gn is necessary ed electronics th	e not under the conti for the proper function ne probability of proble
Physical Mitigation	Change out non working	valves.		
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and en 'flat sat' configuration. to the proper authorities. ad and then retested until	eration is neces d with system le Any deviations Electrical proble I nominal operat	essary. Such testing we evel testing of the elect from nominal operation ems documented in the ion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4

Hazard Numb	eProp-071		Final	RAC	4
Hazard Name	Tr03 Locked Open	Ì	Part N	Name Tr	03 (TrL2b1-01
Pre-mitigation Classi	fication				
Severity Classification	Negligible	Probability Classificatio	Remote	RA	AC 4
Hazard Analysis					
Causes	The Lee Valve desigr continually supplied position is a defectiv	ned is a 'fail safe' de to the solenoid. Th /e part.	sign in that the v erefore, most lik	alve is desigr ely cause of a	ned to close if pov a valve stuck in t
Consequences	The consequences o valves. The thruste from the nozzle; thu mode would release	f such a failure woul r would be activated is causing the satell propellant into the t	d be felt immedia d and a continuou ite to careen out cesting area in an	ately upon op us stream of t of control. nounts possik	eening the two isc propellant would During testing, 1 oly greater than e
Probability	Due to the fail safe r will be stuck in the o	nature of the desigr open position.	ı, it is considered	a remote po	ossibility that the
Physical	All defective valves	discovered in the te	sting process wi	ll he renlacer	4
Mitigation			String process wi		
Procedural Mitigation	Thorough testing of as the fume hood pr from nominal operat achieve nominal ope	all valves will be co esent in the SSE lab ion will be recorded eration will be repla	onducted. All tes) to mitigate the l and reported to ce.	sting will occ risk of prope the proper	ur in well ventilat ellant exposure. , authorities. All v
Prost-mitigation Clas	ssification				

Hazard Numb	elProp-072		Final RAC	4
Hazard Name	Tr03 Clogged		Part Name	Tr03 (TrL2b1-01
Pre-mitigation Class	ification			
Severity Classification	Negligible	Probability Classificatio Frequen	t	RAC 3
Hazard Analysis				
Causes	The inner mechanisms of easily clogged with foreig construction process suc	the valves as well as th gn material present with h as metallic shavings)	e throat of the r hin the propellar	nozzle are extremely nt lines. (Left over r
Consequences	Foreign material lodged w lock the valve in either th would prevent propellant	vithin the valve can inte e open or closed positio flow and end the useful	rfere with the w on. Foreign mat ness of the thru	vorkings of the intern erial lodged within the ister.
Probability	Since all parts of the prop the propellant lines can no likely to be a frequent oc	pulsion system are mac ot be discounted. With currence.	hined, the possion and the pos	ibility of foreign debr clog of the valve and/
Physical	Fine mesh filters added b	efore each valve within	the system will	capture any debris b
Mitigation	interfere with the interna	al workings of the valve	ene of occur min 9.	
Procedural	Each part will be cleaned	with isopropyl alcohol	prior to incorpo	oration within the sys
Mitigation		ig debris.		
Prost-mitigation Cla	ssification			

Severity
ClassificationProbability
ClassificatioRAC4

Hazard Numb	Prop-073		Final RAC	3	
Hazard Name	Tr03 Burst		Part Name	Tr03 (TrL2b1	-01
Pre-mitigation Class	fication				
Severity Classification	Critical Pro	bability sificatio Remote		RAC 3	
Hazard Analysis					
Causes	For the thruster to burst, it v pressure. Additionally, over he rupture.	vould have to exper eating of the valve c	ience a propel could cause the	lant pressure grea e outer casing of th	ter i he va
Consequences	If Thruster Tr03 was to burst trigger a safe mode within the ended prematurely and extend happen during testing, the res and increase the risk of expos	, the resulting property e satellite. Thus, the ded mission operatic sulting propellant los sure.	ellant loss wou e formation fli ons would be ir ss could releas	Ild send the satelli ght portion of the n jeopardy. Should e unexpected amo	te o miss the ounts
Probability	Valve rupture due to over pre associated with the valve. The the pressure regulator, at the FOS is still a respectable 3.66 possibility based upon the exp and has been observed during greater than 100 C.	ssurization is a remo e valve is rated to 1 100 psi setting, th . Valve rupture due bected temperature functional testing k	ote possibility 125 psi; there e FOS is great to over heati range for the by MAS to fund	due to the high fa fore even discount er than 11. For th ng is also consider mission. The valve ction properly at te	ctor ing the 30 ed a is ra empe
Physical Mitigation	Physical mitigation is not nece risk down to acceptable levels	essary in this case as s for flight.	s the factors o	f safety are suffici	ient
Procedural Mitigation	Procedural mitigation comes i within the system and that al of the procedure will be signe to ensure the procedure is fol appropriate authorities. Addi such as the fume hood in the S	n the form of ensur Il procedures (asser d off by the perforn llowed correctly. Al tionally, all system SSE lab.	ing that the c nbly, filling, et ning techniciar I deviations ar testing will be	orrect propellant n c.) are performed n and a quality ass nd problems will be conducted in a w	nass cori uran erep ell v
Prost-mitigation Cla	sification				
Severity Classification	Critical Pro	bability sificatio Remote	[RAC 3	

Hazard Numb	Prop-074				Final RAC	4	ŀ
Hazard Name	Tr03 leak				Part Name	Tr03 (1	rL2b1-01
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	al	RAC	4
Hazard Analysis							
Causes	The most like the Swagelok (ly cause o connection	f a noticeable le I.	ak stemm	ing from the	thruster TrC)3 is improp
Consequences	A leak at this activated and which would le pressure just propulsive ma	point in th formation essen the before the aneuvers.	e system would flight implemen amount of time nozzle would r	not pose ted. At th available educe the	a problem un nat point the for formation thrust produ	til the propu leak would ca flight. Addi ced by this t	lsion syster ause propel itionally, th chruster and
Probability	When assemb followed exac situations can	ling a systo tly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	ccount. If p t implement	rocedures a ation, hazaı
Physical Mitigation	No physical m	nitigation i	s possible for t	nis hazard			
Procedural Mitigation	The prevention tightening pro- step by step in assembly pro- technician to reported to the controlled mat	n of leaks ocedures an nanner the cedure will ensure the ne appropr nner to en	stemming from re followed. Ass proper method be signed off b e procedure is f riate authorities isure any poten	improper sembly pro of tighteni y the perf ollowed co . Additior tial leak is	connections ocedures have ing each conn forming techr prrectly. All o nally, the fina addressed pr	requires that been develor ection point. nician and a or deviations ar I assembly v rior to launch	t the manu oped which Each step quality assu nd problems vill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	erProp-075		Final RAC	4
Hazard Name	Voltage step-down m	alfunction	Part Name	Tr03 (TrL2b1-01
Pre-mitigation Classi	fication			
Severity Classification	Marginal	Probability Classificatio Probabl	e	RAC 3
Hazard Analysis				
Causes	The voltage step-down i cause of the failure of v electronics board either	s accomplished by the prolage step-down for the due to component malfu	ropulsion electro solation valve unction or impro	nics board. The most would be the failure of per design.
Consequences	The Lee valves used for then stepped down to 5 within the time specified heat and possibly ruptu	the MR SAT propulsion sy volts to maintain the ope I, the excess voltage coul re.	ystem rely on a and a state. If the st d destroy the so	24 V pulse to open. T ep-down process does lenoid and cause the v
Probability	The design of the electr the propulsion subsyste system. Due to the dep currently rated as prob	ical boards which control m. However, a working endence on as yet untest able.	l the isolation va design is necess ted electronics tl	Ilves are not under the ary for the proper fur he probability of proble
Physical Mitigation	A properly designed elec remote.	ctronics board controlling	g the system co	uld reduce the probab
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and er 'flat sat' configuration. o the proper authorities. ed and then retested unti	peration is neces ad with system le Any deviations Electrical probl il nominal operat	ssary. Such testing w evel testing of the elec from nominal operatio ems documented in the cion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Marginal	Probability Classificatio Remote		RAC 4

Hazard Numb	eProp-076		Final RAC	4
Hazard Name	Tr04 stuck closed		Part Name	Tr04 (TrL2b2-01
Pre-mitigation Classi	fication			
Severity Classification	Negligible	Probability Classificatio Probabl	e	RAC 3
Hazard Analysis				
Causes	The most likely cause for preventing the opening pulse required for openi	or a thruster valve being of the valve. This could b ng, or physical damage to	locked in the c be the electrical o the internal so	losed position is an ele l board never sending t olenoid of the valve.
Consequences	Thruster Tr04 is respon (assuming positive x ax rotation maneuvers arou negatively impact forma would be impaired. This	nsible for providing count is runs through panel 4) und the y axis would be li ation flight goals. Also, t hazard presents no dang	terclockwise rot . With this thru imited to the cl translational ma ger to equipmer	tation around the y av uster stuck in the clos ockwise direction whic aneuvers in the positiv at or testing personnel
Probability	The design of the electr propulsion subsystem. system. Due to the dep currently rated as prob	ical boards which control However, a working desig endence on as yet untest able.	the thrusters a gn is necessary ed electronics t	re not under the conti for the proper functic he probability of proble
Physical Mitigation	Change out non working	valves.		
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and en 'flat sat' configuration. o the proper authorities. ed and then retested unti	peration is nece d with system I Any deviations Electrical prob I nominal opera	ssary. Such testing w evel testing of the elec from nominal operation lems documented in the tion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4

Hazard Numb	Prop-077		F	inal RAC	4	
Hazard Name	Tr04 Locked Open		Pa	art Name	Tr04 (Tr	L2b2-01
Pre-mitigation Classi	fication					
Severity Classification	Negligible	Probability Classificatio	Remote	Ľ	RAC	4
Hazard Analysis						
Causes	The Lee Valve designed continually supplied to to position is a defective p	is a 'fail safe' de the solenoid. Th part.	sign in that t erefore, mos	he valve is de t likely cause	esigned to d e of a valve	close if pov stuck in t
Consequences	The consequences of suvalves. The thruster w from the nozzle; thus c mode would release pro	uch a failure woul ould be activated ausing the satell opellant into the t	d be felt imm d and a conti ite to careen cesting area i	nediately upo nuous strean n out of cont n amounts p	n opening t n of propella rol. During ossibly grea	he two isc ant would 9 testing, 1 ater than e
Probability	Due to the fail safe nati will be stuck in the ope	ure of the desigr n position.	ı, it is conside	ered a remot	e possibility	y that the
Physical	All defective valves disc	covered in the te	sting proces	s will be repl	aced.	
Mitigation						
Procedural Mitigation	Thorough testing of all as the fume hood prese from nominal operation achieve nominal operat	valves will be co ent in the SSE lab will be recorded ion will be repla	onducted. Al) to mitigate I and reporte ce.	II testing will the risk of p ed to the pro	occur in w propellant e pper author	ell ventila xposure. , ities. All v
Prost-mitigation Clas	ssification					

Hazard Numb	elProp-078		Final RA	AC 4	
Hazard Name	Tr04 Clogged		Part Nar	ne Tr04 (Tr	L2b2-01
Pre-mitigation Class	fication				
Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3
Hazard Analysis					
Causes	The inner mechanisms easily clogged with fo construction process	of the valves as w preign material pres such as metallic sh	rell as the throat of sent within the pro navings)	^E the nozzle are e opellant lines. (L	xtremely eft over r
Consequences	Foreign material lodge lock the valve in eithe would prevent propell	ed within the valve r the open or close ant flow and end th	can interfere with d position. Foreign to usefulness of the	the workings of t n material lodged e thruster.	the intern within the
Probability	Since all parts of the the propellant lines ca likely to be a frequent	propulsion system n not be discounted c occurrence.	are machined, the d. Without mitigat	possibility of for ion a clog of the v	eign debr valve and/
Physical	Fine mesh filters adde	d before each valv	e within the syster	n will capture and	y debris b
Mitigation	interfere with the inte	ernal workings of t	he valve.		
Procedural	Each part will be clear	ned with isopropyl	alcohol prior to in	corporation withi	n the sys
Mitigation	should limit the rema	אוווווש עפטרוג.			
Prost-mitigation Cla	ssification				

SeverityProbabilityRACClassificationRemoteRAC

Hazard Numb	elProp-079		Final RAC	3	
Hazard Name	Tr04 Burst		Part Name	Tr04 (T	rL2b2-01
Pre-mitigation Class	ification				
Severity Classification	Critical Cla	obability ssificatio Remote	[RAC	3
Hazard Analysis					
Causes	For the thruster to burst, it pressure. Additionally, over h rupture.	would have to exper leating of the valve o	ience a prope could cause th	llant pressur e outer casin	e greater i ig of the va
Consequences	If Thruster Tr04 was to burs trigger a safe mode within th ended prematurely and exten happen during testing, the re and increase the risk of expo	t, the resulting prop e satellite. Thus, th ded mission operatio sulting propellant lo sure.	ellant loss wor e formation fli ons would be in ss could releas	uld send the ght portion n jeopardy. S se unexpecte	satellite o of the miss Should the ed amounts
Probability	Valve rupture due to over pre associated with the valve. Th the pressure regulator, at the FOS is still a respectable 3.66 possibility based upon the exp and has been observed during greater than 100 C.	essurization is a rem he valve is rated to 1 e 100 psi setting, th 5. Valve rupture due pected temperature g functional testing l	ote possibility 125 psi; there le FOS is great to over heati range for the by MAS to fund	due to the h fore even di- rer than 11. ng is also co mission. The ction properl	high factor scounting For the 30 nsidered a e valve is ra y at tempe
Physical Mitigation	Physical mitigation is not nec risk down to acceptable leve	essary in this case a Is for flight.	s the factors o	of safety are	sufficient
Procedural	Procedural mitigation comes	in the form of ensur	ing that the c	orrect prope	llant mass
<u>Mitigation</u>	within the system and that a of the procedure will be signe to ensure the procedure is fo appropriate authorities. Add such as the fume hood in the	all procedures (assen ed off by the perforr ollowed correctly. A litionally, all system SSE lab.	nbly, filling, ei ning technicia Il deviations ai testing will be	tc.) are perfo n and a quali nd problems conducted	ormed cori ty assuran will be rep in a well v
Prost-mitigation Cla	ssification				
Severity	Pro	obability	l l	DAC	

Hazard Numb	Prop-080				Final RAC	۷	ł
Hazard Name	Tr04 leak				Part Name	Tr04 (1	rL2b2-01
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	al	RAC	4
Hazard Analysis							
Causes	The most likely the Swagelok c	y cause of onnection	f a noticeable le	eak stemm	ing from the	thruster Tr()4 is improp
Consequences	A leak at this p activated and f which would le pressure just b propulsive ma	point in th formation ssen the pefore the neuvers.	e system would flight implemer amount of time nozzle would r	I not pose nted. At th available reduce the	a problem un nat point the for formation thrust produ	itil the propu leak would ca flight. Add liced by this f	lsion syster ause propel itionally, th thruster and
Probability	When assembli followed exact situations can	ing a systo ly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	iccount. If p	rocedures a ation, hazai
Physical Mitigation	No physical mi	itigation i	s possible for t	his hazard			
Procedural Mitigation	The preventior tightening proc step by step m assembly proc technician to e reported to th controlled man	n of leaks cedures ar lanner the edure will ensure the e appropr nner to en	stemming from re followed. As proper method be signed off t procedure is f riate authorities sure any poten	n improper sembly pro of tighteni by the perf followed co s. Addition tial leak is	connections ocedures have ing each conn forming techr prrectly. All o hally, the fina addressed pr	requires tha e been develo ection point. nician and a deviations ar I assembly v rior to launch	t the manu oped which Each step quality assund problems vill be press n.
Prost-mitigation Clas	sification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-081		Final RAC	4
Hazard Name	Voltage step-dov	vn malfunction	Part Name	Tr04 (TrL2b2-01
Pre-mitigation Classi	fication			
Severity Classification	Marginal	Probability Classificatio Pr	obable	RAC 3
Hazard Analysis				
Causes	The voltage step-d cause of the failure electronics board e	own is accomplished by e of voltage step-down f either due to component	the propulsion electro or the isolation valve malfunction or impro	nics board. The most would be the failure of per design.
Consequences	The Lee valves use then stepped down within the time spe heat and possibly r	d for the MR SAT propuls to 5 volts to maintain th cified, the excess voltage rupture.	sion system rely on a l e open state. If the st e could destroy the so	24 V pulse to open. T ep-down process does lenoid and cause the v
Probability	The design of the e the propulsion sub- system. Due to the currently rated as	electrical boards which c system. However, a wo e dependence on as yet o probable.	ontrol the isolation va rking design is necess untested electronics tl	Ives are not under the ary for the proper fur ne probability of proble
Physical Mitigation	A properly designe remote.	d electronics board cont	rolling the system co	uld reduce the probab
Procedural Mitigation	Thorough testing of functional testing of valves integrated i recorded and repor process will be add	of all electronics for pro of the board electronics a nto a 'flat sat' configura rted to the proper autho lressed and then reteste	per operation is neces and end with system le ation. Any deviations rities. Electrical probl d until nominal operat	ssary. Such testing w evel testing of the elec from nominal operation ems documented in the cion is achieved.
Prost-mitigation Clas	sification			
Severity Classification	Marginal	Probability Classificatio	emote	RAC 4

Hazard Numb	eProp-082		Final RAC	4	ł
Hazard Name	Tr07 stuck closed		Part Name	Tr07 (TrL3a-01)
Pre-mitigation Classi	fication				
Severity Classification	Negligible	Probability Classificatio Probable	e	RAC	3
Hazard Analysis					
Causes	The most likely cause for preventing the opening of pulse required for opening	or a thruster valve being of the valve. This could b ng, or physical damage to	locked in the be the electric b the internal	closed posit al board nev solenoid of t	ion is an el er sending he valve.
Consequences	Thruster Tr07 is responsil rotation maneuvers aroun maneuverability in the neg to be canceled out and the in the negative y direction personnel.	ble for providing the count d the x axis (positive x axi gative y direction. With Tri satellite would deviate fr would be impaired. This h	ter force neces s directed thro 07 stuck closed from the format azard presents	sary to preve ugh panel 4) d, the translat ion. Addition no danger to	ent translatio and translat tional force ally, translat equipment
Probability	The design of the electr propulsion subsystem. system. Due to the dep currently rated as prob	ical boards which control However, a working desig endence on as yet untest able.	the thrusters gn is necessar ed electronics	are not unde y for the pro the probabili	er the conti oper functic ity of proble
Physical Mitigation	Change out non working	valves.			
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and en 'flat sat' configuration. o the proper authorities. d and then retested until	eration is nec d with system Any deviation Electrical pro I nominal oper	essary. Suc level testing s from nomi blems docun ation is achie	h testing w g of the elec nal operationented in the eved.
Prost-mitigation Clas	ssification				
Severity Classification	Negligible	Probability Classificatio Remote		RAC	4

Hazard Numb	eProp-083	Final RAC	4
Hazard Name	Tr07 Locked Open	Part Name	Tr07 (TrL3a-01)
Pre-mitigation Classi	ification		
Severity Classification	Probability Negligible Classificatio	Remote	RAC 4
Hazard Analysis			
Causes	The Lee Valve designed is a 'fail safe' des continually supplied to the solenoid. The position is a defective part.	ign in that the valve is de refore, most likely cause	signed to close if pov of a valve stuck in t
Consequences	The consequences of such a failure would valves. The thruster would be activated from the nozzle; thus causing the satellite During testing, this failure mode would r greater than expected.	be felt immediately upor and a continuous stream e to translate unexpected elease propellant into the	n opening the two isc of propellant would Ily along the negative e testing area in ame
Probability	Due to the fail safe nature of the design, will be stuck in the open position.	it is considered a remote	e possibility that the
Physical Mitigation	All defective valves discovered in the tes	sting process will be repla	aced.
Procedural Mitigation	Thorough testing of all valves will be cor as the fume hood present in the SSE lab) from nominal operation will be recorded achieve nominal operation will be replac	nducted. All testing will to mitigate the risk of p and reported to the pro e.	occur in well ventilar ropellant exposure. , per authorities. All v
Prost-mitigation Clas	ssification		
Severity Classification	Probability Negligible Classificatio	Remote	RAC 4

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Hazard Numb	elProp-084		Final RAC	4
Hazard Name	Tr07 Clogged		Part Name	Tr07 (TrL3a-01)
Pre-mitigation Class	ification			
Severity Classification	Negligible	Probability Classificatio Frequen	t	RAC 3
Hazard Analysis				
Causes	The inner mechanisms of easily clogged with fore construction process su	of the valves as well as th eign material present with uch as metallic shavings)	e throat of the n hin the propellan	iozzle are extremely it lines. (Left over r
Consequences	Foreign material lodged lock the valve in either would prevent propellan	within the valve can inte the open or closed position It flow and end the useful	erfere with the w on. Foreign mate Iness of the thrus	orkings of the intern erial lodged within the ster.
Probability	Since all parts of the pr the propellant lines can likely to be a frequent o	opulsion system are mac not be discounted. Witho occurrence.	hined, the possil out mitigation a c	bility of foreign debr clog of the valve and/
Physical	Fine mesh filters added	before each valve within	the system will	capture any debris b
Mitigation	interfere with the inter	nal workings of the valve	e.	
Procedural	Each part will be cleane	ed with isopropyl alcohol	prior to incorpo	ration within the sys
Mitigation	should limit the remain	וווש מפטרוג.		
Prost-mitigation Cla	ssification			

Severity
ClassificationProbability
RemoteRAC4

Hazard Numb	Prop-085	Final RAC	3
Hazard Name	Tr07 Burst	Part Name	Tr07 (TrL3a-01)
Pre-mitigation Classi	ification		
Severity Classification	Probability Critical Classificatio Remote	9	RAC 3
Hazard Analysis			
Causes	For the thruster to burst, it would have to experience pressure. Additionally, over heating of the value rupture.	erience a prope could cause th	llant pressure greater i e outer casing of the va
Consequences	If Thruster Tr07 was to burst, the resulting pro trigger a safe mode within the satellite. Thus, t ended prematurely and extended mission operat happen during testing, the resulting propellant I and increase the risk of exposure.	pellant loss wo he formation fl ions would be i oss could relea	uld send the satellite o ight portion of the miss n jeopardy. Should the se unexpected amounts
Probability	Valve rupture due to over pressurization is a rer associated with the valve. The valve is rated to the pressure regulator, at the 100 psi setting, the FOS is still a respectable 3.66. Valve rupture due possibility based upon the expected temperature and has been observed during functional testing greater than 100 C.	mote possibility 1125 psi; there the FOS is great ue to over heat e range for the by MAS to fun	due to the high factor fore even discounting t ter than 11. For the 30 ing is also considered a mission. The valve is ra ction properly at tempe
Physical Mitigation	Physical mitigation is not necessary in this case risk down to acceptable levels for flight.	as the factors o	of safety are sufficient
Procedural Mitigation	Procedural mitigation comes in the form of ensu within the system and that all procedures (asso of the procedure will be signed off by the perfo to ensure the procedure is followed correctly. appropriate authorities. Additionally, all system such as the fume hood in the SSE lab.	uring that the c embly, filling, e rming technicia All deviations a n testing will be	correct propellant mass tc.) are performed corr n and a quality assuran nd problems will be rep conducted in a well v
Prost-mitigation Clas	ssification		
Severity Classification	Critical Probability Classificatio Remote	9	RAC 3

Hazard Numb	Prop-086				Final RAC	4	ł
Hazard Name	Tr07 leak				Part Name	Tr07 (TrL3a-01)
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona		RAC	4
Hazard Analysis							
Causes	The most likel the Swagelok c	y cause of connection	f a noticeable le	eak stemm	ing from the	thruster TrC)7 is improț
Consequences	A leak at this p activated and which would le pressure just b propulsive ma	point in th formation essen the a pefore the neuvers.	e system would flight implemer amount of time nozzle would r	I not pose ited. At th available t educe the	a problem un nat point the for formation thrust produ	itil the propu leak would ca flight. Addi iced by this t	lsion syster ause propel itionally, th thruster and
Probability	When assembl followed exact situations can	ing a syste ly and ste occur.	em, human erro ps are not take	r has to be n to ensur	e taken into a e their correc	iccount. If pi	rocedures a ation, hazai
Physical Mitigation	No physical m	itigation is	s possible for t	his hazard			
Procedural Mitigation	The prevention tightening proc step by step m assembly proc technician to e reported to th controlled mar	n of leaks cedures ar anner the edure will ensure the e appropr nner to en	stemming from re followed. As: proper method be signed off k procedure is f iate authorities sure any poten	n improper sembly pro of tighteni by the perf collowed co s. Addition tial leak is	connections ocedures have ng each conn forming techr prrectly. All o hally, the fina addressed pr	requires tha e been develo ection point. nician and a o deviations ar I assembly v rior to launch	t the manu oped which Each step quality assu d problems vill be press n.
Prost-mitigation Clas	ssification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-087				Final RAC	Z	ł
Hazard Name	Voltage step-	down m	alfunction		Part Name	Tr07 (TrL3a-01)
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Probable)	RAC	3
Hazard Analysis							
Causes	The voltage ste cause of the fa electronics boa	ep-down i ilure of vo ard either	s accomplished oltage step-do due to compo	l by the pro wn for the nent malfu	opulsion elect isolation valve nction or imp	ronics board e would be tl roper design	. The most he failure of
Consequences	The Lee valves then stepped d within the time heat and possi	used for own to 5 specified bly ruptu	the MR SAT provide the MR SAT provides to mainta , the excess volume the excess volu	opulsion sy: in the open Itage could	stem rely on a state. If the destroy the s	a 24 V pulse step-down p solenoid and	to open. T rocess does cause the v
Probability	The design of t the propulsion system. Due to currently rated	the electr subsyste the depo as prob	ical boards whi m. However, a endence on as able.	ch control a working d yet unteste	the isolation s esign is nece ed electronics	valves are no ssary for the the probabil	ot under the proper fur ity of proble
Physical Mitigation	A properly desi remote.	igned elec	ctronics board	controlling	the system o	could reduce	the probab
Procedural Mitigation	Thorough testi functional testi valves integrat recorded and re process will be	ng of all o ng of the ed into a eported t addresse	electronics for board electror 'flat sat' confi o the proper a d and then ret	proper open nics and end guration. A uthorities. ested until	eration is nec d with system Any deviatior Electrical pro nominal oper	essary. Suc a level testing as from nomi blems docur ation is achie	h testing w 3 of the elec nal operation nented in the eved.
Prost-mitigation Clas	ssification						
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-088		Final RAC	4
Hazard Name	Tr08 stuck closed		Part Name	Tr08 (TrL3b-01)
Pre-mitigation Classi	fication			
Severity Classification	Negligible	Probability Classificatio Probabl	e	RAC 3
Hazard Analysis				
Causes	The most likely cause for preventing the opening pulse required for openi	or a thruster valve being of the valve. This could l ng, or physical damage t	locked in the clo be the electrical k o the internal sol	esed position is an ele poard never sending enoid of the valve.
Consequences	Thruster Tr08 is responsi rotation maneuvers aroun maneuverability in the neg to be canceled out and th in the negative x direction personnel.	ble for providing the count d the y and z axes (positiv gative x direction. With Tr he satellite would deviate fr h would be impaired. This h	ter force necessar ve x axis directed t 08 stuck closed, t rom the formation nazard presents no	y to prevent translation chrough panel 4) and t the translational force . Additionally, translat danger to equipment
Probability	The design of the electr propulsion subsystem. system. Due to the dep currently rated as prob	ical boards which control However, a working desig endence on as yet untest able.	the thrusters are gn is necessary f ed electronics the	e not under the contr or the proper functic e probability of proble
Physical Mitigation	Change out non working	valves.		
Procedural Mitigation	Thorough testing of all functional testing of the valves integrated into a recorded and reported t process will be addresse	electronics for proper op board electronics and en 'flat sat' configuration. to the proper authorities. ad and then retested unti	peration is necess ad with system lev Any deviations f Electrical proble I nominal operation	sary. Such testing w vel testing of the elec rom nominal operation ms documented in the on is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Negligible	Probability Classificatio Remote		RAC 4

Hazard Numb	Prop-089		Final	RAC	4
Hazard Name	Tr08 Locked Ope	en	Part N	lame Tr08	8 (TrL3b-01)
Pre-mitigation Classi	fication				
Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4
Hazard Analysis					
Causes	The Lee Valve desi continually supplie position is a defec	gned is a 'fail safe' de d to the solenoid. Th tive part.	sign in that the va erefore, most like	alve is designed ely cause of a v	to close if pov alve stuck in t
Consequences	The consequences valves. The thrus from the nozzle; th During testing, thi greater than expec	of such a failure woul ter would be activated nus causing the satelli s failure mode would ted.	d be felt immedia d and a continuou te to translate un release propellan	tely upon open s stream of pro expectedly alor t into the testi	ing the two isc opellant would ng the negative ng area in ame
Probability	Due to the fail safe will be stuck in the	e nature of the desigr e open position.	ı, it is considered	a remote possi	bility that the
Physical	All defective value	a discovered in the te	eting process will	l bo roplacod	
Mitigation		s discovered in the te	sung process wi	i be replaced.	
Procedural Mitigation	Thorough testing as the fume hood from nominal oper achieve nominal o	of all valves will be co present in the SSE lab ation will be recorded peration will be repla	onducted. All tes) to mitigate the I and reported to ce.	ting will occur risk of propella the proper au	in well ventilat nt exposure thorities. All v
Prost-mitigation Clas	ssification				

Hazard Numb	Prop-090	F	Final RAC	4	
Hazard Name	Tr08 Clogged	Pa	art Name	Tr08 (T	rL3b-01)
Pre-mitigation Class	fication				
Severity Classification	Negligible Probab	lity atio Frequent		RAC	3
Hazard Analysis					
Causes	The inner mechanisms of the valve easily clogged with foreign mater construction process such as met	es as well as the th ial present within allic shavings)	nroat of the the the propella	nozzle are e nt lines. (L	extremely .eft over r
Consequences	Foreign material lodged within the lock the valve in either the open of would prevent propellant flow and	valve can interfe r closed position. end the usefulnes	re with the v Foreign mat ss of the thru	vorkings of erial lodged ıster.	the intern I within the
Probability	Since all parts of the propulsion s the propellant lines can not be disc likely to be a frequent occurrence	ystem are machin counted. Without	ed, the poss mitigation a	ibility of for clog of the	reign debr valve and/
Physical	Fine mesh filters added before ear	ch valve within the	e system will	capture an	v debris b
Mitigation	interfere with the internal workin	gs of the valve.			
Procedural	Each part will be cleaned with iso	propyl alcohol prio	or to incorpo	oration with	in the sys
Mitigation	should limit the remaining debris				
Prost-mitigation Cla	ssification				

Severity
ClassificationProbability
RemoteRAC4

Hazard Numb	Prop-091		Final RAC	3
Hazard Name	Tr08 Burst		Part Name	Tr08 (TrL3b-01)
Pre-mitigation Class	fication			
Severity Classification	Critical Pro	bability ssificatio Remote		RAC 3
Hazard Analysis				
Causes	For the thruster to burst, it v pressure. Additionally, over h rupture.	vould have to exper eating of the valve o	ience a propel could cause the	lant pressure greater t e outer casing of the va
Consequences	If Thruster Tr08 was to burst trigger a safe mode within th ended prematurely and exten happen during testing, the re and increase the risk of expos	, the resulting prop e satellite. Thus, th ded mission operations sulting propellant loss sure.	ellant loss wou e formation flig ons would be ir ss could releas	Ild send the satellite o ght portion of the miss a jeopardy. Should the e unexpected amounts
Probability	Valve rupture due to over pre associated with the valve. Th the pressure regulator, at the FOS is still a respectable 3.66 possibility based upon the exp and has been observed during greater than 100 C.	essurization is a rem e valve is rated to 1 e 100 psi setting, th 5. Valve rupture due pected temperature g functional testing b	ote possibility 125 psi; there le FOS is great to over heatin range for the r by MAS to func	due to the high factor fore even discounting t er than 11. For the 30 ng is also considered a mission. The valve is ra ction properly at tempe
Physical Mitigation	Physical mitigation is not neco risk down to acceptable level	essary in this case a s for flight.	s the factors o	f safety are sufficient
Procedural Mitigation	Procedural mitigation comes within the system and that a of the procedure will be signe to ensure the procedure is fo appropriate authorities. Add such as the fume hood in the s	in the form of ensur Il procedures (asser ed off by the perforr llowed correctly. Al itionally, all system SSE lab.	ing that the co mbly, filling, et ning techniciar Il deviations an testing will be	orrect propellant mass c.) are performed con n and a quality assuran nd problems will be rep conducted in a well v
Prost-mitigation Cla	sification			
Severity Classification	Critical Pro	bability ssificatio Remote		RAC 3

Hazard Numb	Prop-092				Final RAC	۷	ł
Hazard Name	Tr08 leak				Part Name	Tr08 (TrL3b-01)
Pre-mitigation Classi	fication						
Severity Classification	Marginal		Probability Classificatio	Occasiona	al	RAC	4
Hazard Analysis							
Causes	The most likel <u></u> the Swagelok c	y cause of onnection	f a noticeable le	eak stemm	ing from the	thruster Tr()7 is improț
Consequences	A leak at this p activated and t which would le pressure just b propulsive ma	point in th formation ssen the pefore the neuvers.	e system would flight implemer amount of time nozzle would r	I not pose nted. At th available reduce the	a problem un nat point the for formation thrust produ	itil the propu leak would ca flight. Add liced by this t	lsion syster ause propel itionally, th thruster and
Probability	When assembli followed exact situations can	ing a systo ly and ste occur.	em, human errc ps are not take	n has to be n to ensur	e taken into a e their correc	iccount. If p t implement	rocedures a ation, hazai
Physical Mitigation	No physical mi	itigation i	s possible for t	his hazard			
Procedural Mitigation	The prevention tightening proc step by step m assembly proc technician to e reported to th controlled mar	n of leaks cedures ar lanner the edure will ensure the e appropr nner to en	stemming from re followed. As proper method be signed off I e procedure is f riate authorities sure any poten	n improper sembly pro of tighteni by the perf followed co s. Addition tial leak is	connections ocedures have ing each conn forming techr prrectly. All o hally, the fina addressed pr	requires tha e been develo ection point. nician and a deviations ar I assembly v rior to launch	t the manu oped which Each step quality assu d problems vill be press n.
Prost-mitigation Clas	sification				-		
Severity Classification	Marginal		Probability Classificatio	Remote		RAC	4

Hazard Numb	Prop-093		Final RAC	4
Hazard Name	Voltage step-down ma	lfunction	Part Name	Tr08 (TrL3b-01)
Pre-mitigation Classi	fication		-	
Severity Classification	Marginal	Probability Classificatio Probable	9	RAC 3
Hazard Analysis				
Causes	The voltage step-down is cause of the failure of vo electronics board either o	accomplished by the pro ltage step-down for the lue to component malfu	opulsion electroi isolation valve v nction or improp	nics board. The most vould be the failure of per design.
Consequences	The Lee valves used for t then stepped down to 5 v within the time specified, heat and possibly rupture	he MR SAT propulsion sy olts to maintain the oper the excess voltage could a.	rstem rely on a 2 1 state. If the sto 1 destroy the sol	24 V pulse to open. T ep-down process does enoid and cause the v
Probability	The design of the electric the propulsion subsystem system. Due to the deper currently rated as proba	al boards which control n. However, a working c ndence on as yet untesto ble.	the isolation val lesign is necessa ed electronics th	ves are not under the ary for the proper fur le probability of proble
Physical Mitigation	A properly designed elect remote.	ronics board controlling	the system cou	Ild reduce the probab
Procedural Mitigation	Thorough testing of all e functional testing of the k valves integrated into a ' recorded and reported to process will be addressed	lectronics for proper op board electronics and en- flat sat' configuration. the proper authorities. I and then retested until	eration is neces d with system le Any deviations Electrical proble nominal operat	sary. Such testing weight testing of the electron from nominal operation operation of the decomposition operation is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Marginal	Probability Classificatio Remote		RAC 4

Hazard Numb	Prop-094	Final RAC	3
Hazard Name	SS Tubing Burst	Part Name	Variable Prop Lines
Pre-mitigation Classi	fication	-	
Severity Classification	Critical Probability Classification	Remote	RAC 3
Hazard Analysis			
Causes	For the MR SAT propellant lines to bu its yield point by the pressure within	rst, the stainless steal ma the lines.	terial would have to be
Consequences	A rupture of the propellant lines woul a consequence, the satellite mission to flying debris and possible injury to	d cause the release of pro likely would end in failure testing personnel or han	opellant in an undirecte . During testing, ruptu m to surrounding equip
Probability	Propellant line rupture due to over pr safety associated with the valve. The 100 psi setting, the FOS is greater th 32.57.	ressurization is a remote p e stainless steel lines are rainan 100. For the 307 psi	possibility due to the h ated to 10000 psi; the setting, the FOS is stil
Physical Mitigation	Physical mitigation is not necessary in risk down to acceptable levels for flig	this case as the factors on the factors of the fact	of safety are sufficient
Procedural Mitigation	Procedural mitigation comes in the for within the system and that all proced of the procedure will be signed off by to ensure the procedure is followed of appropriate authorities. Additionally, such as the fume hood in the SSE lab.	orm of ensuring that the c dures (assembly, filling, et the performing technicia orrectly. All deviations an all system testing will be	orrect propellant mass tc.) are performed corr n and a quality assuran nd problems will be rep e conducted in a well v
Prost-mitigation Clas	ssification		
Severity Classification	Critical Probability	Remote	RAC 3

Hazard Numb	Prop-095		Final RAC	3
Hazard Name	Tank Heater (HTk0	01) Stuck On	Part Name	HTk01
Pre-mitigation Classi	fication			
Severity Classification	Critical	Probability Classificatio Pr	obable	RAC 2
Hazard Analysis				
Causes	The tank heater stuc error within the cont	k in the on position co rol code.	uld be caused by eith	ner an electrical malfur
Consequences	The tank heater stuc over heating of the p heater itself could be phase change of the	k in the on position co propellant which could l damaged, limiting the propellant.	uld have several poss ead to over pressuriz systems response to	ible consequences. Th zation of the tank. See o temperature loss and
Probability	The design of the ele propulsion subsyster system. Due to the o currently rated as p	ectrical boards which co n. However, a working dependence on as yet u robable.	ontrol the heaters are design is necessary intested electronics t	not under the control for the proper functic he probability of proble
Physical Mitigation	A properly designed remote.	electronics board cont	rolling the system cc	ould reduce the probab
Procedural Mitigation	Thorough testing of functional testing of heaters integrated ir recorded and reporte process will be addre	all electronics for prop the board electronics a nto a 'flat sat' configur ed to the proper autho essed and then reteste	per operation is nece and end with system l ation. Any deviation rities. Electrical prob d until nominal opera	ssary. Such testing w evel testing of the elect is from nominal operat lems documented in th tion is achieved.
Prost-mitigation Clas	ssification			
Severity Classification	Critical	Probability Classificatio	emote	RAC 3

Hazard Numb	elProp-096		Final RAC	4	
Hazard Name	Tank Heater (HTk01)	Non-Function	Part Name	HTk01	
Pre-mitigation Class	ification				
Severity Classification	Marginal	Probability Classificatio Prob	able	RAC	3
Hazard Analysis					
Causes	The tank heater failing within the control code.	to turn on could be ca	used by either a	n electrical malfuno	ction
Consequences	While propellant freezin mission, low propellant change from occurring	g is not a major conce temperature within th and thus severely limit	ern given the terr e storage tank w t system perforn	perature range exp ould prevent the n nance.	pecte ieces
Probability	The design of the electr propulsion subsystem. system. Due to the dep currently rated as prob	ical boards which cont However, a working d pendence on as yet unt pable.	rol the heaters an esign is necessar ested electronics	e not under the co y for the proper fu the probability of p	ontrol unctic oroble
Physical Mitigation	A properly designed ele remote.	ctronics board control	ling the system o	ould reduce the pr	robab
Procedural	Thorough testing of all	electronics for proper	operation is nec	essary. Such test	ina w
Mitigation	functional testing of the heaters integrated into recorded and reported to process will be addresse	e board electronics and a 'flat sat' configurati to the proper authoriti ed and then retested u	end with system on. Any deviatic es. Electrical pro Intil nominal oper	level testing of th ns from nominal of blems documented ation is achieved.	e elec perat d in th
Prost-mitigation Cla	ssification				
Severity Classification	marginal	Probability Classificatio Remo	ote	RAC	4

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VITA

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While Attending UMR, Joe was a member of AIAA and president of Sigma Gamma Tau. He also participated in the UMR Satellite Program as a member of the Propulsion subsystem; taking over as subsystem lead in the fall of 2006.