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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

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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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Much appreciation and many thanks must be given to the members, both past and present, of the M-SAT design team. The success of the project could not have occurred without the hard work of those individuals who gave their time, efforts, and passion to a goal that often seemed out of reach. Such people kept the team moving forward and provided the base upon which future projects will be built.

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.

Table 1.1: Satellite Classification System [1]

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

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 ± 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.

Table 1.2 Sealed Container Classification Limits [2]

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

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 developments. The work is further expanded to include a hazard analysis and a 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.

Table 2.1: Expected I_{sp} Ranges for Propulsion Systems [6]

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

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 (SF_6) as a propellant. As designed, the 10 mL propellant tank stored sufficient SF_6 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 cm^3. 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 ±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, μPPTs 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, μPPTs would be a possibility for the attitude control requirement. For this reason, a prototype μPPT 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 non-reactive, 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.

Table 3.1: Propellant Tank Requirements [21]

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.

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.

Table 3.2: Flight Tank Specifications [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	

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.

Table 3.3: Isolation Valve Requirements

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.

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.

Table 3.4: MR SAT Valve Specifications [22]

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

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.

Table 3.5: Pressure Regulator Requirements

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 with R-134a	Many regulators have internal components of plastic or rubber which must be compatible with the propellant
Low pressure setting	A lower regulated pressure reduces the impulse of each thruster firing, and thus allows for more 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.

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.

Table 3.6: MR SAT Pressure Regulator Specifications [22]

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 x 10^{-9} std. cm^3/sec

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.

Table 3.7: Configuration Requirements for Thruster Assembly

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 solar cells being contaminated by R-134a.
Allow for straightforward propellant line attachment	The propellant lines must be connected to the thruster in a manner that provides support for the lines.

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.

Table 3.8: Nozzle Design Requirements

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.
Simple interior shape	Complex interior surfaces are difficult to accurately manufacture due to the small part size. 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.

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.

Figure 3.7: Nozzle Schematic

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.

Table 3.9: Propellant Line and Fitting Requirements

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.

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.

Table 3.10: Propellant Tank and Line Heater Requirements

Requirement	Reason
Low power consumption	The power of any satellite is limited and each component must minimize the power consumed.
Made of low-outgassing material	Low-outgassing materials are mandated by the 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.

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.

Table 3.11: Heater Specifications [21]

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

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.

Table 3.12: Pressure Transducer Requirements

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.

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.

Table 3.13: Pressure Transducer Specifications [22]

Pressure range	0 – 200 psia (0 – 1378.96 kPa)
Mass	140 g
Operating temperature range	-54 °C – 121 °C
Casing material	Stainless Steel
Connection type	7/16-20 UNF
Electrical connection	PRIH-10-6P

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

"Refrigerant Based Propulsion System for Small Spacecraft;" however, the basic assumptions and results are listed below.

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.

Table 3.14: Predicted Thrust Performance

I_{SP}	43.71 sec
Thrust	37.37 mN
Mass flow rate	0.0889 g/s

Table 3.15: Predicted ΔV Performance for Three Pressure Regimes

Max Tank Pressure at 100 °C (psi)	ΔV (m/s)	Total Thrust Exhaust 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 auto-ignition. 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.

Table 4.1: SAWP Hazard Classification Matrix

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

Table 4.1 SAWP Hazard Classification Matrix (Cont.)

Hazard	Classification	Associated Risk	Methods of Mitigation	Reclassification After Mitigation
Propellant Leakage	Critical	Risks of exposure to propellant: Ground operations and flight materials	Methods for exposure to propellant: ground operations and flight materials. Selection of connections with minimized leak rates. Selection of system materials with appropriate factor of safety to ensure a high leak-before-burst point.	Tolerable
Exposure to Propellant: Ground Operations	Tolerable	Skin irritation and/or frostbite Asphyxiation	Post warnings of exposure hazard Wear suitable skin protection and eyewear and implement approved ventilation	Tolerable
Material Elongation	Critical	Added stress at connections Possible leaks and/or burst	Properly selecting fittings	Tolerable
Different Material Thermal Expansions Rates and/or Thermal Gradients	Critical	Possible leaks	Properly select materials	Tolerable

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 Temperature 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 Mitigation
Thermal Increase	Catastrophic	Risks of system pressure increase Risks of material elongation Risks of different thermal expansion rates and/or thermal gradient Risks of decomposition Risks of fire and/or auto-ignition	Methods for pressure increase Methods for material elongation Methods for different material thermal expansion rates and/or thermal gradient Methods for decomposition Methods for fire and/or auto-ignition	Catastrophic
Propellant Freezing	Critical	Potential damage to internal mechanics of system components Reduced effectiveness of internal mechanics of system	Apply active thermal controls (i.e. heaters) during propellant storage Insulation Temperature monitoring	Tolerable
Fire and/or Auto-ignition	Catastrophic	Possible fire with exposure to high concentrations of Oxygen and ignition source	Avoid high temperatures, high concentration of Oxygen, ignition sources, and use proper storage procedures	Catastrophic

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 4.2. Hazard Severity Classifications [25]

Description	Category	Environmental, Safety, and Health Result Criteria
Catastrophic	I	Could result in death, permanent total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation.
Critical	II	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	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.
Negligible	IV	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.

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.

Table 4.3: Probability Estimate Classification [25]

Description	Category	Applicable Criteria
Frequent	A	Likely to occur often during the operational lifetime of the system, with a probability of occurrence greater than 10^{-1} in that life.
Probable	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	C	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 4.4: 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.

Table 5.1: Experiment Loading Requirements

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

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 Numbe	Prop-001	Final RAC	3
Hazard Name	Propellant Tank Rupture	Part Name	Tk01

Pre-mitigation Classification

Severity Classification	Catastrophic	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

Propellant tank rupture is caused by the structural failure of the tank. The most lik
such an occurrence is the propellant pressure exceeding the yield point of the tank m

Consequences

The rupture of the propellant tank would be an extremely dangerous situation. It inv
spontaneous and sudden release all propellant stored within the propellant tank. The
a release could severely damage nearby equipment (including satellite and launch veh
equipment) and cause injury or death to personnel.

Probability

The probability of propellant tank rupture within the MR SAT propulsion system is c
remote. This is mainly due to the limited propellant mass which is to be stored withi
the 100 psi equivalent point, a FOS greater than 14 is achieved with regard to the th
Pressure (1421 psi) for the Marrotta tank and a FOS greater than 2 exists with rega
pressure (235 psi). At the maximum operational pressure being considered (307 ps
greater than 4 is still achieved.

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 Mitigation

Maintaining the factors of safety within the propellant tank requires that the specifie
mass be added to the tank. Filling procedures have been developed that incorporate m
measuring equipment to ensure the correct propellant mass is added. These procedu
implemented each time the propellant tank is charged with propellant. Each step of
procedure will be signed off by the performing technician and a quality assurance tec
ensure the procedure is followed correctly. All deviations and problems will be repor
appropriate authorities.

Prost-mitigation Classification

Severity Classification	Catastrophic	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-002	Final RAC	3
Hazard Name	Propellant Tank Leak	Part Name	Tk01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	A leak from the propellant tank could be caused by two possible failures. The first f the yielding of the tank material in a manner that allows propellant to slowly be expe pressurized tank. The second failure involves the inadequate tightening of the fittings and outlet end of the tank.
Consequences	A leak of the propellant from the tank during flight would immediately put the succes completion of mission objectives in jeopardy due to lack of sufficient propellant to co maneuvers. Additionally, leaked propellant could interact with nearby materials to th said materials. Finally, should the leak occur during testing or loading, nearby perso exposed to R-134a which can cause skin irritation, frost-bite, or asphyxiation in en
Probability	The first failure mode is considered unlikely due to the factory testing performed by (leak test performed using He and proof tested to 16 bar) and due to the high factors o within the system. The second failure mode is considered more likely to occur if suff procedures and quality assurance policies are not implemented.
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 Mitigation	Maintaining the factors of safety within the propellant tank requires that the specifie mass be added to the tank. Filling procedures have been developed that incorporate m measuring equipment to ensure the correct propellant mass is added. These procedu implemented each time the propellant tank is charged with propellant. Each step of t procedure will be signed off by the performing technician and a quality assurance tec ensure the procedure is followed correctly. All deviations and problems will be repor appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Number	prop-003	Final RAC	3
Hazard Name	Special Elbow Fitting Material Yield	Part Name	ESML01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	For the material of the special elbow fitting to experience yield, the pressure seen by would have to greatly exceed the specified ranges for this mission.
Consequences	Should the material of the special elbow fitting yield, at minimum the resulting prope would put the successful completion of mission objectives in doubt. Additionally, dama occur to surrounding equipment and personnel should the release of propellant result flying parts.
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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass 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 assuran to ensure the procedure is followed correctly. All deviations and problems will be rep appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	prop-004	Final RAC	4
Hazard Name	Special Elbow Fitting Leak	Part Name	ESML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most obvious cause for a loss of propellant stemming from the special elbow is th tightening at the connection points of the fitting.
Consequences	Leaks both small and large at this point of the system will have detrimental effects on performance of system objectives. Leaks stemming from such a cause would not have nature of a rupture and as such are less likely to cause damage. However, leaking pro increase risk of asphyxiation and propellant reactions with nearby materials.
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, hazar situations can occur.
Physical Mitigation	Physical mitigation is not possible for this hazard.
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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-005	Final RAC	4
Hazard Name	TML01 leak	Part Name	TML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes

The most probable cause for a loss of propellant stemming from the first Swagelok Te
improper tightening at the connection points of the fitting. Additionally, the manufac
tubing connection also can have an effect on the connection point since for a proper se
the tubing needs to have a smooth, flat end.

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. Also, any lo
reduces the chances of mission success.

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 Mitigation

Ensuring the tubing connected to the Tee fitting is correctly manufactured with flat an
ends.

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 problem
reported to the appropriate authorities. Additionally, the final assembly will be pres
controlled manner to ensure any potential leak is addressed prior to launch.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-006	Final RAC	3
Hazard Name	TML01 Rupture	Part Name	TML01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	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
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.

Procedural Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-007	Final RAC	4
Hazard Name	CpML01 Leak	Part Name	CpML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	As with all fittings the most likely cause of a leak is an improper connection.
Consequences	Leaks both small and large at this point of the system will have detrimental effects on performance of system objectives. Additionally, leaking propellant could increase ris asphyxiation and propellant reactions with nearby materials.
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 Mitigation	No physical mitigation is possible for this hazard.
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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Number	Prop-008	Final RAC	3
Hazard Name	CpML01 Rupture	Part Name	CpML01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	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 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.
Procedural Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass 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 assuran to ensure the procedure is followed correctly. All deviations and problems will be rep appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-009	Final RAC	4
Hazard Name	CpML01 Bending/Crimping	Part Name	CpML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Frequent	RAC	2

Hazard Analysis

Causes	The two sections of the coupling are connected by a very narrow (1/16" OD) tubing v be bent if excessive stress is placed upon it during assembly (tightening of fittings)
Consequences	A bending of the tubing could cause the tubing to crimp which would cut off the attach transducer from the system. Without the pressure transducer reading tank conditions monitored which could increase the subsequent risk of hazards.
Probability	The delicate nature of the connecting tubing means that it is very susceptible to being much stress is applied to the tubing during the assembly process the tubing will bend crimp.
Physical Mitigation	Should a bend occur during the assembly process a new part will be substituted for the part.
Procedural Mitigation	The assembly procedures for this connection are designed to minimize the force place tubing by isolating the tubing during the tightening process with the aid of a vice. Eac procedure will be signed off by the performing technician and a quality assurance tec ensure the procedure is followed correctly. All deviations and problems will be report appropriate authorities.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Numbe	Prop-010	Final RAC	4
Hazard Name	PtML01 electrical failure	Part Name	PtML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The pressure transducers require specific voltages and power levels to maintain prop The electrical conditioning could be altered by flaws in the circuitry or problems with wires.
Consequences	Should the electronics of the first pressure transducer fail, the tank pressure would unmonitored for the duration of the mission. This could allow a potentially hazardous go unnoticed and have detrimental effects on the mission.
Probability	The possibility of an electrical failure cannot be entirely discounted; however, such de detected during testing in a safe manner. Therefore, the probability of electrical failu dangerous situation is considered remote.
Physical Mitigation	The boards will be designed in such a way that the pressure transducers receive the p they need to accurately record the tank pressure.
Procedural Mitigation	In order to prevent a possible hazard, the electronics connected to the pressure trans thoroughly tested prior to charging the tank. Any and all defects or discrepancies will and reported to the proper authorities.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-011	Final RAC	4 (for 100 psi)
Hazard Name	PtML01 Burst	Part Name	PtML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	? ?	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
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 Mitigation

If tank pressure greater than 100 psi are to be used for the MR SAT propulsion syster
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 proc
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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote (100 ps	RAC	4 (100 ps

Hazard Number	Prop-012	Final RAC	4
Hazard Name	VML01 stuck closed	Part Name	VML01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The most likely cause for an isolation valve being locked in the closed position is an e problem preventing the opening of the valve. This could be the electrical board never 24 volt pulse required for opening, or physical damage to the internal solenoid of the
Consequences	With the first isolation valve stuck in the closed position, formation flight is unachiev there is not a potential risk of injury or further equipment damage associated with th
Probability	The design of the electrical boards which control the isolation valves are not under the the propulsion subsystem. However, a working design is necessary for the proper fu system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	Change out non working valves.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in t process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-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 that the valve is designed to close if po continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	With the valve stuck in the open position, the tank's isolation from the rest of the sys along with one of the three system inhibits. This is not directly detrimental to missio the first isolation valve is to remain open throughout the period of formation flight a however, the lack of isolation of the tank prior to the start of formation flight increas probability of propellant loss due to connection leakage (as the propellant is exposed t
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. Any deviations from nominal operat recorded and reported to the proper authorities. All valves failing to achieve nomina be replace.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-014	Final RAC	4
Hazard Name	VML01 Clogged	Part Name	VML01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the isolation valves are extremely narrow and easily clogge 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-015	Final RAC	3
Hazard Name	VML01 Burst	Part Name	VML01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	For the isolation valve to burst, it would have to experience a propellant pressure gre yield pressure. Additionally, over heating of the valve could cause the outer casing of rupture.
Consequences	A rupture of the first isolation valve would release most of the stored propellant and any chance of mission success. Also, such a release of energy could cause damage to ne equipment and injuries to nearby personnel.
Probability	Valve rupture due to over pressurization is a remote possibility due to the high factor associated with the valve. The valve is rated to 1125 psi; therefore, at the 100 psi se greater than 11. For the 307 psi setting, the FOS is still a respectable 3.66. Valve r over heating is also considered a remote possibility based upon the expected temperat the mission. The valve is rated to 70 C and has been observed during functional testin function properly at temperatures greater than 100 C.
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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass within the system and that all procedures (assembly, filling, etc.) are performed corr 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 appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-016	Final RAC	4
Hazard Name	VML01 leak	Part Name	VML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability 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 Mitigation	No physical mitigation is possible for this hazard.
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 problem reported to the appropriate authorities. Additionally, the final assembly will be pres controlled manner to ensure any potential leak is addressed prior to launch.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-017	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	VML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under the the propulsion subsystem. However, a working design is necessary for the proper fun system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-018	Final RAC	3
Hazard Name	RML01 burst	Part Name	RML01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

The rupture of the pressure regulator would be caused by an over pressurization of th
which results in material yield.

Consequences

Should the material of the pressure regulator yield, at minimum the resulting propel
put the successful completion of mission objectives in doubt. Additionally, damage co
surrounding equipment and personnel should the release of propellant result in shra
parts.

Probability

The inlet portion of the pressure regulator is rated to 1000 psi. Therefore at the 10
mark a FOS of 10 exists. At the maximum pressure being considered for the system
of 3.25 is maintained. Therefore, material yield is considered a remote possibility.

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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Number	Prop-019	Final RAC	4
Hazard Name	RML01 leak	Part Name	RML01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a noticeable leak stemming from the pressure regulator is i tightening of the Swagelok connections.
Consequences	Assuming the first isolation valve remains closed (and holds seal) until the beginning flight, a small leak at this point of the system would not prevent the implementation o flight, but could drastically reduce the duration which formation flight can be held. A would prevent formation flight being maintained for any meaningful duration.
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 Mitigation	No physical mitigation is possible for this hazard.
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 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	Remote	RAC	4

Hazard Numbe	Prop-020	Final RAC	4
Hazard Name	RML01 Failure to Regulate Pressur	Part Name	RML01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The pressure regulator is preset at the factory to a specific outlet pressure. For the to reduce outlet pressure, the internal mechanism of the regulator would have to fail.
Consequences	With out the benefit of pressure regulation, the remainder of the system would be expo pressure remaining in the tank. The exposure would not likely result in problems as components are rated to withstand the full system pressure. However, the loss of reg have a detrimental effect on system performance as the thrust produced by the nozzle continually be changing as the tank pressure is reduced.
Probability	The possibility of a factory defect is considered remote.
Physical Mitigation	No physical mitigation is possible in this case.
Procedural Mitigation	Thorough testing of the pressure regulator will be conducted. Any deviations from no operation will be recorded and reported to the proper authorities.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-021	Final RAC	4
Hazard Name	TML02 leak	Part Name	TML02

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes

The most probable cause for a loss of propellant stemming from the second Swagelok
the improper tightening at the connection points of the fitting. Additionally, the manu
tubing connection also can have an effect on the connection point since for a proper sea
the tubing needs to have a smooth, flat end.

Consequences

With the tee placed after the first isolation valve, a leak stemming from it will not ca
propellant loss before the beginning of formation flight (assuming the valve seal is m
However, any loss of propellant reduces the possible duration of the formation flight p
pressure loss associated with the leak would disrupt the readings of the second pressu
and affect the monitoring of the regulated pressure.

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, hazar
situations can occur.

Physical Mitigation

No physical mitigation is possible for this hazard.

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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-022	Final RAC	3
Hazard Name	TML02 Rupture	Part Name	TML02

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	The material yields due to excessive stress caused by over-pressurization
Consequences	A rupture could damage surrounding equipment such as the pressure transducer and l hazards. Additionally, the loss of propellant would end the mission.
Probability	The fitting in question is after the pressure regulation device within the system. The experience at most 24.7 psi of pressure which is well within the capabilities of the f the regulator should fail, the Swagelok fittings are rated to even higher pressures tha propellant tank. (~4000 psig) Therefore, the chance for material yield leading to lea 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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass within the system and that all procedures (assembly, filling, etc.) are performed corr 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 appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Number	Prop-023	Final RAC	4
Hazard Name	CpML02 Leak	Part Name	CpML02

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a leak regarding a Swagelok fitting is an improper connectior could be cause by either improper tightening or improper tubing construction.
Consequences	Given that the fitting in question is after the first isolation valve, propellant loss ster leak at this point of the system would not occur until formation flight had been engage a leak would limit the ability of the second pressure transducer to monitor regulated would reduce the time available for formation flight.
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, hazaı situations can occur.
Physical Mitigation	No physical mitigation is possible for this hazard.
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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-024	Final RAC	3
Hazard Name	CpML02 Rupture	Part Name	CpML02

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	The material yields due to excessive stress caused by over-pressurization
Consequences	A rupture could damage surrounding equipment such as the pressure transducer and l hazards. Additionally, the loss of propellant would end the mission.
Probability	The fitting in question is after the pressure regulation device within the system. The experience at most 24.7 psi of pressure which is well within the capabilities of the f the regulator should fail, the Swagelok fittings are rated to even higher pressures tha propellant tank. (~4000 psig) Therefore, the chance for material yield leading to lea 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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass within the system and that all procedures (assembly, filling, etc.) are performed corr 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 appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-025	Final RAC	4
Hazard Name	CpML02 Bending/Crimping	Part Name	CpML02

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Frequent	RAC	2

Hazard Analysis

Causes	The two sections of the coupling are connected by a very narrow (1/16" OD) tubing v be bent if excessive stress is placed upon it during assembly (tightening of fittings)
Consequences	A bending of the tubing could cause the tubing to crimp which would cut off the attach transducer from the system. Without the pressure transducer reading tank conditions monitored which could increase the subsequent risk of hazards.
Probability	The delicate nature of the connecting tubing means that it is very susceptible to being much stress is applied to the tubing during the assembly process the tubing will bend crimp.
Physical Mitigation	Should a bend occur during the assembly process a new part will be substituted for the part.
Procedural Mitigation	The assembly procedures for this connection are designed to minimize the force placed tubing by isolating the tubing during the tightening process with the aid of a vice. Eac procedure will be signed off by the performing technician and a quality assurance tec ensure the procedure is followed correctly. All deviations and problems will be report appropriate authorities.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Numbe Prop-026

Final RAC 4

Hazard Name PtML02 electrical failure

Part Name PtML02

Pre-mitigation Classification

Severity Classification	Marginal	**Probability Classificatio**	Remote	**RAC**	4

Hazard Analysis

Causes

The pressure transducers require specific voltages and power levels to maintain prop
The electrical conditioning could be altered by flaws in the circuitry or problems with
wires.

Consequences

Should the electronics of the second pressure transducer fail, the regulated pressure
unmonitored for the duration of the mission. This could allow a potentially hazardous
go unnoticed and have detrimental effects on the mission.

Probability

The possibility of an electrical failure cannot be entirely discounted; however, such de
detected during testing in a safe manner. Therefore, the probability of electrical failu
dangerous situation is considered remote.

Physical Mitigation

The boards will be designed in such a way that the pressure transducers receive the p
they need to accurately record the tank pressure.

Procedural Mitigation

In order to prevent a possible hazard, the electronics connected to the pressure trans
thoroughly tested prior to charging the tank. Any and all defects or discrepancies will
and reported to the proper authorities.

Prost-mitigation Classification

Severity Classification	Marginal	**Probability Classificatio**	Remote	**RAC**	4

Hazard Numbe	Prop-027	Final RAC	3
Hazard Name	PtML02 Burst	Part Name	PtML02

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

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 sys
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. As this pressure transducer is after the regulator, it should experience
low pressures; therefore, the possibility of rupture is considered remote.

Physical Mitigation

To entirely prevent this hazard from occurring, a new pressure transducer rated to a
greater than the tank pressure is required. However, as currently designed the prob
occurrence is such than no physical mitigation is necessary.

Procedural Mitigation

The safety of this device depends on the operation of the pressure regulation device.
system testing is imperative. Any and all deviations with system components will be r
proper authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-028	Final RAC	4
Hazard Name	VML02 stuck closed	Part Name	VML02

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes

The most likely cause for an isolation valve being locked in the closed position is an e
problem preventing the opening of the valve. This could be the electrical board never
24 volt pulse required for opening, or physical damage to the internal solenoid of the

Consequences

With the second isolation valve stuck in the closed position, formation flight is unachi
However, there is not a potential risk of injury or further equipment damage associat
failure mode.

Probability

The design of the electrical boards which control the isolation valves are not under the
the propulsion subsystem. However, a working design is necessary for the proper fun
system. Due to the dependence on as yet untested electronics the probability of proble
currently rated as probable.

Physical Mitigation

Change out non working valves.

Procedural Mitigation

Thorough testing of all electronics for proper operation is necessary. Such testing w
functional testing of the board electronics and end with system level testing of the ele
valves integrated into a 'flat sat' configuration. Any deviations from nominal operati
recorded and reported to the proper authorities. Electrical problems documented in th
process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-029	Final RAC	4
Hazard Name	VML02 Locked Open	Part Name	VML02

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if pov continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	With the valve stuck in the open position, the second of the three system inhibits is lo directly detrimental to mission objectives as the first isolation valve maintains tank i second isolation valve is to remain open throughout the period of formation flight any
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. Any deviations from nominal operat recorded and reported to the proper authorities. All valves failing to achieve nomina be replace.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-030	Final RAC	4
Hazard Name	VML02 Clogged	Part Name	VML02

Pre-mitigation Classification

Severity Classificatio	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the isolation valves are extremely narrow and easily clogge 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classificatio	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-031	Final RAC	3
Hazard Name	VML02 Burst	Part Name	VML02

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	For the isolation valve to burst, it would have to experience a propellant pressure gr yield pressure. Additionally, over heating of the valve could cause the outer casing of rupture.
Consequences	A rupture of the second isolation valve would prevent propellant from reaching the t assemblies, and thus end the formation flight portion of the mission. Also, such a rele could cause damage to nearby equipment and injuries to nearby personnel.
Probability	Valve rupture due to over pressurization is a remote possibility due to the high factor associated with the valve. The valve is rated to 1125 psi; therefore even discounting the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 3 FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a possibility based upon the expected temperature range for the mission. The valve is r and has been observed during functional testing by MAS to function properly at temp greater than 100 C.
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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass 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 assuran to ensure the procedure is followed correctly. All deviations and problems will be rep appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-032	**Final RAC**	4
Hazard Name	VML02 leak	**Part Name**	VML02

Pre-mitigation Classification

Severity Classification	Marginal	**Probability Classificatio**	Occasional	**RAC**	4

Hazard Analysis

Causes	The most likely cause of a noticeable leak stemming from the second isolation valve i tightening of the Swagelok connections.
Consequences	A leak in the second isolation valve would not immediately cause a loss of propellant (first isolation valve is functioning properly). However, once formation flight operati leaking propellant would limit the duration of the formation flight mission phase.
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 Mitigation	No physical mitigation is possible for this hazard.
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 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**	Remote	**RAC**	4

Hazard Numbe	Prop-033	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	VML02

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under the the propulsion subsystem. However, a working design is necessary for the proper fun system. Due to the dependence on as yet untested electronics the probability of probl currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the elec valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-034	**Final RAC**	4
Hazard Name	Swagelok Cross (CML01) Leak	**Part Name**	CML01

Pre-mitigation Classification

Severity Classificatio	Marginal	**Probability Classificatio**	Occasional	**RAC**	4

Hazard Analysis

Causes	The most likely cause of a leak regarding a Swagelok fitting is an improper connectio could be cause by either improper tightening or improper tubing construction.
Consequences	A leak stemming from the Swagelok cross would cause a loss of propellant during the flight phase of the mission. Thus that phase of the mission would be reduced in time a goals may not be met. There is little to no danger to personnel as the two isolation va prevent propellant from reaching the cross fitting except during controlled testing of
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 Mitigation	No physical mitigation is possible for this hazard.
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 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 Classificatio	Marginal	**Probability Classificatio**	Remote	**RAC**	4

Hazard Numbe	Prop-035	Final RAC	3
Hazard Name	Swagelok Cross (CML01) Rupture	Part Name	CML01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

The material yields due to excessive stress caused by over-pressurization

Consequences

A rupture at this point within the system would immediately end the formation flight
mission and seriously jeopardize extended mission operations. A rupture could also ca
to other near by satellite equipment; thus, further reducing the chances of mission su

Probability

The fitting in question is after the pressure regulation device within the system. The
experience at most 24.7 psi of pressure which is well within the capabilities of the f
the regulator should fail, the Swagelok fittings are rated to even higher pressures tha
propellant tank. (~4000 psig) Therefore, the chance for material yield leading to lea
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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-036	Final RAC	4
Hazard Name	TL101 leak	Part Name	TL101

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a leak regarding a Swagelok fitting is an improper connectio could be cause by either improper tightening or improper tubing construction.
Consequences	A leak stemming from the Swagelok tee TL101 would cause a loss of propellant during flight phase of the mission. Thus that phase of the mission would be reduced in time a goals may not be met. There is little to no danger to personnel as the two isolation val prevent propellant from reaching the fitting except during controlled testing of the sy
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 Mitigation	No physical mitigation is possible for this hazard.
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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-037	Final RAC	3
Hazard Name	TL101 Rupture	Part Name	TL101

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

The material yields due to excessive stress caused by over-pressurization

Consequences

A rupture at this point within the system would immediately end the formation flight
mission and seriously jeopardize extended mission operations. A rupture could also ca
to other near by satellite equipment; thus, further reducing the chances of mission su

Probability

The fitting in question is after the pressure regulation device within the system. The
experience at most 24.7 psi of pressure which is well within the capabilities of the f
the regulator should fail, the Swagelok fittings are rated to even higher pressures tha
propellant tank. (~4000 psig) Therefore, the chance for material yield leading to lea
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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-038	Final RAC	4
Hazard Name	TL201 leak	Part Name	TL201

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a leak regarding a Swagelok fitting is an improper connectior could be cause by either improper tightening or improper tubing construction.
Consequences	A leak stemming from the Swagelok tee TL201 would cause a loss of propellant during flight phase of the mission. Thus that phase of the mission would be reduced in time a goals may not be met. There is little to no danger to personnel as the two isolation val prevent propellant from reaching the fitting except during controlled testing of the sy
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, hazar situations can occur.
Physical Mitigation	No physical mitigation is possible for this hazard.
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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-039	Final RAC	3
Hazard Name	TL201 Rupture	Part Name	TL201

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	The material yields due to excessive stress caused by over-pressurization
Consequences	A rupture at this point within the system would immediately end the formation flight mission and seriously jeopardize extended mission operations. A rupture could also ca to other near by satellite equipment; thus, further reducing the chances of mission su
Probability	The fitting in question is after the pressure regulation device within the system. The experience at most 24.7 psi of pressure which is well within the capabilities of the f the regulator should fail, the Swagelok fittings are rated to even higher pressures tha propellant tank. (~4000 psig) Therefore, the chance for material yield leading to lea 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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass 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 assuran to ensure the procedure is followed correctly. All deviations and problems will be rep appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-040	Final RAC	4
Hazard Name	TL301 leak	Part Name	TL301

Pre-mitigation Classification

Severity Classificatio	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a leak regarding a Swagelok fitting is an improper connectio could be cause by either improper tightening or improper tubing construction.
Consequences	A leak stemming from the Swagelok tee TL301 would cause a loss of propellant during flight phase of the mission. Thus that phase of the mission would be reduced in time a goals may not be met. There is little to no danger to personnel as the two isolation val prevent propellant from reaching the fitting except during controlled testing of the sy
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 Mitigation	No physical mitigation is possible for this hazard.
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 pres controlled manner to ensure any potential leak is addressed prior to launch.

Prost-mitigation Classification

Severity Classificatio	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-041	Final RAC	3
Hazard Name	TL301 Rupture	Part Name	TL301

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

The material yields due to excessive stress caused by over-pressurization

Consequences

A rupture at this point within the system would immediately end the formation flight
mission and seriously jeopardize extended mission operations. A rupture could also ca
to other near by satellite equipment; thus, further reducing the chances of mission su

Probability

The fitting in question is after the pressure regulation device within the system. The
experience at most 24.7 psi of pressure which is well within the capabilities of the f
the regulator should fail, the Swagelok fittings are rated to even higher pressures tha
propellant tank. (~4000 psig) Therefore, the chance for material yield leading to lea
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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-042	Final RAC	4
Hazard Name	TL2a01 leak	Part Name	TL2a01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a leak regarding a Swagelok fitting is an improper connectior could be cause by either improper tightening or improper tubing construction.
Consequences	A leak stemming from the Swagelok tee TL2a01 would cause a loss of propellant durin formation flight phase of the mission. Thus that phase of the mission would be reduce mission goals may not be met. There is little to no danger to personnel as the two isol should prevent propellant from reaching the fitting except during controlled testing of
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 Mitigation	No physical mitigation is possible for this hazard.
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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-043	Final RAC	3
Hazard Name	TL2a01 Rupture	Part Name	TL2a01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	The material yields due to excessive stress caused by over-pressurization
Consequences	A rupture at this point within the system would immediately end the formation flight mission and seriously jeopardize extended mission operations. A rupture could also ca to other near by satellite equipment; thus, further reducing the chances of mission su
Probability	The fitting in question is after the pressure regulation device within the system. The experience at most 24.7 psi of pressure which is well within the capabilities of the f the regulator should fail, the Swagelok fittings are rated to even higher pressures tha propellant tank. (~4000 psig) Therefore, the chance for material yield leading to lea 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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass 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 assuran to ensure the procedure is followed correctly. All deviations and problems will be rep appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-044	Final RAC	4
Hazard Name	TL2b01 leak	Part Name	TL2b01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes

The most likely cause of a leak regarding a Swagelok fitting is an improper connectior
could be cause by either improper tightening or improper tubing construction.

Consequences

A leak stemming from the Swagelok tee TL2b01 would cause a loss of propellant durin
formation flight phase of the mission. Thus that phase of the mission would be reduce
mission goals may not be met. There is little to no danger to personnel as the two isol
should prevent propellant from reaching the fitting except during controlled testing of

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, hazar
situations can occur.

Physical Mitigation

No physical mitigation is possible for this hazard.

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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-045	Final RAC	3
Hazard Name	TL2b01 Rupture	Part Name	TL2b01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	The material yields due to excessive stress caused by over-pressurization
Consequences	A rupture at this point within the system would immediately end the formation flight mission and seriously jeopardize extended mission operations. A rupture could also ca to other near by satellite equipment; thus, further reducing the chances of mission su
Probability	The fitting in question is after the pressure regulation device within the system. The experience at most 24.7 psi of pressure which is well within the capabilities of the f the regulator should fail, the Swagelok fittings are rated to even higher pressures tha propellant tank. (~4000 psig) Therefore, the chance for material yield leading to lea 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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass 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 assuran to ensure the procedure is followed correctly. All deviations and problems will be rep appropriate authorities.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-046	Final RAC	4
Hazard Name	Tr05 stuck closed	Part Name	Tr05 (TrL1a01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The most likely cause for a thruster valve being locked in the closed position is an el preventing the opening of the valve. This could be the electrical board never sending pulse required for opening, or physical damage to the internal solenoid of the valve.
Consequences	Thruster Tr05 is responsible for providing counterclockwise rotation around the x ax (assuming positive x axis runs through panel 4). With this thruster stuck in the clos rotation maneuvers around the x axis would be limited to the clockwise direction whic negatively impact formation flight goals. Also, translational maneuvers in the positi would be impaired. This hazard presents no danger to equipment or testing personnel
Probability	The design of the electrical boards which control the thrusters are not under the contr propulsion subsystem. However, a working design is necessary for the proper functio system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	Change out non working valves.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-047	Final RAC	4
Hazard Name	Tr05 Locked Open	Part Name	Tr05 (TrL1a01)

Pre-mitigation Classification

Severity Classificatio	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if po continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	The consequences of such a failure would be felt immediately upon opening the two iso valves. The thruster would be activated and a continuous stream of propellant would from the nozzle; thus causing the satellite to careen out of control. During testing, t mode would release propellant into the testing area in amounts possibly greater than e
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. All testing will occur in well ventila as the fume hood present in the SSE lab) to mitigate the risk of propellant exposure. from nominal operation will be recorded and reported to the proper authorities. All achieve nominal operation will be replace.

Prost-mitigation Classification

Severity Classificatio	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-048	Final RAC	4
Hazard Name	Tr05 Clogged	Part Name	Tr05 (TrL1a01)

Pre-mitigation Classification

Severity Classificatio	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the valves as well as the throat of the nozzle are extremely easily clogged with foreign material present within the propellant lines. (Left over r construction process such 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. Foreign material lodged within th would prevent propellant flow and end the usefulness of the thruster.
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 and/ likely to be a 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classificatio	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-049	Final RAC	3
Hazard Name	Tr05 Burst	Part Name	Tr05 (TrL1a01)

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

For the thruster to burst, it would have to experience a propellant pressure greater
pressure. Additionally, over heating of the valve could cause the outer casing of the v
rupture.

Consequences

If Thruster Tr05 was to burst, the resulting propellant loss would send the satellite o
trigger a safe mode within the satellite. Thus, the formation flight portion of the mis
ended prematurely and extended mission operations would be in jeopardy. Should the
happen during testing, the resulting propellant loss could release unexpected amounts
and increase the risk of exposure.

Probability

Valve rupture due to over pressurization is a remote possibility due to the high factor
associated with the valve. The valve is rated to 1125 psi; therefore even discounting
the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 3
FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a
possibility based upon the expected temperature range for the mission. The valve is r
and has been observed during functional testing by MAS to function properly at tempe
greater than 100 C.

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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities. Additionally, all system testing will be conducted in a well v
such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-050	**Final RAC**	4
Hazard Name	Tr05 leak	**Part Name**	Tr05 (TrL1a01)

Pre-mitigation Classification

Severity Classification	Marginal	**Probability Classificatio**	Occasional	**RAC**	4

Hazard Analysis

Causes	The most likely cause of a noticeable leak stemming from the thruster Tr05 is improp the Swagelok connection.
Consequences	A leak at this point in the system would not pose a problem until the propulsion syste activated and formation flight implemented. At that point the leak would cause propel which would lessen the amount of time available for formation flight. Additionally, th pressure just before the nozzle would reduce the thrust produced by this thruster an propulsive maneuvers.
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 Mitigation	No physical mitigation is possible for this hazard.
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 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**	Remote	**RAC**	4

Hazard Number	Prop-051	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	Tr05 (TrL1a01)

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under the the propulsion subsystem. However, a working design is necessary for the proper fur system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the elec valves integrated into a 'flat sat' configuration. Any deviations from nominal operatic recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-052	Final RAC	4
Hazard Name	Tr06 stuck closed	Part Name	Tr06 (TrL1b01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The most likely cause for a thruster valve being locked in the closed position is an el preventing the opening of the valve. This could be the electrical board never sending pulse required for opening, or physical damage to the internal solenoid of the valve.
Consequences	Thruster Tr06 is responsible for providing clockwise rotation around the x axis of th (assuming positive x axis runs through panel 4). With this thruster stuck in the clos rotation maneuvers around the x axis would be limited to the counterclockwise direct could negatively impact formation flight goals. Also, translational maneuvers in the p direction would be impaired. This hazard presents no danger to equipment or testing
Probability	The design of the electrical boards which control the thrusters are not under the contr propulsion subsystem. However, a working design is necessary for the proper functio system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	Change out non working valves.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-053	Final RAC	4
Hazard Name	Tr06 Locked Open	Part Name	Tr06 (TrL1b01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if po continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	The consequences of such a failure would be felt immediately upon opening the two iso valves. The thruster would be activated and a continuous stream of propellant would from the nozzle; thus causing the satellite to careen out of control. During testing, t mode would release propellant into the testing area in amounts possibly greater than e
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. All testing will occur in well ventilat as the fume hood present in the SSE lab) to mitigate the risk of propellant exposure. from nominal operation will be recorded and reported to the proper authorities. All v achieve nominal operation will be replace.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-054	Final RAC	4
Hazard Name	Tr06 Clogged	Part Name	Tr06 (TrL1b01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the valves as well as the throat of the nozzle are extremely easily clogged with foreign material present within the propellant lines. (Left over r construction process such 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. Foreign material lodged within th would prevent propellant flow and end the usefulness of the thruster.
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 and/ likely to be a 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-055	Final RAC	3
Hazard Name	Tr06 Burst	Part Name	Tr06 (TrL1b01)

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

For the thruster to burst, it would have to experience a propellant pressure greater
pressure. Additionally, over heating of the valve could cause the outer casing of the v
rupture.

Consequences

If Thruster Tr06 was to burst, the resulting propellant loss would send the satellite o
trigger a safe mode within the satellite. Thus, the formation flight portion of the mis
ended prematurely and extended mission operations would be in jeopardy. Should the
happen during testing, the resulting propellant loss could release unexpected amount
and increase the risk of exposure.

Probability

Valve rupture due to over pressurization is a remote possibility due to the high factor
associated with the valve. The valve is rated to 1125 psi; therefore even discounting
the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 3
FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a
possibility based upon the expected temperature range for the mission. The valve is r
and has been observed during functional testing by MAS to function properly at tempe
greater than 100 C.

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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities. Additionally, all system testing will be conducted in a well v
such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Number	Prop-056	Final RAC	4
Hazard Name	Tr06 leak	Part Name	Tr06 (TrL1b01)

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes

The most likely cause of a noticeable leak stemming from the thruster Tr06 is improp the Swagelok connection.

Consequences

A leak at this point in the system would not pose a problem until the propulsion syster activated and formation flight implemented. At that point the leak would cause propel which would lessen the amount of time available for formation flight. Additionally, th pressure just before the nozzle would reduce the thrust produced by this thruster anc propulsive maneuvers.

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, hazar situations can occur.

Physical Mitigation

No physical mitigation is possible for this hazard.

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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-057	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	Tr06 (TrL1b01)

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes

The voltage step-down is accomplished by the propulsion electronics board. The most
cause of the failure of voltage step-down for the isolation valve would be the failure o
electronics board either due to component malfunction or improper design.

Consequences

The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T
then stepped down to 5 volts to maintain the open state. If the step-down process does
within the time specified, the excess voltage could destroy the solenoid and cause the v
heat and possibly rupture.

Probability

The design of the electrical boards which control the isolation valves are not under the
the propulsion subsystem. However, a working design is necessary for the proper fu
system. Due to the dependence on as yet untested electronics the probability of probl
currently rated as probable.

Physical Mitigation

A properly designed electronics board controlling the system could reduce the probab
remote.

Procedural Mitigation

Thorough testing of all electronics for proper operation is necessary. Such testing w
functional testing of the board electronics and end with system level testing of the ele
valves integrated into a 'flat sat' configuration. Any deviations from nominal operati
recorded and reported to the proper authorities. Electrical problems documented in t
process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-058	Final RAC	4
Hazard Name	Tr01 stuck closed	Part Name	Tr01 (TrL2a101

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes

The most likely cause for a thruster valve being locked in the closed position is an el
preventing the opening of the valve. This could be the electrical board never sending t
pulse required for opening, or physical damage to the internal solenoid of the valve.

Consequences

Thruster Tr01 is responsible for providing clockwise rotation around the y axis of th
(assuming positive x axis runs through panel 4). With this thruster stuck in the clos
rotation maneuvers around the y axis would be limited to the counterclockwise direct
could negatively impact formation flight goals. Also, translational maneuvers in the p
direction would be impaired. This hazard presents no danger to equipment or testing

Probability

The design of the electrical boards which control the thrusters are not under the contr
propulsion subsystem. However, a working design is necessary for the proper functio
system. Due to the dependence on as yet untested electronics the probability of proble
currently rated as probable.

Physical Mitigation

Change out non working valves.

Procedural Mitigation

Thorough testing of all electronics for proper operation is necessary. Such testing w
functional testing of the board electronics and end with system level testing of the ele
valves integrated into a 'flat sat' configuration. Any deviations from nominal operati
recorded and reported to the proper authorities. Electrical problems documented in th
process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-059	**Final RAC**	4
Hazard Name	Tr01 Locked Open	**Part Name**	Tr01 (TrL2a101)

Pre-mitigation Classification

Severity Classification	Negligible	**Probability Classificatio**	Remote	**RAC**	4

Hazard Analysis

Causes	The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if po continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	The consequences of such a failure would be felt immediately upon opening the two iso valves. The thruster would be activated and a continuous stream of propellant would from the nozzle; thus causing the satellite to careen out of control. During testing, t mode would release propellant into the testing area in amounts possibly greater than e
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. All testing will occur in well ventilat as the fume hood present in the SSE lab) to mitigate the risk of propellant exposure. from nominal operation will be recorded and reported to the proper authorities. All achieve nominal operation will be replace.

Prost-mitigation Classification

Severity Classification	Negligible	**Probability Classificatio**	Remote	**RAC**	4

Hazard Numbe	Prop-060	Final RAC	4
Hazard Name	Tr01 Clogged	Part Name	Tr01 (TrL2a101)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the valves as well as the throat of the nozzle are extremely easily clogged with foreign material present within the propellant lines. (Left over r construction process such 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. Foreign material lodged within th would prevent propellant flow and end the usefulness of the thruster.
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 and/ likely to be a 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-061	Final RAC	3
Hazard Name	Tr01 Burst	Part Name	Tr01 (TrL2a101)

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

For the thruster to burst, it would have to experience a propellant pressure greater
pressure. Additionally, over heating of the valve could cause the outer casing of the v
rupture.

Consequences

If Thruster Tr01 was to burst, the resulting propellant loss would send the satellite o
trigger a safe mode within the satellite. Thus, the formation flight portion of the mis
ended prematurely and extended mission operations would be in jeopardy. Should the
happen during testing, the resulting propellant loss could release unexpected amount
and increase the risk of exposure.

Probability

Valve rupture due to over pressurization is a remote possibility due to the high factor
associated with the valve. The valve is rated to 1125 psi; therefore even discounting
the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 3
FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a
possibility based upon the expected temperature range for the mission. The valve is r
and has been observed during functional testing by MAS to function properly at tempe
greater than 100 C.

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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities. Additionally, all system testing will be conducted in a well v
such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-062	Final RAC	4
Hazard Name	Tr01 leak	Part Name	Tr01 (TrL2a101)

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a noticeable leak stemming from the thruster Tr01 is improp the Swagelok connection.
Consequences	A leak at this point in the system would not pose a problem until the propulsion syster activated and formation flight implemented. At that point the leak would cause propel which would lessen the amount of time available for formation flight. Additionally, th pressure just before the nozzle would reduce the thrust produced by this thruster an propulsive maneuvers.
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 Mitigation	No physical mitigation is possible for this hazard.
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 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	Remote	RAC	4

Hazard Numbe	Prop-063	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	Tr01 (TrL2a1-01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under the the propulsion subsystem. However, a working design is necessary for the proper fur system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in t process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-064	Final RAC	4
Hazard Name	Tr02 stuck closed	Part Name	Tr02 (TrL2a2-01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The most likely cause for a thruster valve being locked in the closed position is an el preventing the opening of the valve. This could be the electrical board never sending pulse required for opening, or physical damage to the internal solenoid of the valve.
Consequences	Thruster Tr02 is responsible for providing counterclockwise rotation around the z ax (assuming positive x axis runs through panel 4). With this thruster stuck in the clos rotation maneuvers around the z axis would be limited to the clockwise direction whic negatively impact formation flight goals. Also, translational maneuvers in the positiv would be impaired. This hazard presents no danger to equipment or testing personnel
Probability	The design of the electrical boards which control the thrusters are not under the contr propulsion subsystem. However, a working design is necessary for the proper functio system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	Change out non working valves.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in t process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-065	Final RAC	4
Hazard Name	Tr02 Locked Open	Part Name	Tr02 (TrL2a2-01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if pov continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	The consequences of such a failure would be felt immediately upon opening the two isc valves. The thruster would be activated and a continuous stream of propellant would from the nozzle; thus causing the satellite to careen out of control. During testing, t mode would release propellant into the testing area in amounts possibly greater than e
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. All testing will occur in well ventila as the fume hood present in the SSE lab) to mitigate the risk of propellant exposure. from nominal operation will be recorded and reported to the proper authorities. All achieve nominal operation will be replace.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-066	Final RAC	4
Hazard Name	Tr02 Clogged	Part Name	Tr02 (TrL2a2-01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the valves as well as the throat of the nozzle are extremely easily clogged with foreign material present within the propellant lines. (Left over construction process such 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. Foreign material lodged within th would prevent propellant flow and end the usefulness of the thruster.
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 and/ likely to be a 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-067	Final RAC	3
Hazard Name	Tr02 Burst	Part Name	Tr02 (TrL2a2-01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

For the thruster to burst, it would have to experience a propellant pressure greater t
pressure. Additionally, over heating of the valve could cause the outer casing of the va
rupture.

Consequences

If Thruster Tr02 was to burst, the resulting propellant loss would send the satellite o
trigger a safe mode within the satellite. Thus, the formation flight portion of the miss
ended prematurely and extended mission operations would be in jeopardy. Should the
happen during testing, the resulting propellant loss could release unexpected amounts
and increase the risk of exposure.

Probability

Valve rupture due to over pressurization is a remote possibility due to the high factor
associated with the valve. The valve is rated to 1125 psi; therefore even discounting t
the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 30
FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a
possibility based upon the expected temperature range for the mission. The valve is ra
and has been observed during functional testing by MAS to function properly at tempe
greater than 100 C.

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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
within the system and that all procedures (assembly, filling, etc.) are performed corr
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
appropriate authorities. Additionally, all system testing will be conducted in a well v
such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-068	Final RAC	4
Hazard Name	Tr02 leak	Part Name	Tr02 (TrL2a2-01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes

The most likely cause of a noticeable leak stemming from the thruster Tr02 is improp
the Swagelok connection.

Consequences

A leak at this point in the system would not pose a problem until the propulsion syste
activated and formation flight implemented. At that point the leak would cause propel
which would lessen the amount of time available for formation flight. Additionally, th
pressure just before the nozzle would reduce the thrust produced by this thruster an
propulsive maneuvers.

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 Mitigation

No physical mitigation is possible for this hazard.

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 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	Remote	RAC	4

Hazard Number	Prop-069	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	Tr02 (TrL2a2-01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under the the propulsion subsystem. However, a working design is necessary for the proper fu system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-070	Final RAC	4
Hazard Name	Tr03 stuck closed	Part Name	Tr03 (TrL2b1-01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes

The most likely cause for a thruster valve being locked in the closed position is an el
preventing the opening of the valve. This could be the electrical board never sending
pulse required for opening, or physical damage to the internal solenoid of the valve.

Consequences

Thruster Tr03 is responsible for providing clockwise rotation around the z axis of th
(assuming positive x axis runs through panel 4). With this thruster stuck in the clos
rotation maneuvers around the z axis would be limited to the counterclockwise direct
could negatively impact formation flight goals. Also, translational maneuvers in the
direction would be impaired. This hazard presents no danger to equipment or testing

Probability

The design of the electrical boards which control the thrusters are not under the contr
propulsion subsystem. However, a working design is necessary for the proper functio
system. Due to the dependence on as yet untested electronics the probability of probl
currently rated as probable.

Physical Mitigation

Change out non working valves.

Procedural Mitigation

Thorough testing of all electronics for proper operation is necessary. Such testing
functional testing of the board electronics and end with system level testing of the ele
valves integrated into a 'flat sat' configuration. Any deviations from nominal operati
recorded and reported to the proper authorities. Electrical problems documented in t
process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-071	Final RAC	4
Hazard Name	Tr03 Locked Open	Part Name	Tr03 (TrL2b1-01

Pre-mitigation Classification

Severity Classificatio	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes

The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if pov
continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t
position is a defective part.

Consequences

The consequences of such a failure would be felt immediately upon opening the two isc
valves. The thruster would be activated and a continuous stream of propellant would
from the nozzle; thus causing the satellite to careen out of control. During testing, t
mode would release propellant into the testing area in amounts possibly greater than e

Probability

Due to the fail safe nature of the design, it is considered a remote possibility that the
will be stuck in the open position.

Physical Mitigation

All defective valves discovered in the testing process will be replaced.

Procedural Mitigation

Thorough testing of all valves will be conducted. All testing will occur in well ventilat
as the fume hood present in the SSE lab) to mitigate the risk of propellant exposure.
from nominal operation will be recorded and reported to the proper authorities. All v
achieve nominal operation will be replace.

Prost-mitigation Classification

Severity Classificatio	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-072	Final RAC	4
Hazard Name	Tr03 Clogged	Part Name	Tr03 (TrL2b1-01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the valves as well as the throat of the nozzle are extremely easily clogged with foreign material present within the propellant lines. (Left over construction process such 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. Foreign material lodged within th would prevent propellant flow and end the usefulness of the thruster.
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 and/ likely to be a 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-073	Final RAC	3
Hazard Name	Tr03 Burst	Part Name	Tr03 (TrL2b1-01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	For the thruster to burst, it would have to experience a propellant pressure greater t pressure. Additionally, over heating of the valve could cause the outer casing of the va rupture.
Consequences	If Thruster Tr03 was to burst, the resulting propellant loss would send the satellite o trigger a safe mode within the satellite. Thus, the formation flight portion of the miss ended prematurely and extended mission operations would be in jeopardy. Should the happen during testing, the resulting propellant loss could release unexpected amounts and increase the risk of exposure.
Probability	Valve rupture due to over pressurization is a remote possibility due to the high factor associated with the valve. The valve is rated to 1125 psi; therefore even discounting t the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 30 FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a possibility based upon the expected temperature range for the mission. The valve is ra and has been observed during functional testing by MAS to function properly at tempe greater than 100 C.
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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass within the system and that all procedures (assembly, filling, etc.) are performed corr 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 appropriate authorities. Additionally, all system testing will be conducted in a well v such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-074	Final RAC	4
Hazard Name	Tr03 leak	Part Name	Tr03 (TrL2b1-01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes

The most likely cause of a noticeable leak stemming from the thruster Tr03 is improp
the Swagelok connection.

Consequences

A leak at this point in the system would not pose a problem until the propulsion syste
activated and formation flight implemented. At that point the leak would cause propel
which would lessen the amount of time available for formation flight. Additionally, th
pressure just before the nozzle would reduce the thrust produced by this thruster an
propulsive maneuvers.

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 Mitigation

No physical mitigation is possible for this hazard.

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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-075	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	Tr03 (TrL2b1-01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under th the propulsion subsystem. However, a working design is necessary for the proper fun system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-076	**Final RAC**	4
Hazard Name	Tr04 stuck closed	**Part Name**	Tr04 (TrL2b2-01

Pre-mitigation Classification

Severity Classificatio	Negligible	**Probability Classificatio**	Probable	**RAC**	3

Hazard Analysis

Causes

The most likely cause for a thruster valve being locked in the closed position is an el
preventing the opening of the valve. This could be the electrical board never sending
pulse required for opening, or physical damage to the internal solenoid of the valve.

Consequences

Thruster Tr04 is responsible for providing counterclockwise rotation around the y a
(assuming positive x axis runs through panel 4). With this thruster stuck in the clo
rotation maneuvers around the y axis would be limited to the clockwise direction whi
negatively impact formation flight goals. Also, translational maneuvers in the positi
would be impaired. This hazard presents no danger to equipment or testing personnel

Probability

The design of the electrical boards which control the thrusters are not under the cont
propulsion subsystem. However, a working design is necessary for the proper functi
system. Due to the dependence on as yet untested electronics the probability of probl
currently rated as probable.

Physical Mitigation

Change out non working valves.

Procedural Mitigation

Thorough testing of all electronics for proper operation is necessary. Such testing w
functional testing of the board electronics and end with system level testing of the ele
valves integrated into a 'flat sat' configuration. Any deviations from nominal operati
recorded and reported to the proper authorities. Electrical problems documented in t
process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classificatio	Negligible	**Probability Classificatio**	Remote	**RAC**	4

Hazard Number	Prop-077	Final RAC	4
Hazard Name	Tr04 Locked Open	Part Name	Tr04 (TrL2b2-01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if pov continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	The consequences of such a failure would be felt immediately upon opening the two isc valves. The thruster would be activated and a continuous stream of propellant would from the nozzle; thus causing the satellite to careen out of control. During testing, t mode would release propellant into the testing area in amounts possibly greater than e
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. All testing will occur in well ventilat as the fume hood present in the SSE lab) to mitigate the risk of propellant exposure. from nominal operation will be recorded and reported to the proper authorities. All v achieve nominal operation will be replace.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-078	Final RAC	4
Hazard Name	Tr04 Clogged	Part Name	Tr04 (TrL2b2-01

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the valves as well as the throat of the nozzle are extremely easily clogged with foreign material present within the propellant lines. (Left over r construction process such 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. Foreign material lodged within th would prevent propellant flow and end the usefulness of the thruster.
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 and/ likely to be a 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-079	Final RAC	3
Hazard Name	Tr04 Burst	Part Name	Tr04 (TrL2b2-01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

For the thruster to burst, it would have to experience a propellant pressure greater
pressure. Additionally, over heating of the valve could cause the outer casing of the v
rupture.

Consequences

If Thruster Tr04 was to burst, the resulting propellant loss would send the satellite o
trigger a safe mode within the satellite. Thus, the formation flight portion of the miss
ended prematurely and extended mission operations would be in jeopardy. Should the
happen during testing, the resulting propellant loss could release unexpected amount
and increase the risk of exposure.

Probability

Valve rupture due to over pressurization is a remote possibility due to the high factor
associated with the valve. The valve is rated to 1125 psi; therefore even discounting
the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 3
FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a
possibility based upon the expected temperature range for the mission. The valve is r
and has been observed during functional testing by MAS to function properly at tempe
greater than 100 C.

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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
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 assuran
to ensure the procedure is followed correctly. All deviations and problems will be rep
appropriate authorities. Additionally, all system testing will be conducted in a well v
such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Number	Prop-080	Final RAC	4
Hazard Name	Tr04 leak	Part Name	Tr04 (TrL2b2-01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a noticeable leak stemming from the thruster Tr04 is improp the Swagelok connection.
Consequences	A leak at this point in the system would not pose a problem until the propulsion syster activated and formation flight implemented. At that point the leak would cause propel which would lessen the amount of time available for formation flight. Additionally, th pressure just before the nozzle would reduce the thrust produced by this thruster and propulsive maneuvers.
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, hazar situations can occur.
Physical Mitigation	No physical mitigation is possible for this hazard.
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.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Number	Prop-081	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	Tr04 (TrL2b2-01

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under the the propulsion subsystem. However, a working design is necessary for the proper fur system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the elec valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-082	Final RAC	4
Hazard Name	Tr07 stuck closed	Part Name	Tr07 (TrL3a-01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The most likely cause for a thruster valve being locked in the closed position is an el preventing the opening of the valve. This could be the electrical board never sending pulse required for opening, or physical damage to the internal solenoid of the valve.
Consequences	Thruster Tr07 is responsible for providing the counter force necessary to prevent translati rotation maneuvers around the x axis (positive x axis directed through panel 4) and translat maneuverability in the negative y direction. With Tr07 stuck closed, the translational force to be canceled out and the satellite would deviate from the formation. Additionally, translat in the negative y direction would be impaired. This hazard presents no danger to equipment personnel.
Probability	The design of the electrical boards which control the thrusters are not under the contr propulsion subsystem. However, a working design is necessary for the proper functio system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	Change out non working valves.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in th process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-083	Final RAC	4
Hazard Name	Tr07 Locked Open	Part Name	Tr07 (TrL3a-01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if po continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	The consequences of such a failure would be felt immediately upon opening the two iso valves. The thruster would be activated and a continuous stream of propellant would from the nozzle; thus causing the satellite to translate unexpectedly along the negativ During testing, this failure mode would release propellant into the testing area in am greater than expected.
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. All testing will occur in well ventilat as the fume hood present in the SSE lab) to mitigate the risk of propellant exposure. from nominal operation will be recorded and reported to the proper authorities. All achieve nominal operation will be replace.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-084	Final RAC	4
Hazard Name	Tr07 Clogged	Part Name	Tr07 (TrL3a-01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the valves as well as the throat of the nozzle are extremely easily clogged with foreign material present within the propellant lines. (Left over r construction process such 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. Foreign material lodged within th would prevent propellant flow and end the usefulness of the thruster.
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 and/ likely to be a 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-085	Final RAC	3
Hazard Name	Tr07 Burst	Part Name	Tr07 (TrL3a-01)

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes

For the thruster to burst, it would have to experience a propellant pressure greater t
pressure. Additionally, over heating of the valve could cause the outer casing of the va
rupture.

Consequences

If Thruster Tr07 was to burst, the resulting propellant loss would send the satellite o
trigger a safe mode within the satellite. Thus, the formation flight portion of the miss
ended prematurely and extended mission operations would be in jeopardy. Should the
happen during testing, the resulting propellant loss could release unexpected amounts
and increase the risk of exposure.

Probability

Valve rupture due to over pressurization is a remote possibility due to the high factor
associated with the valve. The valve is rated to 1125 psi; therefore even discounting t
the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 30
FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a
possibility based upon the expected temperature range for the mission. The valve is ra
and has been observed during functional testing by MAS to function properly at tempe
greater than 100 C.

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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
within the system and that all procedures (assembly, filling, etc.) are performed corr
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
appropriate authorities. Additionally, all system testing will be conducted in a well ve
such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-086	Final RAC	4
Hazard Name	Tr07 leak	Part Name	Tr07 (TrL3a-01)

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Occasional	RAC	4

Hazard Analysis

Causes	The most likely cause of a noticeable leak stemming from the thruster Tr07 is improp the Swagelok connection.
Consequences	A leak at this point in the system would not pose a problem until the propulsion syste activated and formation flight implemented. At that point the leak would cause propel which would lessen the amount of time available for formation flight. Additionally, th pressure just before the nozzle would reduce the thrust produced by this thruster an propulsive maneuvers.
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 Mitigation	No physical mitigation is possible for this hazard.
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 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	Remote	RAC	4

Hazard Numbe	Prop-087	**Final RAC**	4
Hazard Name	Voltage step-down malfunction	**Part Name**	Tr07 (TrL3a-01)

Pre-mitigation Classification

Severity Classificatio	Marginal	**Probability Classificatio**	Probable	**RAC**	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under th the propulsion subsystem. However, a working design is necessary for the proper fu system. Due to the dependence on as yet untested electronics the probability of probl currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in t process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classificatio	Marginal	**Probability Classificatio**	Remote	**RAC**	4

Hazard Number	Prop-088	Final RAC	4
Hazard Name	Tr08 stuck closed	Part Name	Tr08 (TrL3b-01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes

The most likely cause for a thruster valve being locked in the closed position is an el
preventing the opening of the valve. This could be the electrical board never sending t
pulse required for opening, or physical damage to the internal solenoid of the valve.

Consequences

Thruster Tr08 is responsible for providing the counter force necessary to prevent translatio
rotation maneuvers around the y and z axes (positive x axis directed through panel 4) and t
maneuverability in the negative x direction. With Tr08 stuck closed, the translational force
to be canceled out and the satellite would deviate from the formation. Additionally, translat
in the negative x direction would be impaired. This hazard presents no danger to equipment
personnel.

Probability

The design of the electrical boards which control the thrusters are not under the contr
propulsion subsystem. However, a working design is necessary for the proper functio
system. Due to the dependence on as yet untested electronics the probability of proble
currently rated as probable.

Physical Mitigation

Change out non working valves.

Procedural Mitigation

Thorough testing of all electronics for proper operation is necessary. Such testing w
functional testing of the board electronics and end with system level testing of the ele
valves integrated into a 'flat sat' configuration. Any deviations from nominal operati
recorded and reported to the proper authorities. Electrical problems documented in t
process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-089	Final RAC	4
Hazard Name	Tr08 Locked Open	Part Name	Tr08 (TrL3b-01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Analysis

Causes	The Lee Valve designed is a 'fail safe' design in that the valve is designed to close if po continually supplied to the solenoid. Therefore, most likely cause of a valve stuck in t position is a defective part.
Consequences	The consequences of such a failure would be felt immediately upon opening the two iso valves. The thruster would be activated and a continuous stream of propellant would from the nozzle; thus causing the satellite to translate unexpectedly along the negativ During testing, this failure mode would release propellant into the testing area in am greater than expected.
Probability	Due to the fail safe nature of the design, it is considered a remote possibility that the will be stuck in the open position.
Physical Mitigation	All defective valves discovered in the testing process will be replaced.
Procedural Mitigation	Thorough testing of all valves will be conducted. All testing will occur in well ventila as the fume hood present in the SSE lab) to mitigate the risk of propellant exposure. from nominal operation will be recorded and reported to the proper authorities. All achieve nominal operation will be replace.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-090	Final RAC	4
Hazard Name	Tr08 Clogged	Part Name	Tr08 (TrL3b-01)

Pre-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Frequent	RAC	3

Hazard Analysis

Causes	The inner mechanisms of the valves as well as the throat of the nozzle are extremely easily clogged with foreign material present within the propellant lines. (Left over r construction process such 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. Foreign material lodged within th would prevent propellant flow and end the usefulness of the thruster.
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 and/ likely to be a 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.
Procedural Mitigation	Each part will be cleaned with isopropyl alcohol prior to incorporation within the sys should limit the remaining debris.

Prost-mitigation Classification

Severity Classification	Negligible	Probability Classificatio	Remote	RAC	4

Hazard Numbe Prop-091

Final RAC 3

Hazard Name Tr08 Burst

Part Name Tr08 (TrL3b-01)

Pre-mitigation Classification

Severity Classification	Critical	**Probability Classificatio**	Remote	**RAC**	3

Hazard Analysis

Causes

For the thruster to burst, it would have to experience a propellant pressure greater t
pressure. Additionally, over heating of the valve could cause the outer casing of the va
rupture.

Consequences

If Thruster Tr08 was to burst, the resulting propellant loss would send the satellite o
trigger a safe mode within the satellite. Thus, the formation flight portion of the miss
ended prematurely and extended mission operations would be in jeopardy. Should the
happen during testing, the resulting propellant loss could release unexpected amounts
and increase the risk of exposure.

Probability

Valve rupture due to over pressurization is a remote possibility due to the high factor
associated with the valve. The valve is rated to 1125 psi; therefore even discounting t
the pressure regulator, at the 100 psi setting, the FOS is greater than 11. For the 30
FOS is still a respectable 3.66. Valve rupture due to over heating is also considered a
possibility based upon the expected temperature range for the mission. The valve is ra
and has been observed during functional testing by MAS to function properly at tempe
greater than 100 C.

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 Mitigation

Procedural mitigation comes in the form of ensuring that the correct propellant mass
within the system and that all procedures (assembly, filling, etc.) are performed corr
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
appropriate authorities. Additionally, all system testing will be conducted in a well v
such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classification	Critical	**Probability Classificatio**	Remote	**RAC**	3

Hazard Numbe Prop-092

Final RAC 4

Hazard Name Tr08 leak

Part Name Tr08 (TrL3b-01)

Pre-mitigation Classification

Severity Classification Marginal

Probability Classificatio Occasional

RAC 4

Hazard Analysis

Causes

The most likely cause of a noticeable leak stemming from the thruster Tr07 is improp the Swagelok connection.

Consequences

A leak at this point in the system would not pose a problem until the propulsion syster activated and formation flight implemented. At that point the leak would cause propel which would lessen the amount of time available for formation flight. Additionally, th pressure just before the nozzle would reduce the thrust produced by this thruster an propulsive maneuvers.

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 Mitigation

No physical mitigation is possible for this hazard.

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 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 Remote

RAC 4

Hazard Numbe	Prop-093	Final RAC	4
Hazard Name	Voltage step-down malfunction	Part Name	Tr08 (TrL3b-01)

Pre-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes	The voltage step-down is accomplished by the propulsion electronics board. The most cause of the failure of voltage step-down for the isolation valve would be the failure o electronics board either due to component malfunction or improper design.
Consequences	The Lee valves used for the MR SAT propulsion system rely on a 24 V pulse to open. T then stepped down to 5 volts to maintain the open state. If the step-down process does within the time specified, the excess voltage could destroy the solenoid and cause the v heat and possibly rupture.
Probability	The design of the electrical boards which control the isolation valves are not under the the propulsion subsystem. However, a working design is necessary for the proper fu system. Due to the dependence on as yet untested electronics the probability of probl currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele valves integrated into a 'flat sat' configuration. Any deviations from nominal operati recorded and reported to the proper authorities. Electrical problems documented in t process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Marginal	Probability Classificatio	Remote	RAC	4

Hazard Numbe	Prop-094	Final RAC	3
Hazard Name	SS Tubing Burst	Part Name	Variable Prop Line

Pre-mitigation Classification

Severity Classificatio	Critical	Probability Classificatio	Remote	RAC	3

Hazard Analysis

Causes	For the MR SAT propellant lines to burst, the stainless steal material would have to be its yield point by the pressure within the lines.
Consequences	A rupture of the propellant lines would cause the release of propellant in an undirecte a consequence, the satellite mission likely would end in failure. During testing, ruptu to flying debris and possible injury to testing personnel or harm to surrounding equip
Probability	Propellant line rupture due to over pressurization is a remote possibility due to the h safety associated with the valve. The stainless steel lines are rated to 10000 psi; the 100 psi setting, the FOS is greater than 100. For the 307 psi setting, the FOS is stil 32.57.
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 Mitigation	Procedural mitigation comes in the form of ensuring that the correct propellant mass 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 assuran to ensure the procedure is followed correctly. All deviations and problems will be rep appropriate authorities. Additionally, all system testing will be conducted in a well v such as the fume hood in the SSE lab.

Prost-mitigation Classification

Severity Classificatio	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-095	Final RAC	3
Hazard Name	Tank Heater (HTk01) Stuck On	Part Name	HTk01

Pre-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Probable	RAC	2

Hazard Analysis

Causes	The tank heater stuck in the on position could be caused by either an electrical malfur error within the control code.
Consequences	The tank heater stuck in the on position could have several possible consequences. Th over heating of the propellant which could lead to over pressurization of the tank. Se heater itself could be damaged, limiting the systems response to temperature loss and phase change of the propellant.
Probability	The design of the electrical boards which control the heaters are not under the control propulsion subsystem. However, a working design is necessary for the proper functio system. Due to the dependence on as yet untested electronics the probability of proble currently rated as probable.
Physical Mitigation	A properly designed electronics board controlling the system could reduce the probab remote.
Procedural Mitigation	Thorough testing of all electronics for proper operation is necessary. Such testing w functional testing of the board electronics and end with system level testing of the ele heaters integrated into a 'flat sat' configuration. Any deviations from nominal operat recorded and reported to the proper authorities. Electrical problems documented in t process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classification	Critical	Probability Classificatio	Remote	RAC	3

Hazard Numbe	Prop-096	Final RAC	4
Hazard Name	Tank Heater (HTk01) Non-Functio	Part Name	HTk01

Pre-mitigation Classification

Severity Classificatio	Marginal	Probability Classificatio	Probable	RAC	3

Hazard Analysis

Causes

The tank heater failing to turn on could be caused by either an electrical malfunction
within the control code.

Consequences

While propellant freezing is not a major concern given the temperature range expecte
mission, low propellant temperature within the storage tank would prevent the neces
change from occurring and thus severely limit system performance.

Probability

The design of the electrical boards which control the heaters are not under the control
propulsion subsystem. However, a working design is necessary for the proper functio
system. Due to the dependence on as yet untested electronics the probability of proble
currently rated as probable.

Physical Mitigation

A properly designed electronics board controlling the system could reduce the probab
remote.

Procedural Mitigation

Thorough testing of all electronics for proper operation is necessary. Such testing w
functional testing of the board electronics and end with system level testing of the ele
heaters integrated into a 'flat sat' configuration. Any deviations from nominal operat
recorded and reported to the proper authorities. Electrical problems documented in t
process will be addressed and then retested until nominal operation is achieved.

Prost-mitigation Classification

Severity Classificatio	marginal	Probability Classificatio	Remote	RAC	4

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VITA

Joseph R. Siebert was born on November 20th 1983 in Saint Louis, Mo. He graduated from Lindbergh High School in May of 2002 and went on to receive a Bachelor's of Science degree in Aerospace Engineering from the University of Missouri – Rolla in May of 2006. Upon completion of his Bachelor's degree, Joe began his Master's studies in Aerospace Engineering at UMR. While in pursuit of his Master's, Joe interned with the Air Force Research Laboratory working with externally wetted electro-spray thrusters for small satellite propulsion. In May of 2009, he completed his studies and received Master's degree.

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.