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MANAGEMENT OF A UNIVERSITY SATELLITE PROGRAM WITH FOCUS ON A
REFRIGERANT-BASED PROPULSION SYSTEM

by

SHAWN WAYNE MILLER

A THESIS

Presented to the Faculty of the Graduate School of the
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

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Approved by

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ABSTRACT

The Missouri University of Science and Technology Satellite (M-SAT) design team has established a satellite program to develop a pair of satellites to perform an autonomous formation flight mission. The resulting configuration was assembled for the Air Force Research Lab University Nanosat Program. This document, written by the Program Manager and former member of the Propulsion subsystem, is a description of the management process used by the team to develop a satellite configuration. Included in the document is a discussion of team organization, techniques for managing a program, and lessons learned during the 2007 to 2008 timeframe. The managing techniques impact the development of subsystems. The propulsion system is discussed further as an example to highlight a successful subsystem in both management and design development. The propulsion system is required to perform orbital maneuvers and three-axis attitude control to complete the mission objective of autonomous formation flight. This thesis specifically documents the research and selection of hardware and the integration of the system into the primary satellite. Also, seal material selection and outgassing challenges are discussed.

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1. INTRODUCTION

1.1. BACKGROUND

Since the start of the space race, satellite technology has become an integral part of daily life and is always in greater demand. The way systems and spacecraft were designed in the past is becoming obsolete due to the demand of lower associated cost, increased functionality, and mission adaptability. Past and current satellites are large, complex systems consuming a great deal of resources to launch and operated with less of a return in the investment. The modern spacecraft design is shifting away from the larger systems to smaller satellites and a distributed network of systems. Smaller satellites require less cost to construct and launch. Configured into constellations small satellites can utilize the distributed systems across the large network to complete mission objectives instead of a single system. Failure in one spacecraft will not end in mission failure as has happened in past larger satellites. To build modern satellite networks, the space industry requires new engineers and scientists with novel solutions and trained and educated in spacecraft design. Programs implemented in universities and federal entities have begun to fulfill industry demands for a workforce and new systems in the areas of micro-propulsion, communication, and control are being developed and evaluated.

1.2. SMALL SATELLITE CLASSIFICATION

The most useful and typical classification of a satellite is based on the mass at time of launch (i.e. the satellite wet mass). These classes are as follows: large satellite, medium satellite, minisatellite, microsatellite, nanosatellite, and picosatellite. The masses of each of these classes are listed in Table 1.1. Each of these classes is suited for use with certain mission or research objectives. In recent years, the interest in using satellites with masses in the range of 1kg to 100 kg has grown as satellite cost continues to climb. This range of masses enables a variety of missions to be conducted in a smaller spacecraft without reducing the ability to meet mission objectives. For the remainder of this paper, the use of “small satellite,” “nanosatellite,” or “spacecraft” (s/c) refers to a satellite with a mass range less than 100 kg.

Table 1.1. Typical Satellite Classification [1], [2]

Satellite Classification	Wet Mass Range (kg)
Large Satellite	>1000
Medium Satellite	500-1000
Minisatellite	100-500
Microsatellite	10-100
Nanosatellite	1-10
Picosatellite	< 1

1.3. UNIVERSITY NANOSAT PROGRAM

The University Nanosat Program (UNP) is a joint program established between the Air Force Research Laboratory's Space Vehicles Directorate (AFRL/RV), the Air Force Office of Scientific Research (AFOSR) and the American Institutes of Aeronautics and Astronautics (AIAA) with the aim to educate and train the next generation of engineers and scientists. Multiple universities are selected to compete in the program exposing the involved students to real, professional satellite design, fabrication, and testing. The UNP consists of two stages: the nanosat design and protoflight build competition, and the flight-ready integration and testing of the best performing satellite [3].

The first stage of the UNP is a two-year competition in which each university designs, developments, and assembles a proto-flight satellite with a research based mission of interest to the Department of Defense (DOD). The universities are partially funded by AFRL to support construction of the protoflight spacecraft and university participation in program-sponsored hands-on workshops and all design reviews. Four design reviews are held throughout the two-year competition for the purpose of tracking progress of satellite development and to convey constructive feedback to improve each team's potential for success. The competition culminates in a fifth review, Flight Competition Review (FCR). All university protoflight satellites are evaluated based on criteria that include spacecraft flyability, technical relevance/excellency, and student

participation/education. The satellite with the best performance in the criteria is selected to proceed to the second stage.

The second stage requires the winning team to deliver a flight-ready nanosat to AFRL after FCR. The flight-ready satellite is integrated with a launch vehicle separation mechanism and undergoes rigorous environmental testing. These final efforts culminate in a potential launch of the university nanosat.

1.4. UNP DESIGN CONSTRAINTS

The UNP has established guidelines and requirements to which the participating universities must adhere in order to successfully produce a flyable s/c. These guidelines and requirements are consolidated into a User's Guide (UG) which is distributed to all teams. The UG was compiled using some of the space industry's strictest requirements to ensure that the university s/c can be launched on a variety of launch vehicles. The requirements delineated in the UG can be categorized as general and are typical restrictions that any satellite must meet. The UG specifies the payload requirements (including the design envelop) of the nanosat and payload analysis and testing requirements that enable a flyable s/c to be produced.

The s/c is restricted physically to meet the constraints to be considered a secondary payload and to endure the rigors of the space environment and launch vehicle. Listed below are some of the main requirements placed on the s/c designed for the UNP Nanosat-4 (NS-4) competition [4,5]. Additional requirements pertinent to the propulsion system design are presented in later sections of this paper.

Physical Requirements.

- Mass of s/c less than 30 kg (66 lb)
- Volume of s/c fit within design envelop of a 47.5 cm (18.7 in.) diameter cylinder with a height of 47.5 cm (18.7 in.)
- Center of gravity less than 0.64 cm (0.25 in.) along the centerline of the s/c and less than 30.5 cm (12.0 in.) above the satellite interface plane
- Stiffness fundamental frequency above 100 Hz
- Limit load factors on structure plus or minus 20 g along all three axes

- Electrical and Mechanical interfaces comply with the Lightband separation device

1.5. MISSOURI S&T SATELLITE PROGRAM

In 2001, the Space Systems Engineering (SSE) Laboratory was established at Missouri University of Science and Technology (S&T) (formerly University of Missouri-Rolla). The lab serves as the primary facility for all designing and construction of student designed s/c. The student team M-SAT (then MR SAT) was assembled to formulate a mission and develop the design of an s/c capable of successfully completing that mission. In 2005, a proposed s/c UMR SAT (University of Missouri-Rolla Satellite) was accepted into the UNP NS-4 competition. The proposed satellite was derived from the heritage of previous s/c designed by the teams of the SSE Lab. The UMR SAT consisted of two smaller microsatellites, MR SAT (Missouri-Rolla Satellite) and MRS SAT (Missouri-Rolla Second Satellite). Figure 1.1 shows the docked configuration of the satellite pair, while Figure 1.2 illustrates the release of MRS SAT from MR SAT.

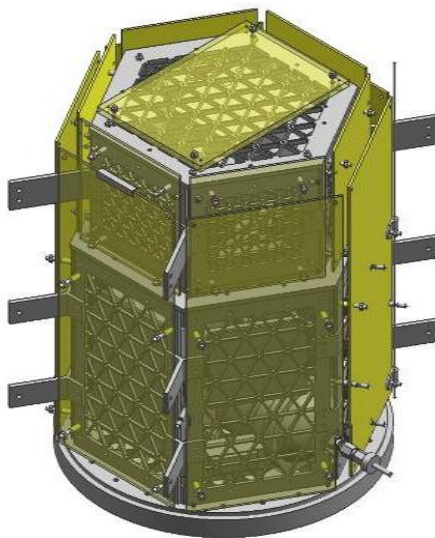


Figure 1.1. MR and MRS SAT in Docked Configuration

Originally, the mission called for flying the satellite pair in close formation flight maintained by two different methods. As the competition progressed, the focus shifted to a technology demonstration of autonomous formation flight. The goals of the UMR SAT were to test new technologies for Distributed Space Systems missions. The technologies included the study of the dynamics of the tightly controlled formation flight of the satellites, the implementation of a new orbit controller developed at S&T, the development of a low cost wireless intersatellite communication link (specifically Bluetooth communication), and the development of a novel cold gas propulsion system utilizing the saturated liquid R-134a.

The M-SAT team placed third out of the eleven teams entered in the NS-4 competition. This was a notable achievement given that this was the first entry of the team into the UNP. The team was also named the Most Improved School.

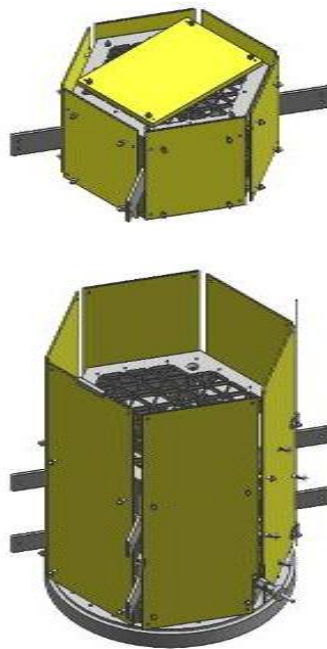


Figure 1.2. MR and MRS SAT Post-Separation

Since the conclusion of the NS-4 competition, the team has submitted proposals to the two subsequent UNP competitions, NS-5 and NS-6. While the NS-5 proposed mission and s/c were not selected for that round of competition, the NS-6 proposal was accepted and a new s/c built on the heritage of the NS-4 system has been vying for the NS-6 launch opportunity. Though the NS-5 proposal was not selected, the team chose to continue developing the NS-4 UMR SAT s/c taking the system from protoflight to flight ready during the intermission in UNP participation. In doing so, the team had the opportunity to learn skills and lessons to successfully take the s/c to a flight ready level.

The focus during the “intermission” was to successfully complete the “Flat Sat” phase of development. Flat Sat is a testing stage where components and systems are tested individual and collectively ultimately resulting in all systems being integrated together. Tested together, the systems can be proven to work effectively together. For the team to complete Flat Sat and conduct flight-ready integration, continued construction on electronics and software codes was needed so systems could be properly tested and evaluated.

The mission of the UMR SAT s/c is organized into a modes of operation plan. The plan delineates the needed systems and actions required to successfully complete each mode and ultimately the overall mission. Upon integration into the launch vehicle, the satellites follow a chronological order of events: Launch, Initialization, Power-up, Detumble, Pre-deploy, Separation, Formation Flight, Range Test, and Extended Mission [6]. The satellites will be in the docked configuration as seen in Figure 1.1 during launch, detumble, and pre-deploy modes. The formation flight mode features the operation of many of the novel approaches implemented on the s/c including the propulsion system and intersatellite communication.

1.6. PURPOSE

This thesis presents two parts of an established university satellite program: program management and the development of a subsystem. The two parts are bridged by featuring the propulsion system as a case study. Previous work by Stewart established a guide to setting up a university satellite program [4]. The work is predominately

presented from the view of a systems engineer and sets up the role of Chief Engineer. While the material is insightful and provides a basis for initiating a program, further details are needed to delineate the full leadership role shared by the Program Manager and Systems Engineer. This thesis presents the role of a Program Manager, expands on the techniques useful in successfully completing a project, and highlights areas for the team to improve. Finally the design of the propulsion system is discussed and the integration of the system presented. Many lessons were learned through the design and integration of the system. These lessons are discussed in-turn.

The material presented in this paper covers the time from mid-way through the NS-4 competition to the beginning of the NS-6 competition. The author has been involved with the M-SAT team since acceptance in the NS-4 competition to current acceptance in NS-6. Many roles and responsibilities have been experienced during that time of involvement. The author spent several years as a member of the Propulsion subsystem including interim lead. New leadership was needed at the end of NS-4. The author served as Program Manager for a year leading the team toward the production of a flight ready s/c.

1.7. THESIS ORGANIZATION

This thesis is organized into four sections detailing the topics listed in the preceding section. Section 2 discusses the management of an established university satellite program. Specifically, the team organization is reviewed, responsibilities of the team members are explained, management techniques are presented and evaluated, and finally lessons learned in managing a university satellite program are discussed. Section 3 covers the hardware selection and design considerations the propulsion subsystem evaluated in producing a functioning system for NS-4. Section 4 reviews polymeric materials for outgassing properties and compatibility with R-134a. The material would be a candidate to be used for replacement seals in the propulsion system valves. In addition, the standard outgassing test is reviewed for potential implementation by the team. Section 5 explains the assembly of the propulsion system and the steps to integrate the system into the MR SAT s/c.

2. MANAGEMENT OF AN ESTABLISHED UNIVERSITY PROGRAM

2.1. INTRODUCTION

For any design program to be success, a management structure must be established to control and organize tasks, information, and resources. Stewart set up a guide to establishing a university satellite program and the role of a systems engineer in an earlier Master's thesis [4]. As a continuous of Stewart's work, this thesis focuses partly on expanding the management role in a university program from the point of view of the Program Manager (PM) position. This section reviews the organization of a university team and responsibilities of team members, discusses the role of PM, reviews the M-SAT management post NS-4, presents the tools for potential success of project, and lessons learned. Throughout this section, the Propulsion subsystem is used as a case study of a successful subsystem.

2.2. TEAM ORGANIZATION

An organization structure is necessary to establish a clear chain of command for flow of information, final decisions, accountability for completing tasks, and successful completion of the project. This section presents the organization of the M-SAT team and responsibilities of team members.

2.2.1. Organization Levels of the Team and Subsystem Division. The M-SAT team was established with three organization levels. The levels can be seen in Figure 2.1. At the top, the Project Director/Principal Investigator (PI) supervises the project (i.e. "head of state" as suggested by UNP [7]). The PI is a university professor with industry experience and can provide technical mentorship regarding the team's decision making process. As required by the university, the PI has oversight on the entire expense budget and signs off on all purchases. The leadership rests in the hands of involved students, not the professor. UNP guidelines [7] suggest that in addition to the responsibilities above, the PI empower students to: complete tasks, make design decisions, and productivity self-policing.

The second level of the team is the student leadership. The leadership is divided into two positions: Program Manager and Systems Engineer (SE). Ideally, the two roles should be balanced in responsibilities. The responsibilities and roles of these two positions are detailed in a later section. The third level of the organization consists of the breakdown into subsystems. At this level the team members are divided into student subsystem leads and student participants. The leads oversee the development of a particular system of the s/c and the student participants work to design, construct, test, and integrate the components of the subsystem into the s/c. The responsibilities at this level are reviewed in the following section.

Depending on the mission, some subsystems may not be necessary. Typically, the primary subsystems for an s/c include Command and Data Handling (C&DH), Power, Structures, Thermal, and Communication. Additional subsystems are established for particular payloads being integrated into the s/c. Examples of such subsystems include Propulsion, Tether, and Optics. For M-SAT, twelve subsystems were formed to manage the development of the systems of UMR SAT. As seen in Figure 2.1, these subsystems were Structures, Attitude Determination and Control (ADAC), Orbit, Propulsion, C&DH, Power, Communication, Thermal, Ground Support Equipment (GSE), Ground Station, Testing, and Integration. Additional subsystems including Documentation, Outreach, and SSE Lab were formed to support the other twelve.

2.2.2. Responsibilities of Team Members. With a clear chain of command, responsibilities can be distributed among the various levels of the organization. The generalized lists of responsibilities for the team leadership, subsystem leads, and team participants follow below. Two distinct points are iterated in all three lists. Point one is the continuous learning and self-education that is entailed in all positions. Participants should be learning about leadership, the systems engineering process, subsystems, and specific research topics. A university satellite program is not a typical class with a planned agenda of material to cover each week, but instead is a project that requires continued educational growth to build individual strengths from weaknesses and combining the strengths of the participants to minimize team weaknesses. Point two is staying productive and understanding the direction and path for successful completion of the project. No one should be waiting to be assigned a task; particularly the leaders of the

team. Taking the initiative and volunteering for tasks should be a developed trait in all participants.

Team Leadership

Learn systems engineering process and program management

Project program vision and establish direction for team

Focus on producing results

Oversee project design and construction

Maintain schedule and deliver project/product on-time

Oversee usage of management tools

Establish configuration and risk management tools

Foster leadership in team participants

UNP Guidelines [7]:

“head of government”

Technical execution

Financial decisions

Administrative awareness

MUST advise PI on: technical progress, group morale, facility needs

Prevent the need for the professor to “step in”

Subsystem Leadership.

Establish direction for subsystem

Work to fulfill mission objectives and flow-down requirements

Accountable for subsystem progress

Conduct research in subsystem(s) field of study

Build leadership skills

Student Participants.

Conduct becoming of an engineer and maintain integrity of work

Understand the direction of the subsystem and team

Conduct research in subsystem(s) field of study

Maintain records of all relevant documentation

Commitment to completion of agreed work goals

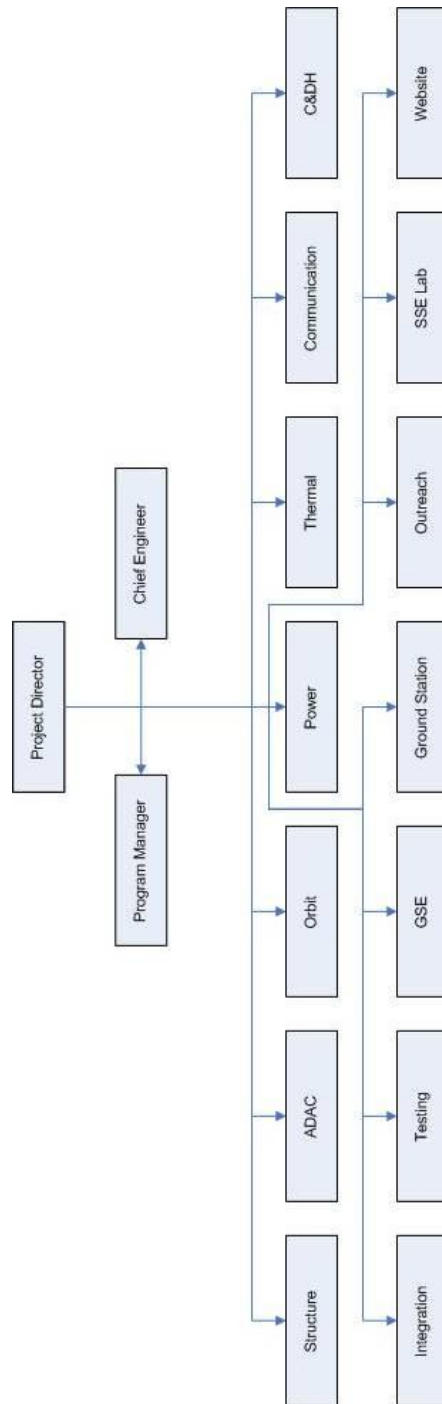


Figure 2.1. Team Organization Including M-SAT Subsystem Division [4]

2.3. ROLE OF PROGRAM MANAGER

In defining the role of the PM, one must start with defining the role of team leadership. As shown in the previous section, the leadership positions have a variety of duties and responsibilities to fulfill to move a project toward completion. The division between the PM and SE at times can be difficult to define. As stated by reference [8], “no matter how the program is organized to manage risk and other matters, systems engineering is inextricably linked to program management.” The responsibilities of leading a complex project such as a satellite program are too much for just one person. To properly manage the team, both positions must share the same tools to monitor team progress and direction of the project. The difference between the two positions is how the tools are used. The role of the PM is to move the team as a whole from start of the project to completion. To do so requires the PM to be focused on maintaining and developing resources (financial, material/equipment, and personnel), setting team vision and keeping the team on schedule for delivery, convey customer interests, and progress of project to the customer. The UNP expects to have a student PM responsible for managing the technical and programmatic aspects of the development effort at the university [5].

As a contrast to the PM, the role of the SE revolves around monitoring the project from the view point of design and construction on a daily basis. As Stewart specified, the SE of the M-SAT team oversees the entire design and construction of the satellites, reviews UNP requirements for team compliance, ensures internal team requirements are followed, enforces a strict schedule, and oversees all iterations associated with an engineering project [4].

2.4. M-SAT TEAM MANAGEMENT POST NS-4

The student leadership of the M-SAT team was structured with both the PM and Systems Engineers (SE) positions and shared the responsibilities of managing the team. For NS-4, the turnover of the PM position resulted in a yearly adjustment to new leadership while no turnover occurred in the SE position. As a result, the direction of the team was managed by the SE and the PM role was limited to managing meetings, public

affairs, and financial and resource budgets. In the post NS-4 timeframe, the roles of PM and SE were reevaluated and restructured to align the responsibilities to the corresponding positions typically seen in industry. In doing so, the burden of leadership would be more equally carried between the two positions. With vacancies in both positions, the team had the opportunity to begin with fresh personnel. The PM had previously worked on the Propulsion subsystem during NS-4 bringing UNP experience to the lead while the SE was an undergraduate senior with fresh ideas interested in exploring the role of systems engineering.

In the post NS-4 timeframe, the team had the opportunity to pursue two courses of action: start over or continue on to constructing a flight-ready s/c. To start over presented the opportunity to improve the mission statement, objectives, and requirements. With a better defined mission, the flow down into the subsystems would allow for improvements and redesigns to all subsystems. Alternatively, continuing the flight-ready s/c route entailed dealing with any flaws remaining in the mission, the requirements, and the s/c design. In industry, a new PM could opt to restart a project from scratch should the project be poorly defined initially. This would be done with the goal of saving cost and resources, but at the expense of time and possibly delaying the project. For the new PM and SE, restarting the project and conducting an extensive redesign was not an option. As discussed earlier, the team had reached the Flat Sat stage at the end of NS-4. The failure of producing the electronics necessary to operate the systems of the s/c inhibited any progress in any system testing and conducting Flat Sat. The goal of the post NS-4 team leadership was to get primarily C&DH, but also Power, Communications (Comm.), and Thermal subsystems fully prepared for Flat Sat. NS-4 ended in April 2007. The target date for Flat Sat was February 2008 and flight-ready s/c May-June 2008.

To enable these subsystems to be prepared for Flat Sat, new resources (financial, equipment/hardware, personnel) had to be gathered. C&DH and Comm. required experienced personnel for board and antenna design and construction. C&DH also needed new main computer boards for both s/c as the original VIPER boards were damaged during NS-4 FCR testing. In addition, all software codes had to be written. The Power subsystem needed to complete the design of the battery box and the power

bus. Thermal had yet to produce a reliable thermal model and required the acquisition of a new thermal software package for completion of their work.

The objectives to complete the NS-4 Flat Sat and a have a flight-ready s/c constructed by June 2008 were not met. Personnel with the expertise to assist in the tasks of C&DH could not be acquired or could not be retained. By June 2008, an adequate design for all the computer boards was established leaving only fabrication as the next step in the development of the subsystem. Since board progress was delayed, little software code was developed during the 2007-2008 academic year. Power was able to design an adequate battery box for Structures to have machined. Thermal acquired the new thermal software package.

The failure to meet the objectives for the 2007-2008 academic year can be traced to failures in three areas: failure to establish a proper breakdown of the needed work, failure to construct a realistic schedule, and failure to maintain experienced personnel to complete the required work.

2.5. TOOLS FOR POTENTIAL TEAM SUCCESS

The success of a project does not only depend on the engineering and design practices, but also on the management process controlling, organizing, and assessing the flow of information and the progress of the project. The challenge of a complex project may come from the management, not the engineering or design. Failure to management the program effectively will prevent the project from succeeding. This section reviews the typical tools for managing a team. If used correctly, these tools can assist in producing a successful program.

2.5.1. Defining Mission Statement, Objectives, and Requirements. Stewart discusses in detail the mission, mission statement, and requirements [4] and should be referenced for further detail. This section is a brief summary regarding the statement, objectives, and requirements.

Any mission starts with a defining mission statement. This should be a concise statement that is not vague or overly detailed. This statement should be the apex of the requirement verification matrix (RVM) and should be the source all requirements

emanate. This is a top-down flow and the statement should drive the requirements, not vice versa. The RVM of NS-4 M-SAT team can be viewed in reference [4]. The mission statement and requirement pertinent to the Propulsion system are provided in Section 3. The flow-down of the Propulsion requirements should be noted.

2.5.2. Establish a Work Breakdown Structure (WBS). The Work Breakdown Structure is exactly what the name suggests; the breakdown of the associated work of the project or subsystem. After the mission statement and RVM are established, the design of the satellite must be developed. Besides constructing a design and building the s/c, the team must conduct analyses and tests to verify that the design will meet or exceed the requirements in the RVM. The design, construction, analyses, and tests make up the tasks a satellite program must undertake.

The WBS is not a Gantt chart, but is instead the collection of all necessary work. The WBS consists of generalized work statements broken down into detailed tasks. These tasks are defined by a specific time interval in which the task is completed. By setting a time interval, the task becomes more manageable. As an example, many WBS use a five-day work week as the time interval a detailed task should be completed. All work is defined in the WBS to ensure an accurate picture of the progress the project must follow to be completely on time. Any missed tasks can lead to slippage or compression of the schedule and possibly delay in project delivery. Once a WBS is constructed, the tasks can be used to fill-out a Gantt chart and establish a schedule. An example WBS from the Propulsion WBS is located in Appendix A. The example is in a outline format instead of a graphical format.

2.5.3. Construct a Resource and Expense Budgets. Two budgets must be established for any project: a resource budget and a expense budget. These budgets should be routinely monitored throughout the life of the project to ensure adequate resources and capital are available for use by the team. The resource budget defines the personnel supporting the program. Each work tasks requires the uses of personnel. With any extensive project, enough personnel must be available at any point in the schedule to complete the required work otherwise the project will fall behind schedule. The expense budget monitors the capital available to the team to spend on required material and hardware. The UNP provides some funding to support the team. These funds provide an

initial stimulus to get the teams started, but are not intended to fund the entire program. The teams must seek alternative funds or donations from university, community, and industry sources.

2.5.4. Setting a Schedule. The schedule followed by a project typically is assembled into a Gantt chart. The chart is assembled from the WBS and resource budget. Exact dates can be applied to the tasks list in the WBS and organized following the flow and interconnections of the tasks in the WBS. Advanced Gantt charts as featured in Microsoft's Project software allow for inclusion of the resource budget. Personnel availability and hours can be accounted for during application of resources to the completion of tasks. Routinely monitoring and updating the schedule provides an instant assessment of the state of the project. Schedule slippage can be identified quickly and corrective action can be taken. The enemy of a project is the lack of schedule monitoring. Ignore the schedule and small setbacks can become compounded ultimately delaying the delivery of the final product. A sample Gantt chart produced by the NS-4 Propulsion subsystem is provided in Appendix A.

2.5.5. Weekly Briefings and Reports. Participants cannot spend all the time reporting progress and developments of the project, which will accomplish nothing. Instead, periodic meetings and reports need to be implemented to allow assessment of the progress of the subsystems. Weekly briefings and reports tend to convey routine activities and progress. The success of the briefings and reports depend on the usage by the project team.

2.5.6. Configuration Management. Part of the role of PM is configuration management. In addition to the UG, the UNP provides a Configuration Management Plan (CMP) that provides additional requirements and suggestions [9]. At a minimum the requirements should be implemented into the management structure. The CMP requirements can be categorized into three management organizations: documentation management, control management (i.e. quality assurance and control), and risk management. To date, only the documentation and control management have been implemented into the M-SAT management. Further work is needed to establish proper risk management and is not featured in this thesis.

2.5.6.1 Documentation management. The UNP requires specific information gathered and documented to convey details about the designed satellite. The details required include aspects associated with design, budgets (e.g. power, mass, and computer), materials, integration, testing, and any relevant analyses. The team has assembled conceptual design documents to convey details about the design of the s/c and supplemental documents detailing conducted analyses. Budgets were established to monitor relevant data. Material lists are constructed to detail the outgassing properties on the materials being utilized in the s/c design. Assembly procedures following the example provided by UNP allows for integration of the systems into the s/c. Test plans and reports have been written to detail tests that provide validation and verification to the design.

2.5.6.2 Quality assurance and control. The CMP also provides sample documents that the team should incorporate into the management techniques to ensure quality in the design. The documents are the certification log, problem failure report, manufacturing deviation notice, and engineering change request. Examples of these documents are provided in Appendix A. The certification log is used to document proof that the protoflight hardware is built in accordance with approved drawings and specifications. Certificates of compliance are used for purchased hardware to show proof of compliance with approved drawings and specifications. The problem failure report details any problems or failures that occur during assembly, integration, or operations. Manufacturing deviation notice details any deviations occurring in manufactured protoflight hardware and the corrective actions taken. The engineering change request is a formalized method to initiate a change in the design. The document details the changes and the impact to the project. A team document was developed from the example provided by the UNP and is intended for implementations after the Critical Design Review (CDR). The sample change request in Appendix A is the team version. A team quality assurance document was created for manufactured parts. The sample version in Appendix A was developed for use in the NS-6 management. A version of this was developed by Ziegler for NS-4 [6]. The new version is structured to connect with the other configuration documents.

2.6. PROGRAM MANAGEMENT LESSONS LEARNED

Compiled in this section are the lessons learned during participation in M-SAT as the PM. There are four specific lessons and recommendations that future member of the team or developing programs should consider.

2.6.1. Well-Defined Objectives and Requirements. A representative group of students with the assistance of the PI develop a proposal for each round of UNP competition. The mission statement and objectives are derived from this proposal. The student participants must further breakdown the objectives into requirements that fit the objectives and follow UNP requirements and recommendations. In this area, the student leadership must be critical of proposed requirements to ensure that quality requirements are established. Poor or ill-defined requirements hamper the development of the project and may require later review and reevaluation, which costs time and money. Defining everything well upfront and using a top-down flow to drive the development of requirements will aid in setting up a successful project.

2.6.2. Establish and Enforce Good Practices. The system tools in the preceding section should be utilized throughout the project. Doing so will improve the chances of the team successfully completing the s/c. Quality examples of these tools should be produced to instruct inexperienced participants on the expectations in using the tools. The M-SAT could improve in the usage of the WBS, Gantt chart, and weekly briefings.

Rarely has the WBS been utilized in the M-SAT program, which could have improved the potential for success of the project. Instead the team tends to define work tasks during the construction of the Gantt chart, which is incorrect and leads to significant oversight of important tasks. To improve the accuracy of the schedule and expected workload, the WBS and Gantt chart must be constructed separately. In addition, the WBS should become an enforced tool and utilized correctly by all levels of the organization. The Gantt chart of the M-SAT was underutilized throughout both NS-4 and post NS-4 timeframes. The primary failure in using the charts was the lack of details. Tasks were not broken down correctly leading to setbacks on all tasks. Overlooked tasks had to be routinely added into the chart compressing an already delayed schedule. Weekly briefing and reports need to be more effectively utilized. Standardization is not

needed, but instead quality examples need to be developed to convey expectation to participants.

2.6.3. Establish Subsystem Journal. The greatest challenge facing any university satellite program is turnover and loss of experienced personnel to industry. One way to mitigate the effect of turnover is continual training the newer members to replace experienced personnel at future dates. However, training can go only so far. There is a limited time before the departure the experienced personnel and not all knowledge can be conveyed. Also the trained participant may leave suddenly. The second way of mitigating the effect of turnover is documentation. The primary documents subsystems create are tailored for a specific audience and are not necessarily going to cover the full details of the subsystem design. To supplement training and documentation, subsystems should establish a journal as a general purpose internal document. The journal entries should detail subsystem successes, failures, history of design changes, and recommendations for future participants. In addition, assessments of the WBS and Gant chart should be stated. By doing so, knowledge is passed on and future participants can better determine detailed tasks and typical timeframe work requires for completion. Better WBS and schedules can be produced from future team participants.

2.6.4. Development of Configuration and Risk Management. These areas have been underutilized in the M-SAT program. A Documentation subsystem has been established to organize and manage the documents generated by the subsystems. Since the documentation process has been standardized, the Documentation subsystem has limited duties. An opportunity exists to expand the role of the Documentation subsystem and establish a Configuration Management subsystem with the duties detailed above.

3. PROPULSION SYSTEM DESIGN

3.1. INTRODUCTION

This chapter describes the propulsion system design integrated into the Nanosat 4 (NS-4) version of the MR SAT spacecraft (s/c). Mission requirements and pertinent UNP constraints are conveyed to relate the influencing in system development. Brief explanations are provided on the selected type of propulsion system, the analysis of potential propellants, and reasoning for selecting R-134a as the propellant of choice. In addition, the design options for hardware and motivations for the final selection of hardware are discussed.

3.2. MISSION AND SYSTEM REQUIREMENTS

A requirement verification matrix (RVM) was developed to define the objectives (e.g. Mission Statements) and system requirements of the project. The system requirements were established to focus the efforts of the team on concise tasks that when met would work to achieve the project objectives. In a top-down approach, each high level requirement breaks down further into specific system requirements. The propulsion system must meet the propulsion subsystem requirements defined in this matrix (e.g. S1.6 requirements). Table 3.1, Table 3.2, and Table 3.3 list the propulsion requirements as defined by the NS-4 RVM. At this point, no comment is made on the quality of these requirements.

Table 3.1 lists the two mission statements. All subsequent requirements (mission requirements in Table 3.2 and system requirement in Table 3.3) emanate from these two statements. Table 3.2 lists the mission requirements M-2, M-3, M-4, M-5, and M-6. These five requirements further flow down to system requirements S1-4, S1-5, and S1-7 which subsequently break down further to S1.6-1, S1.6-2, and S1.6-3 (see Table 3.3). Ultimately requirements S1.6-1 through S1.6-3 specify what services the propulsion system must provide to System 1, MR SAT, to achieve the earlier stated mission. Specifically the propulsion system needs to provide the forces/torques necessary to perform attitude and orbital control during routine operations, attitude control to maintain

50 m separation in formation flight with MRS SAT, and performance characteristics to complete one orbit.

Table 3.1. Mission Statements

Number	Statement
1	The purpose of the UMR SAT project is to investigate the autonomous control of distributed spacecraft flying in close formation.
2	The mission will be accomplished by orbiting two satellites (MR SAT and MRS SAT) in free formation flight.

Table 3.2. Mission Requirements

Number	Requirement
M-1	Formation flight will be conducted with two spacecraft (MR SAT and MRS SAT)
M-2	Control of the formation will be conducted autonomously and monitored by UMR Ground Station
M-3	The formation shall be maintained at fifty meters, \pm five meters
M-4	MR SAT will autonomously initiate separation of MRS SAT and immediately go into free formation flight
M-5	Free formation flight will proceed for a minimum duration of one orbit which demonstrates formationkeeping effectiveness
M-6	MR SAT will be actively controlled to maintain a fifty-meter separation from the uncontrolled MRS SAT

Table 3.3. System Requirements (Propulsion Specific)

Number	Requirement
S1-4	MR SAT must be able to autonomously power on and detumble the spacecraft system
S1-5	MR SAT must be able to autonomously maintain three-axis control
S1-7	MR SAT must autonomously fire its thrusters to maintain free formation flight with MRS SAT
S1.6-1	Provide forces/torques to perform attitude and orbital control
S1.6-2	Provide forces/torques to perform attitude control to maintain fifty meter distance from MRS SAT
S1.6-3	The propulsion system shall have propellant and performance specifications to perform one orbit of formation flight

3.3. UNP DESIGN CONSTRAINTS

Besides meeting the mission requirements, the propulsion system was required to meet the design constraints put in place by UNP. These constraints were established for three motives: convey standard requirements and practices of the space industry, to enhance the attractiveness of a student designed spacecraft, and minimize risk to primary payloads inherent in a student-designed spacecraft. By having imposed further restrictions and meeting stringent safety standards, chances for a student designed spacecraft being selected for a launch vehicle and launched would be improved. As related to the propulsion system, the UNP User's Guide (UG) directly specifies three areas of constraints that must be met; sealed container requirements, material selection and outgassing requirements, and general design guidance. These areas are further discussed in Sections 3.3.1, 3.3.2, and 3.3.3.

3.3.1. Implementations of NASA-STD-5003 for UNP. The UNP UG directly calls for implementation of the NASA-STD-5003-- *Fracture Control Requirements for Payloads Using the Space Shuttle* when a pressurized/sealed system is utilized on a UNP competition spacecraft and that the sealed system meets the requirements to be

considered a sealed container. Pressure vessels are prohibited without a submitted design waiver. This NASA standard specifies that the classification of a sealed container and a pressure vessel is based on the fluid storage pressure and internal energy. Specifically stated, a sealed container is any single, independent container or housing sealed to maintain an internal non-hazardous environment (e.g. stored fluid whose release is not a catastrophic hazard) and has an internal energy of 14,240 ft-lb (19.31 kJ) and an internal pressure of less than 100 psia (689.5 kPa) [10]. If these limits are exceeded, then the system is classified as a pressure vessel. Also this standard calls for the sealed container to be constructed of metal and in the cases of pressurization greater than 1.5 atm (22.04 psi), an analysis showing that the safety factor is greater than 2.5 or the container proof-tested to a minimum of 1.5 the maximum design pressure (MDP) [10].

The NASA standard does make for special case allowances. In special cases where either the pressure or energy exceeds the sealed container limit, the sealed container may be approved by appropriate authorities (see NASA-STD-5003). However at a minimum, an analysis has to be completed to also show that the container has a leak-before-burst (LBB) design and still meet the 2.5 safety factor and 1.5 MDP requirements [10]. LBB design calls for any initial flaw in the vessel material will grow through the wall of a pressure vessel and will cause leakage before burst.

3.3.2. Material Requirement and Outgassing. The materials utilized in the propulsion system design were limited to a selection suitable to the typical launch site conditions and vacuum environment. The UNP UG specifies guidelines for materials to be considered suitable for use in the construction of the spacecraft components. For the propulsion system, the materials of considerations were used in the construction of the pressure vessel, propellant lines, sensors, heaters, and exposed seals. Of concern were the materials response to corrosion (salty environment) and outgassing (vacuum environment). The guidelines that influenced the selection of the material for these components were as follows:

Metallic material: Materials with high resistance to stress corrosion cracking shall be used whenever possible. MSFC-STD-3029 lists materials that suitably meet the guideline on corrosion [5].

Non-metallic material, material outgassing: Restricted to materials possessing a total mass loss of (TML) less than 1.0% and collectable volatile condensable material (CVCM) less than 0.1% [5].

3.3.3. General Design Guidance. Additional design guidelines are stated in the UG that impact the design of the propulsion system. These guidelines are listed as practices deemed discouraged or prohibited. Listed in Table 3.4 are the practices which directly affect the design of a propulsion system [5]. Exceptions to the list should be noted. Deployable devices and composites could be allowed if the assembly/manufacture process were completed or witnessed by aerospace professionals, or if vendor-supplied.

Table 3.4. Discouraged or Prohibited Practices [5]

Discouraged	Prohibited
Material that can undergo a phase change in the launch or on-orbit environment	Pyrotechnic devices/mechanisms
Composite primary structure	Toxic and/or volatile fluids or gasses
Metallic structure built up using adhesives	Welded joints or cast metallic components
Bending as a means of forming primary structure	Parts or assemblies for which safety is highly dependent upon the build or assembly process (e.g. composite materials or certain deployment mechanisms)

3.4. ADDITIONAL REQUIREMENT DOCUMENTS

There is no restriction on the use of applicable requirements located in documents auxiliary to those specifically called out in the UNP UG. There is the possibility that the UG does not provide the needed requirements to limit a particular design. As such, additional requirement documents must be independently sought to ensure the design will

meet all potential safety restrictions. The best policy on addition requirement documents has been to determine the most stringent source of requirements and follow those stated restrictions. By doing so, the developing design will be sufficiently designed no matter the launch provider. Two other safety requirement documents were selected to be utilized for specific aspects of the propulsion design. Each of these documents will be discussed in a subsequent section.

3.4.1. Safety Requirements of NSTS 1700.7B. The NSTS 1700.7B, *Safety Policy and Requirements for Payloads using the Space Transportation System* document covers the majority of the requirements on components to be used in a propulsion system. In the subsequent subsections, each of the requirements are provided as stated in the NSTS 1700.7B document. Later sections of this chapter on component selection make reference to these restrictions provided here.

3.4.1.1 Pressure systems. A pressurized system (including transient pressures) shall have a MDP that is the highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Design factors of safety are applied to the MDP. Devices such as pressure regulators, relief devices, and/or active thermal control must be collectively two-fault tolerant from resulting in the system pressure exceeding MDP [11].

3.4.1.2 Inhibits. A design feature placed in a system that provides a physical interruption between the applied energy source and a function. Examples include a relay between a battery and pyrotechnic initiator or a latch valve between a propellant tank and thruster. Two or more inhibits are independent if no single credible failure, event, or environment can eliminate more than one inhibit [11].

3.4.1.2.1 Mechanical inhibits. To prevent premature firing of a liquid propellant propulsion system, a minimum of three mechanically independent flow control devices placed in series must be included in each propellant delivery system. Bipropellant systems are required to contain a minimum of three mechanically independent flow control devices in series both in the fuel and oxidizer supplies of the system. A minimum of one inhibit must be fail-safe, which means the inhibit is in a closed condition state in the absence of an opening signal [11].

3.4.1.2.2 Electrical inhibits. At least three independent electrical inhibits control the opening of the flow control devices. The arrangement of the electrical inhibits shall be such that the failure of one electrical inhibit will not result in the opening of more than one flow control device. Review the standard for additional requirements on electrical inhibits and the isolation valve, as more are provided in the text. These requirements were not relevant to the proposed system and as such left out of this section.

3.4.1.3 Propellant isolation valve. One of the flow control devices shall isolate the propellant tank(s) from the remainder of the distribution system [11].

3.4.1.4 Pressurized lines, fittings, and components. Pressurized lines and fittings with less than a 1.5 in. outside diameter shall have an ultimate factor of safety equal to or greater than 4.0. Other components (e.g., valves, filters, regulators, sensors, etc.) and their internal parts (e.g., bellows, diaphragms, etc.) which are exposed to system pressure shall have an ultimate factor of safety equal to or greater than 2.5 [11].

3.4.2. Safety Requirements of AFSPCMAN 91-710 V3. The AFSCMAN 91-710V3, *Range Safety User Requirement Manual* contains a broad, general set of requirements pertaining to flight hardware pressure systems applicable to all ranges users conducting or supporting operations on a Air Force Space Command (AFSPC) range. This publication establishes the system safety program requirements, minimum design, test, inspection, hazard analyses, and data requirements for hazardous and safety critical launch vehicles, payloads, and ground support equipment for AFSPC ranges.

The launch vehicle or site is unknown for the M-SAT payload; however, the most likely choice will be an AFSPC range. As such, these requirements should be applicable to the systems of the M-SAT payload no matter the selected range or vehicle. All in-house manufactured, pressurized hardware intended for flight must meet the minimum requirements listed. The aim of the propulsion subsystem was to utilize off-the-shelf hardware designed using industry or government standard processes and procedures for manufacture. Given that there was limited time to fully design the propulsion system and purchase hardware for assembly and testing, this aim was the most feasible option. However, this publication is listed here for any future reference and if necessitated, future development of in-house hardware.

3.5. OPTIONS FOR THE MR SAT PROPULSION SYSTEM

When the team was initially admitted to the NS-4 competition, the propulsion system being considered for use in the MR SAT spacecraft was a cold gas system; however, the system was not fully designed and little detail existed explaining any decisions or analyses conducted prior to acceptance into the UNP. As a result, the propulsion subsystem members at the start of NS-4 chose to reevaluate the options available for providing a propulsion system on MR SAT using the defined NS-4 mission and supporting requirements.

Three types of propulsion systems were considered for use onboard the MR SAT spacecraft: cold gas, electric propulsion, and chemical propulsion. Each type of propulsion has advantages and disadvantages. The chemical propulsion options, while having the desired high thrust performance, were ruled out early on due to the combustible nature of the materials involved. Systems employing combustion would not meet the UNP requirement. Electric propulsion options were also ruled out. The MR SAT spacecraft was limited by power and usable volume. Electric propulsion systems require a significant amount of power and space to operate and house equipment. In addition, the performance of electric systems such as micro-pulsed plasma thruster or colloid thrusters with the capacity to be utilized (μN level of thruster) were below the performance characteristics necessary for formation flight (mN level of thruster). In the end, a cold gas thruster system was selected for implementation onboard MR SAT with the intent to provide three axis control. The decision on this type of system over another such as chemical or electrical was due in part to three factors: UNP requirements (see Section 3.3); expertise and propulsion experience of subsystem members; and time for design, development, and implementation. The cold gas system could provide continuous thrust at the mN level from a propellant that was inert and non-volatile. With the type of propulsion system established the next step was to determine the propellant and possible hardware.

3.6. PROPELLANT SELECTION

The decision for selecting R-134a as the propellant for the cold gas system is briefly discussed in this section. An extensive analysis evaluating each possible propellant was performed by former subsystem member Michael Christie. Reference [12] contains a condensed version of the internal team report on the selection of the propellant if, providing further detail beyond the summary provided in this section. In addition, the thesis “Refrigerant-Based Propulsion System for Small Spacecraft” by Carl Seubert covers additional details related to the propellant performance [13].

When the spacecraft propellants were being analyzed the selection process was broken down into two categories: propellants that could be stored as compressed gasses and propellants that could be stored as saturated liquid vapors. The mission of the s/c dictated that a relatively high thrust, high ΔV propulsion performance was required to achieve the formation flight between MR SAT and MRS SAT. The tradeoff to achieve the high levels was that I_{sp} performance drops. Available ΔV , not efficient utilization of the propellant, was the primary factor in selection process.

Figure 3.1 illustrates the ΔV characteristic of each of the possible propellants as a function of the tank volume. As the trends show, R-134a provided the best possible ΔV performance for volumes below 3500 cm^3 . xenon as a compressed gas option shows to be second best performance wise within the same volume range. Based on the MR SAT layout and available volume for the propulsion system only a storage vessel of less than 4000 cm^3 could feasibly fit within the satellite. See Section 3.8.1 for details on how this maximum volume was determined. Given the space limitations for the tank, R-134a was selected as the primary propellant with Xenon being a backup option. The performance at 2500 cm^3 (the flight tank volume) was tabulated in Table 3.5. R-134a has the highest ΔV value of 1.11 m/s. This is an ideal ΔV value and at this point in the analysis losses were not considered. Reference [13] summaries the effect of losses on ΔV .

The analysis was conducted to meet the sealed container requirements at all times during the satellite mission. A temperature of $100 \text{ }^\circ\text{C}$ ($212 \text{ }^\circ\text{F}$) was used in the analysis. This was a conservative temperature based on the maximum temperature the satellite was expected to survive in the launch vehicle or on orbit. By setting this value, the pressure was limited to 100 psi at the conservative temperature. Being a saturated liquid, R-134a

would undergo a phase change during fluctuations in temperature. Phase changes result in pressure changes. If the maximum temperature was set lower than would be experienced during the mission, the tank pressure could increase beyond the requirement limit. The conservative temperature ensured that the pressure remained under the limit no matter the phase change.

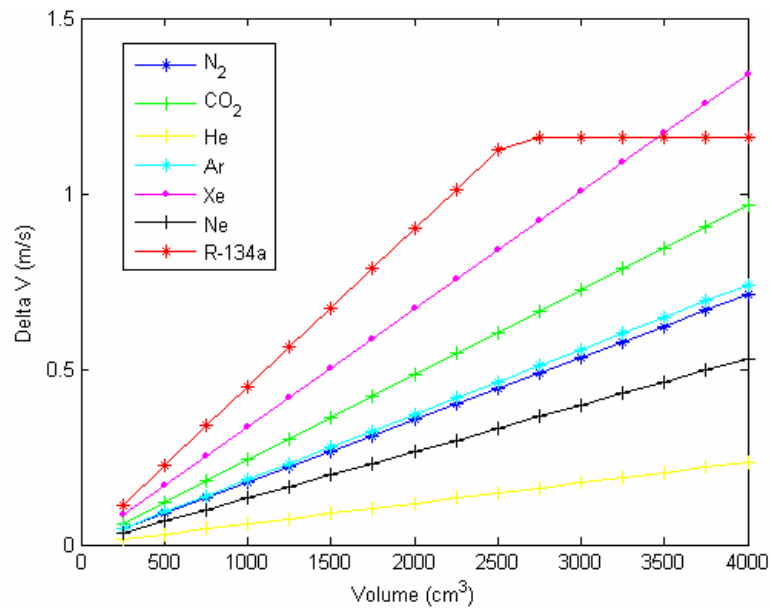


Figure 3.1. ΔV Characteristic of each Possible Propellant [13]

3.7. SYSTEM DESCRIPTION

The generalized description of the system consists of a storage vessel connected to a series of thrusters positioned around the MR SAT spacecraft to provide three axis control. Along with those components pressure and temperature monitor sensors and inhibits would be necessary to complete the system. The selection of each of the components is further discussed in Section 3.8. Figure 3.2 illustrates the final NS-4 propulsion system. The centerpiece of the system is the propellant tank. Each component is identified in Figure 3.3 and is further detailed later.

Table 3.5. Comparison of Propellants Performances [13]

Tank Volume 2500 cm ³		
Propellant	I _{sp} (s)	ΔV (m/s)
R-134a	49.9	1.11
Xe	30.8	0.87
Ar	55.9	0.49
N ₂	76.64	0.47
CO ₂	66.33	0.64
Ne	79.21	0.35
He	176.88	0.15

3.8. COMPONENT SELECTION

Each component in the propulsion system was necessary to safely store the R-134a propellant or meet established requirements of UNP or other spacecraft design authorities. Each of the following subsections describes the requirements influencing the selection, the process used to select a component, and why other potential candidates were not selected. The author was responsible for the selection of the heaters, pressure transducers, pressure regulator, and assisted with the selection of the propellant tank.

3.8.1. Propellant Storage Vessel Requirements. The storage vessel must meet the requirements as specific in Section 3.3. In addition, the available volume for the propulsion system and design envelop of the MR SAT s/c had to be considered. The UNP NS-4 UG specified an allowable design envelop for the s/c as a right cylinder of diameter 47.5 cm (18.7 in.) and height of 47.5 cm (18.7 in.) [5]. Only a fraction of the volume of the design cylinder would be available for the components of MR SAT since both MR SAT and MRS SAT had to fit within the envelop. Both s/c were designed with a hexagonal cross section inscribed in the design cylinder. The MR SAT s/c was designed with a side panel height of 29.7 cm (11.7 in.) and a maximum diameter of 40.0 cm (15.7 in.). The propellant tank would need to fit within the envelop of MR SAT

without consuming all the usable volume of the s/c. Space was necessary for other sizable components such as a battery box and computer box.

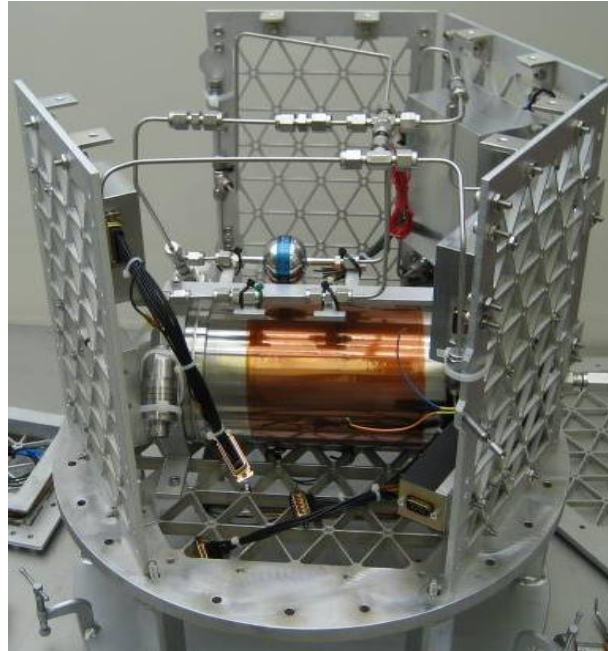


Figure 3.2. NS-4 Propulsion System as Integrated into MR SAT

The total volume of the s/c was established as $30,865 \text{ cm}^3$ and the volume of known sizable components was approximately 6119 cm^3 , making the available volume within the s/c $24,745 \text{ cm}^3$. This available volume consisted of both usable and unusable space and volume which would ultimately be needed for smaller components. The storage vessel could be up to this available volume, but the vessel still had to fit within the design envelop of the s/c.

The center of gravity (CG) requirement places the CG of the s/c within 0.635 cm (0.25 in.) from the centerline of the right cylinder and less than 30.48 cm (12.5 in.) above the satellite interface plane [5]. To minimize the impact to the CG location due to the mass of the tank, the Structures subsystem requested the tank to be placed either

vertically in the center of the spacecraft or horizontally on the bottom panel. Accessibility to at least one end of the tank was necessary to fill with propellant. Because the top and bottom faces were inaccessible due to the interfaces with MRS SAT and the launch vehicle, the best option was to place the tank horizontal with the end of the tank either facing a side panel or the corner of two panels. The length of the vessel would need to be less than 30 cm (11.8 in.) and have a cross sectional area of approximately 135 cm² (20.9 in.). The total volume for such a vessel became less than 4000 cm³. This volume value then became a requirement for selecting a propellant tank.

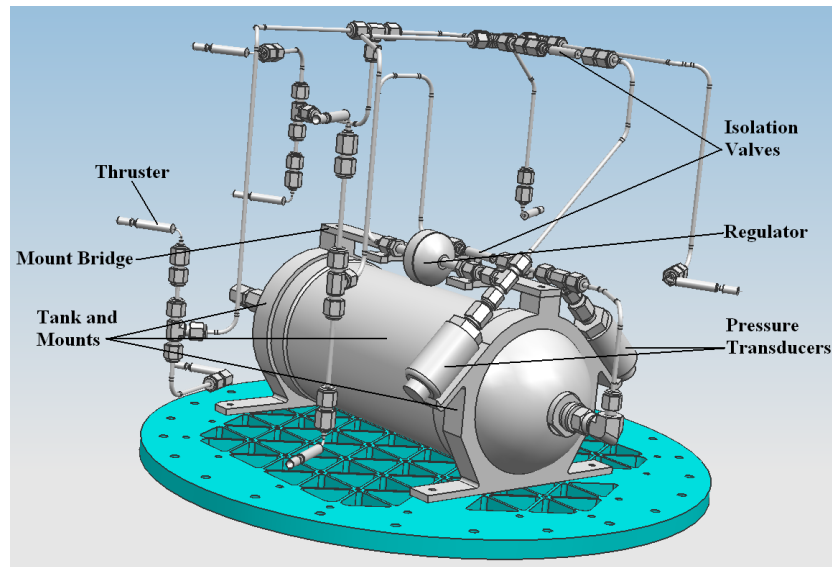


Figure 3.3. Labeled CAD Model of the Final Propulsion System

3.8.2. Selection Process of Propellant Storage Vessel. The selection of the propellant vessel began as an exercise of compiling ideas of all possible options for a storage container. Each option was then evaluated for meeting each requirement and capacity of storing a propellant. Some ideas (i.e. pressurized bladder) were quickly ruled out due to extensive violation of requirements while other options (i.e. composite tank) continued to be considered even though one or more requirement or design suggestion

was not met. Table 3.6 and Table 3.7 list possible container options proposed by not just the author but other members of the propulsion subsystem. Table 3.6 shows whether an option was generally viable and safe, met the sealed container requirement, and UNP UG recommendations. Table 3.7 lists the reasoning against use of the possible options. The most favorable options were the in-house manufactured and of-the-shelf metal tanks.

Table 3.6. Evaluation of the Options for Propellant Container

Container Options	General Viability & Safety in Spacecraft	Sealed Container Requirement Met	UNP User's Guide Recommendations
Coiled metal tubing (i.e. Snap-1 tank)	No	Yes	Yes
Balloon/Bladder	No	No	No
Space Flextanks	Possible	Possible	No
In-house manufactured metal tank	Yes	Yes	Yes
Paintball composite tank	Yes	Yes	No
CO2 cartridge	No	Yes	Yes
Off-the-shelf metal tank	Yes	Yes	Yes

3.8.2.1 Trade study of material for manufactured tank. Both the in-house tank and off-the-shelf tank were initially pursued as an option. For the in-house tank, a trade study was conducted to evaluate a selection of materials for use in tank manufacturing. The materials were varieties of aluminum, titanium, and stainless steel. The material choices were consistent with typical metals used in tank manufacture. If an off-campus manufacturer could be located, the requested material would not be an unreasonable option and add to the cost of manufacture. In the case of aluminum, the 5000 series was appropriate due to the corrosion resistance and strength exhibited by

these aluminums. More specifically, aluminum 5083 was selected due to usage for pressure vessels in cryogenic applications. When considering titanium, Ti-6Al-4V was selected as the best option. Type 304 or 304L was considered for the stainless steel, as these two stainless steel options have been used in multiple tank applications.

Table 3.7. Reason of Elimination of Propellant Container Option

Container Options	Reasons
Coiled metal tubing (i.e. Snap-1 tank)	For propellant volume needed, coil too long for satellite
Balloon/Bladder	Possibly punctured easily
Space Flextanks	Non-metallic Possibly difficult to integrate
In-house/custom manufactured metal tank	None
Paintball composite tank	Not designed to meet outgassing requirements
CO2 canister/cartridge	Small size resulting in multiple canisters needed for propellant volume; Excessive weight from multiple canisters
Off-the-shelf metal tank	None

The completed trade study can be viewed in Appendix B. The criteria for this trade study were selected to determine a material that would provide a tank able to handle launch and on-orbit operations. The criteria were based on strength, weight, heat conductivity, cost, and corrosion resistance. While corrosion resistance was the same for all three, the other factors placed aluminum 5083 as the best solution in tank construction. The titanium had a superior strength-to-weight ratio compared to stainless steel and aluminum. Aluminum possessed a lower density and cost while maintaining an

appropriate strength. With a saturated liquid, a constant temperature must be maintained to keep the R-134a in a desired ratio of gas to liquid within the tank. An active thermal control such as a heater would be required to maintain temperature. The thermal conductivity of the material must be considered for heat transfer from the heaters to the propellant. A higher conductivity would mean less power would be drawn by the heaters to maintain temperature. This is assuming multilayer insulation was implemented to minimize heat radiation. Aluminum surpassed titanium and stainless steel in heat conductivity.

The conclusion of the trade study favored aluminum 5083 as the potential material to use to manufacture the tank. Manufacturing cost or processes still had to be considered and may prevent the use of aluminum. If however one of the other materials would be required, the trade study indicated how the tanks performance would change in such an instance.

3.8.2.2 Propellant management device. As the name suggests, a propellant management device (PMD) provides some control of the liquid propellant stored within the tank of a s/c. A PMD is designed for two functions: slosh control of the stored liquid and to either aid or hinder the extraction of the liquid propellant. The movement of the free floating liquid causes CG migration which can adversely affect the attitude control of the s/c. In addition, some propulsion systems require the extraction of gaseous propellant, not liquid or vice versa. Consumption of the wrong phase of propellant into the downstream components impairs the operation of the entire system. A PMD passively holds and/or directs the liquid over or away from the tank outlet ensuring that the appropriate phase of the propellant is consumed.

A PMD can be classified into two categories: a communication device or a control device [14]. Vane and gallery PMDs are communication devices while sponge, trough, and trap are control devices. PMDs can be configured to incorporate multiple devices to improve performance. Communication PMDs as defined by Jaekles provide gas-free propellant delivery to the tank outlet or other device by forming a path between the propellant reservoir and the outlet/device [14]. Control PMDs use passive control to provide a single phase propellant delivery. Through surface tension (or hydrostatics in the case of troughs) the liquid attaches to the surface of the components of the PMD and

is either channeled and/or collected within the propellant vessel [14,15]. An appropriate PMD configuration would be required to achieve the objectives of the mission, otherwise propulsion performance may be adversely affected by an ineffective PMD. Each typical device is briefly described in the follow paragraphs. Also the conclusion in selecting a device for the MR SAT propulsion is discussed in turn.

In vanes, the structure is placed in proximity to the tank wall. The proximity of the structure establishes an open path where liquid can flow [15]. The liquid typically clings to the wall and vane structure forming fillets along the once open path. Galleries are similar to vanes, but instead internal or closed flow paths are established. Typically galleries are rectangular channels featuring screens, porous elements, or connection tubes transporting the liquid from the bulk reservoir to the channels [16]. Figure 3.4 illustrates the vane style and gallery PMDs. Note the width of the channels and the integrated porous elements featured on the gallery.

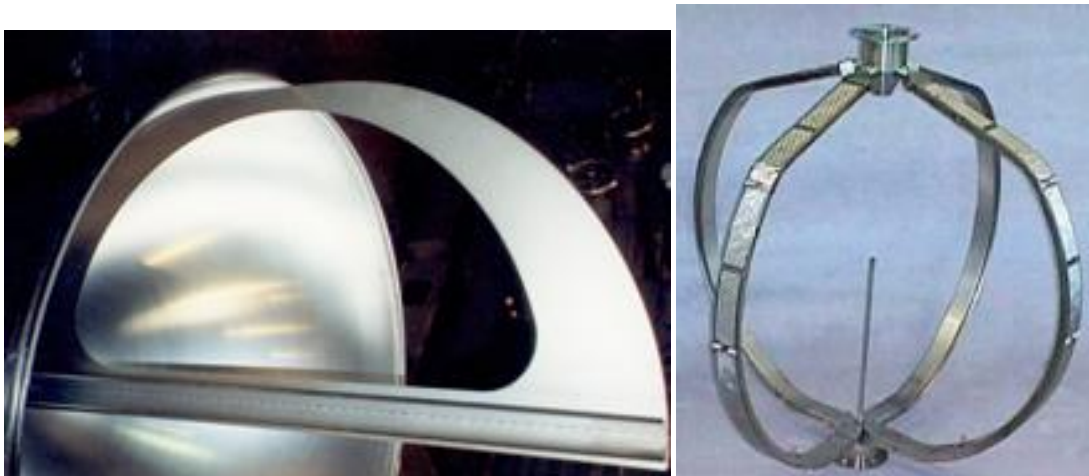


Figure 3.4. Example of a Vane PMD (left) and Gallery PMD (right) [17]



Figure 3.5. Example of a Sponge Device (left) and Trough Style PMD (right) [17]

The different types of control devices are similar in design, but are distinguished by the structure, the ability to refill, and the force used to retain propellant. A sponge is a refillable, open structure designed to hold a specific volume of propellant through the use of surface tension [18]. The sponge featured at the left in Figure 3.5 has a radial design. The propellant is held between the radial panels. A trough (right in Figure 3.5) is also an open structure, but hydrostatic forces are used to retain propellant. Troughs are zero-g refillable and are not acceleration limited. Traps are closed structures and exhibit surface tension forces for liquid retention. The closed structure at the base of the vanes in Figure 3.6 is a trap. No zero-g refill can occur with a trap; however, a trap may be designed for refill. Porous elements such as screens or perforated sheets are featured to retain propellant. An example of a porous element can be seen in Figure 3.7.

Since a saturated liquid was selected for use in the MR SAT s/c, a PMD would need to be implemented in the tank. The device would need to allow gaseous propellant to reach the tank outlet and inhibit liquid migration to the outlet. A variety of PMD configurations have been designed and qualified, but typically a design is specified for a particular mission. As a result, the Propulsion subsystem would need to analyze a variety of PMD configurations to implement into a tank or be fortunate to locate an off-the-shelf tank with an appropriate PMD configuration. Based on the PMD knowledge summarized above, the configuration needed for the MR SAT propulsion system centered on a control device, not a communication device. The control device would isolate the liquid R-134a.

The team-designed PMD did not progress beyond a preliminary design due to progress made in selecting a tank. No surface tension analysis was conducted. The author located an off-the-shelf tank featuring a control style PMD configured to isolate liquid (specifically butane) and extract only gas propellant. Further detail is given in the following section.

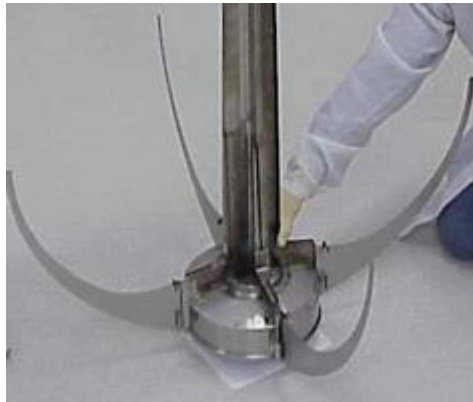


Figure 3.6. Example of a Trap (Plus Vanes) [17]

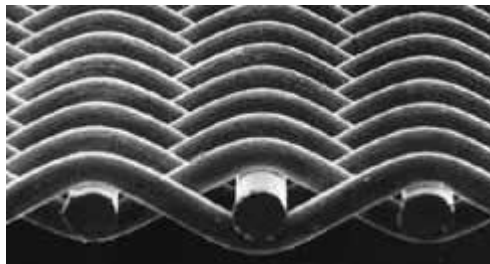


Figure 3.7. Screen Element of a PMD [17]

3.8.2.3 Pursuit of off-the-shelf tank. While the investigation into possible materials for tank construction was being conducted, a search began for an off-the-shelf tank option. Possible metal tanks were available from Marotta UK Ltd, ATK-PSI,

Catalina Tanks, and Luxfer Gas Cylinders. The advantages of an off-the-shelf tank were that the vessel would be readily available and the testing and analysis would already be completed by the manufacturing company.

Time was a large contributor in the selection of the pressure vessel. The design of the propulsion system had to be completely reevaluated and redesigned from the start of NS-4, which put the Propulsion subsystem behind the progress of the other subsystems. A vessel designed, manufactured, and tested at S&T would require a significant amount of time placing the subsystem further behind. Also impacting the development of the in-house tank was the limitation of using welded joints. Unless the welding was conducted by a qualified manufacturer, no welded tank would be acceptable. The tank was limited to using fasteners, seals, and fittings to finish assembling the pieces of the tank. The decision was made to investigate the off-the-shelf options first then pursue an in-house manufactured tank as an alternative. The goal for the off-the-shelf tank would be to locate a metal tank with a liquid isolating PMD already integrated into the vessel. An alternative to this would be to locate a tank manufacturer willing to insert a PMD of the team's design into a vessel and then weld the vessel closed following standard procedures.

Of the four companies listed previously, Marotta UK Ltd was the only company that offered a tank with an appropriate PMD and size. ATK-PSI had vessels with PMDs as well, but the vessels were too large to integrate as designed and required modification and new testing. The Catalina and Luxfer vessels did not feature a PMD. As a result the Marotta PMD vessel, BS25-01, was pursued for integration into the MR SAT s/c. See Figure 3.8 for an image of the tank. The best alternative to the BS25-01 was the Catalina tank 9007. Table 3.8 compares the two tanks. Notice that the characteristics of the two tanks were similar. The obvious difference is the lack of a PMD, use of material, and separate inlet and outlet in the Marotta tank.

Before implementation into MR SAT, the BS25-01 tank had been integrated into other small satellites designed to utilize saturated liquid as a propellant. These satellites were a part of the first generation Disaster Monitoring Constellation (DMC) constructed by SSTL. Alsat-1, BilSAT, NigeriaSAT, UK-DMC were launched in 2002 through 2003 with a nominal mission duration of five years. Butane propellant is stored at a maximum

absolute pressure of 400 kPa (58.0 psia) at 40 °C for use in a 50 mN resistojet [19]. The missions of these satellites were flown successfully.

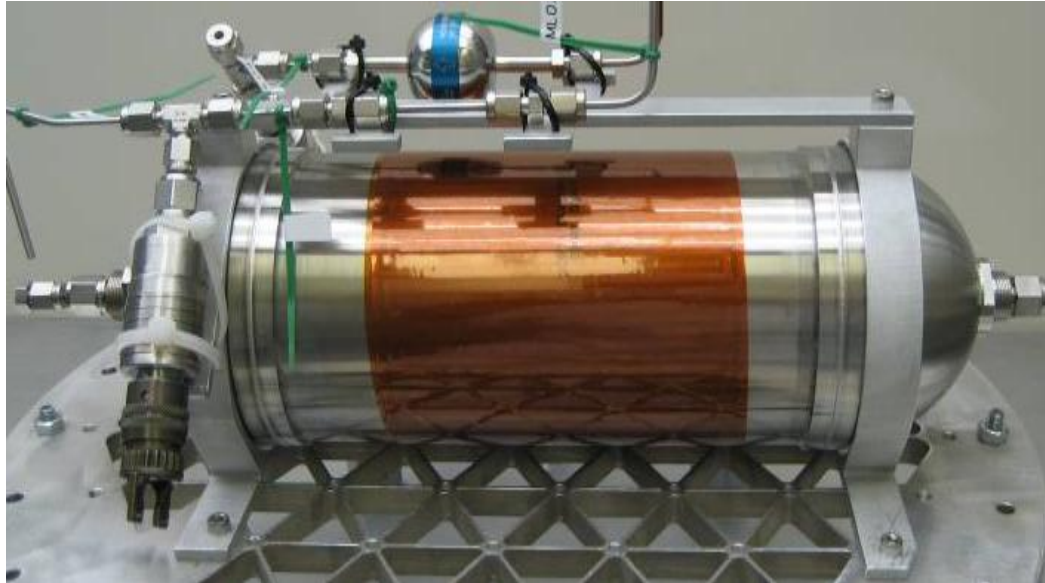


Figure 3.8. The BS25-01 Tank as Integrated into MR SAT

Table 3.8. Comparison of the Marotta and Catalina Tanks [20,21]

Feature	Marotta BS25-01	Catalina 9007
Length, cm (in.)	32.6 (12.83)	26.3 (10.37)
Volume, cm ³ (in. ³)	2500 (152.56)	2556 (156)
Diameter, cm (in.)	11.4 (4.49)	11.1 (4.38)
Weight, kg (lb)	1.5 (3.3)	1.51 (3.3)
Max Operating/Service Pressure Mpa (psi)	9.8 (1421)	12.41 (1800)
Material	Stainless Steel	Aluminum

The Marotta tank was configured with a PMD consisting of a series of sixty eight screens and six baffles. Evenly spaced throughout the tank, the baffles divide the tank into smaller volumes which reduces the volume in which any free floating liquid can move. The multiple screens serve as porous elements to which the liquid propellant can cling to through surface tension. The liquid is isolated away from the outlet of the tank. As can be seen in Figure 3.9, the screens fill the volume between each baffle.

The shell was manufactured with stainless steel 316L with the internal filters manufactured of stainless steel 304L/316L. The internal screens and baffles were of expanded aluminum 901A and aluminum alloy respectively. The stainless steel construction turned out to be an advantage. Since the propellant lines and fittings would be manufactured from stainless steel also, concerns over leaks due to thermal cycling of dissimilar material would be minimal. All final hardware of the propulsion would be of stainless steel to take advantage of similar thermal cycling.

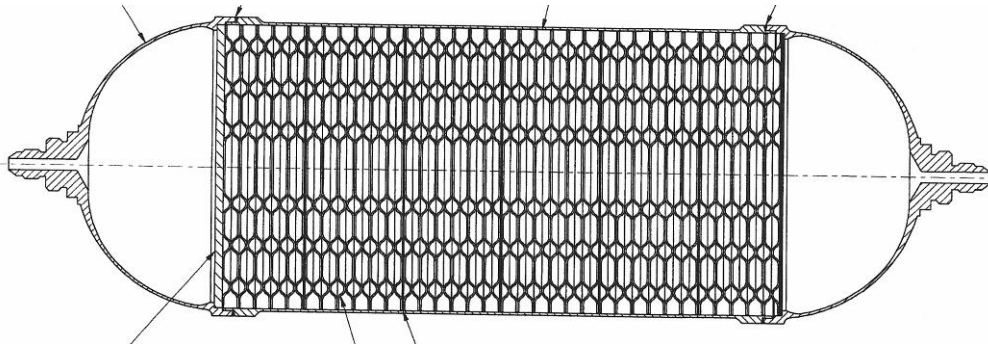


Figure 3.9. PMD Integrated into the Propellant Tank [20]

For NS-4, the specific flight tank had been proof tested to 1.600 MPa (232 psi) by Marotta. The MDP for the MR SAT propulsion was 689.47 kPa (100 psi) without a design wavier. The proof test met and surpassed the requirement of testing to a minimum of 1.5 of the MDP. If a MDP design change were to occur, the flight tank would need to be further proofed tested to maintain a 1.5 minimum. The tank has a establish safety

margin of 14:1 between the MDP and minimum burst pressure (MBP). Table 3.9 lists the specifications for the flight PMD tank. The volume is 2500 cm³ which is under the 4000 cm³ limit. The length of the tank is just within the maximum diameter of MR SAT. With such a length the tank would now need to be integrated on the bottom panel of MR SAT spanning corner to corner.

3.8.3. Pressure Transducers. To monitor the pressure within the system, two pressure transducers were designed into the system. These transducers were placed at the outlet of the tank and downstream of the pressure regulator. By placing the transducers at these locations, pressure measurements could be collected to monitor that no violation of the MDP occurred and to verify that the regulator was providing the regulated pressure. The transducers were required to be able to monitor the pressure up to 200 psi, which is twice the expected operating pressure. In addition, the transducer needed to be small and as light as possible.

Table 3.9. Measured Specifications of the Flight PMD Tank [20]

Operational Temperature, °C (°F)	-40 to 65 (-40 to 150)
Maximum Expected Operating Pressure (MEOP), MPa (psi)	1.600 (232)
Minimum Burst Pressure (MBP), MPa (psi)	9,7975 (1421)
Volume Capacity, cm ³ (in. ³)	2500 (153)
Mass, kg (lbs)	1.476 (3.25)
Maximum Body Length, cm (in.)	32.6 (12.83)
Outside Diameter, cm (in.)	11.03 (4.34)
Safety Margin (MEOP: MBP)	6:1
Leak rate (He – 0.81 MPa)	2x10 ⁻¹⁰ std. cm ³ /s

Three companies were sourced for transducers: Paine Electronics, Honeywell, and Amtek Industrial Power. The Paine transducer was the favored choice since the transducer was space qualified. The transducer possessed a very lightweight, compact design (< 3 oz). The compact design would enable the transducer to be integrated into the s/c between the tank and side panels. The Amtek transducer was the favored second option since the transducer, though not space qualified, was lightweight (< 4 oz.) and designed for industrial applications. The Honeywell transducer was constructed of stainless steel, but was the heaviest option at 5 oz. Ultimately the Honeywell transducer was procured and worked into the system design. This was due to not being able to acquire transducers from the other companies. The standard pressure port was a 7/16-20 in male fitting which is a sizably larger fitting than the 1/8 in Swagelok being used for the propellant lines. The option to customize the port existed, but pursuing this option would add to the cost and lead time. As a trade-off to save money and time, a heavier Swagelok coupling was added to the design of the system to connect the transducers to the lines. Though not designed for space application as previously selected models, the AS17A is designed to be lightweight and rugged per MIL-45208. Figure 3.10 shows the transducer integrated into the propulsion system. Table 3.10 lists the characteristics of the transducer integrated into the NS-4 FCR prototype.

Table 3.10. Pressure Transducer Specifications [13]

Pressure Range, MPa (psi)	0 to 1.379 (0 to 200)
Operating Temperature, °C (°F)	-54 to 149 (-65 to 300)
Mass, g (oz)	140 (5.0)
Pressure Port	7/16-20
Electrical Connection	6 pin, bayonet



Figure 3.10. Featured Pressure Transducer

3.8.4. Pressure Regulator. A pressure regulator was added to the system to improve the predictability of the system performance. The regulator installed in the system was immediately downstream of the propellant tank. The pressure downstream of the regulator opposes the elastic force of a spring trying to open the valve. When the regulated pressure is achieved, the valve is sealed shut. When the pressure drops below the regulated pressure, the valve is forced open by the spring. This allows propellant to repressurize the region between the regulator and the next downstream valve. Having a regulator simplifies the firing process by creating a nearly constant pressure at firing. This is at the expense of extra weight and complications with design and integration, but the regulator does not require power.

A variety of regulators were investigated for implementation into the system. The primary factor in the selection was the expected outlet pressure of 137.95 kPa (20 psia). This was chosen during the propellant selection analysis conducted by Michael Christie. Refer to [13] for further detail on the rationale of setting the expected outlet pressure to 137.95 kPa.

Two other factors were considered in the selection of the regulator: outlet pressure adjustability and reference pressure. Adjustability of the outlet pressure was a feature found in some regulators. Adjustability referred to an outlet pressure adjustment device integrated into the regulator. The UNP discouraged the use of such a feature as the potential was high that an erroneous outlet pressure could be set. Even with a tamper resistant feature the adjustment device was not advised.

Some regulators were designed with a reference port or vent hole. The regulators were designed to reference atmospheric pressure to set the operating pressure of the regulator. Being incompatible with a vacuum environment and discouraged by the UNP and regulator manufacturers, all regulators with such a feature were eliminated from consideration. With such restrictions in place, the selection was narrowed down to the point where no regulator could be located. A possible option weighed was to allow adjustment devices with the tamper resistant feature. Upon taking the job of locating new sources of regulators, the author discovered that the company Swagelok manufactured regulators. These regulators met all three of the above restrictions.

The HFS3B model (see Figure 3.11) was the selected finalist of the Swagelok regulators. The model featured stainless steel construction which was compatible with the propellant lines and could be manufactured to include the 1/8 in Swagelok compression fittings. The welding of the fittings was performed by Swagelok as a custom order. The regulator featured a compact, inline design for use with high-flow gases. The design allowed for easy incorporation into the propulsion system. The drawback of using this regulator was that the pressure calibration could only be factory set to 170.3 kPa (24.7 psia). The regulator was design to handle up to 6.89 MPa on the inlet side which exceeds the minimum safety factor requirement of 2.5 on such a component. Also of note, the regulator design allowed for continued operation even when the inlet pressure dropped to below the outlet pressure 170.3 kPa.

3.8.5. Propellant Distribution Components. The remaining components of the system served to distribute the propellant from the tank to the thrusters. These components were the propellant lines, fittings, and valves. Each of the components are briefly discussed in turn to delineate the full propulsion system. The investigation and selection of these components were conducted by Carl Seubert and Joseph Siebert.

Further detail on these components can be found in these former members' theses [13,22].



Figure 3.11. HFS3B Regulator Integrated into MR SAT

Table 3.11. Pressure Regulator Specifications [13]

Preset Outlet Pressure, kPa (psia)	170.3 (24.7)
Mass, g (oz)	176 (6.2)
Operating Temperature Range, °C (°F)	-23 to 65 (-9.4 to 149)
Inlet Pressure Range, MPa (psig)	Vacuum to 6.89 (1000)

3.8.5.1 Propellant lines and fittings. For the final design of the system, 1/8 in. stainless steel tubing was utilized to connect all the propulsion components. Stainless steel Swagelok fittings were used to tie together the sections of tubing and components. Figure 3.12 illustrates the tubing and Swagelok fittings. The selection of the material and size of the tube was determined based on the ability to be integrated into the s/c in addition to the requirements. The original system was designed to use 1/4 in. aluminum tubing and correspondingly sized fittings. When the system was assembled with the

other s/c components in the Unigraphics software NX 3, almost immediately the members of the subsystem noticed that the 1/4 in. tubing and corresponding fittings would not fit into the s/c [22]. The distribution components required a resizing to fit within the s/c. Also many of the 1/4 in. fittings were not available in aluminum.



Figure 3.12. Propellant Line and a Swagelok Fitting

Based on the suggestions of the UNP and AFRL officials, Swagelok fittings were selected to connect lines and components. Swagelok fittings feature a double ferrule design which contributes to the minimization of propellant leakage at the connection points [22]. With fittings determined, the tubing was reduced to 1/8 in. diameter and constructed of stainless steel. The similar materials of the fittings, tubing, and components minimized leakage due to thermal expansion and contraction. The pressure rating of the tubing and the fittings exceeded the safety factor required by the NSTS-1700-7B requirement. Specifically the rating was 55.3 MPa (8014 psia) for both the tubing and fittings [23].

3.8.5.2 Isolation valves and thrusters. The Lee Company valves used in the propulsion system were selected for the compact design and the ability to be integrated with a nozzle design and Swagelok fittings. The compact design of the valve is shown in Figure 3.13. The valves were featured in the system in two ways: as an isolation valve assembly and as a thruster assembly. The isolation valve assembly had Swagelok fittings welded to the end of the valve so connection could be made to the 1/8 in. tubing. The thruster assembly (see Figure 3.14) featured only one Swagelok for mating to the 1/8 in. tubing. The other end of the assembly featured a welded on nozzle that was designed by Carl Seubert. See Seubert's [13] thesis for the specification of the nozzle design. All welding was completed by Micro Aerospace Solutions.

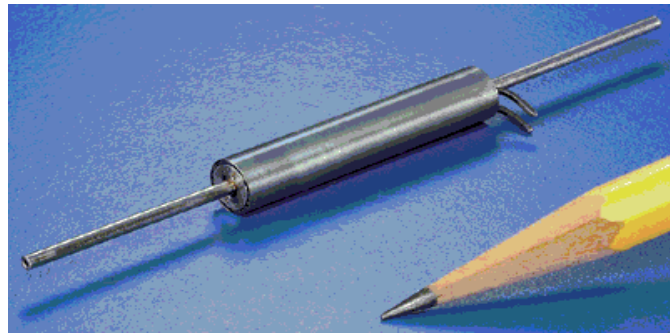


Figure 3.13. Lee Co Valve without Swagelok Fittings

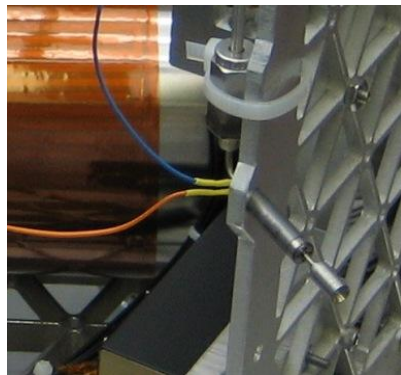


Figure 3.14. Thruster Assembled into a MR SAT Side Panel

The isolation valves were incorporated into the system to isolate the tank and serve as two of the three required mechanical inhibits. The thruster assembly served as the final mechanical inhibit and to operate as a thruster expanding the ejected propellant. The INKX0507800AB Lee valves were designed to with an operating pressure from 0 to 2.59 MPa (375 psia) @ 21.1 °C (70 °F) [24]. The proof pressure for the valves was 5.17 MPa (750 psi) which was twice the maximum operating pressure. This pressure rating met the 2.5 safety factor required by NSTS 1700.7B standards. The valve used in the NS-4 prototype system was designed with stainless steel and ethylene propylene elastomer (EPDM). Material compatibility and outgassing of the valve plunger seal is discussed further in Section 4.

3.8.6. Heaters. The system included thermal control to regulate the temperature of the stored propellant. During expulsion, the phase change of the saturated liquid would result in a cooling of the liquid and surrounding container. The cooling reduces the effectiveness of the system and propellant. The system would be passively controlled by being wrapped in multilayer insulation which would reflect radiated heat back into the system. Active control would be achieved through the use of surface applied resistive heaters. Temperature monitoring would be achieved through the standard thermal sensor placed throughout the MR SAT s/c.

The use of external heaters was elected over any internal style heaters to minimize the number of fittings and connections in the system. This would minimize points of propellant leakage. The number of heaters was set by the available power output of the s/c. The original plan was to use the thermal model of the s/c being developed by the Thermal subsystem to ascertain the temperature range that would occur on the s/c during on-orbit operations. Knowing the temperature range, the number, resistance, and locations of the heaters could be determined. However, the model was not ready when decisions regarding the heaters needed to be made. As a result, the first heating scheme called for heaters to be applied on the tank, at regulator and at each valve (total of ten heaters for the valves). The propellant would be stored or collect at these locations and potentially cool at these points. Heating applied at these locations would minimize cooling of the propellant. The twelve heaters would average a power consumption of 15 W to 25 W. The power bus of MR SAT could only provide at most 5 W for heaters if all

systems of MR SAT were operating that would occur during formation flight. As a result only 5 W would be available for the heaters. The numbers of heaters had to be reduced.

The final configuration of the heaters featured a 3.64 W heater wrapping the tank and a 1.06 W heater wrapping the tubing between the first isolation valve and regulator. Figure 3.15 and Figure 3.16 illustrate the two heaters as applied to stainless steel surfaces. Again the locations were based on the points where propellant would collect and possibly cool. The division of power between the heaters was set by the fact that the tank held a larger volume of propellant and would require more power to heat that volume. Two thermal sensors would be placed on the tank and another one would be placed at the line heater to monitor temperature. Operation of the heaters would be controlled by the onboard computer.

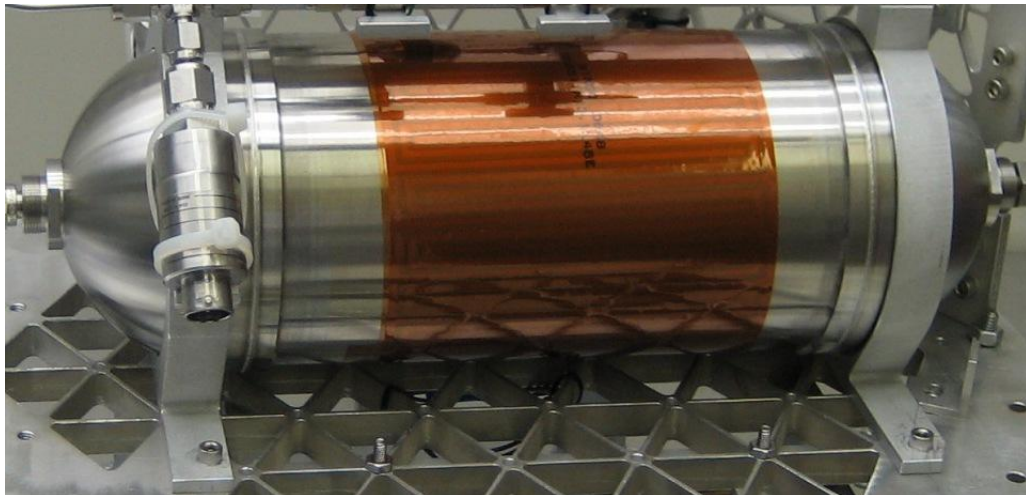


Figure 3.15. Tank Heater Attached to Flight Tank

The Minco heaters used in the system featured a resistive metal coil imbedded in a kapton medium (low outgassing material). The exact heater coil material was determined by the desired resistance and power output. A low outgassing pressure sensitive adhesive held the aluminum backed heaters to the tank and tubing surfaces. A

kapton shrink band was also employed as well to ensure that the heaters would remain attached should the adhesive fail.



Figure 3.16. Line Heater Attached to Tubing

With no accurate thermal model to design by and a limited power budget, the only way to compensate for temperature variations was to plan system operations to take advantage of heater operation. The modes of operation for the two s/c were configured to operate the heaters for extended periods when power was not critical. The stored propellant would be heated up to a temperature above the operation temperature of 20 °C. When the propulsion system was needed for maneuvers the propellant would not drop immediately from 20 °C, but instead the elevated temperature. This operation would prolong the availability of propellant at or near the operating temperature. The heaters would continue to operate during maneuvers to delay the temperature drop below the operating temperature. The heater configuration would be reevaluated once the thermal model would be completed.

4. OUTGASSING AND R-134A COMPATIBILITY OF SYSTEM VALVES

4.1. INTRODUCTION

When the valves were selected for use in the propulsion system the polymeric seal integrated into the plunger was overlooked. In the process of verifying that all the components met the outgassing requirement, the subsystem discovered the oversight and set out to correct it. Two considerations had to be met: the outgassing requirement and R-134a compatibility. The following sections of this chapter discuss possible seal materials, a process to minimize outgassing, and testing for outgassing of materials. At the end, a recommendation is presented for future propulsion members to consider for solving the seal dilemma.

4.2. VALVE MATERIALS

The Lee Company valves featured in the system were designed to have a polymeric seal on the face of the internal plunger. See Figure 4.1 for a schematic of the valve. The original seal material used in the valve was Viton[®] which met the outgassing requirements. However, as discovered by Carl Seubert, the seal material and R-134a were not compatible. The seal material experiences severely unacceptable changes when the propellant comes in contact with the seal [13]. As a result, other material options were pursued for the valve seal including other materials offered by Lee. Of the other options offered by Lee, only EPDM was compatible with R-134a. Lee's standard EPDM was listed as Nordel[™] IP EPDM, but various types of Nordel[™] exist. Knowing the exact type was necessary to determine the outgassing data of the material. Due to proprietary reasons, Lee could not release the exact EPDM type when Seubert was configuring the valves with new seals. Since the EPDM type could not be determined and any EPDM listed in the NASA outgassing database did not meet outgassing requirements, EPDM was ruled out for seal use.

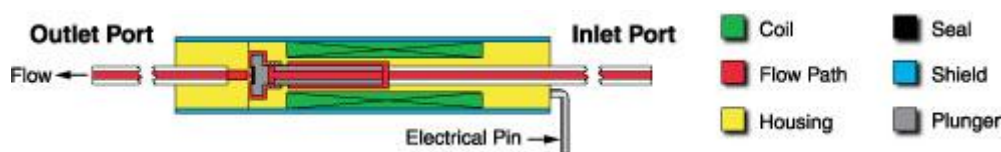


Figure 4.1. Internal Configuration of the Extended Performance Solenoid Valve [24]

Lee tried molding seals from two other low outgassing materials suggested by the M-SAT team. Unfortunately, the new materials were not moldable. For the prototype and ground testing, the valves were configured with the EPDM seals. The author began to research other low outgassing, compatible materials.

After reviewing the correspondence with Lee, a new approach was employed to obtain the outgassing properties of the EPDM. The earlier correspondence suggested that the team was looking for compositional data of the EPDM, which tend to be proprietary. New correspondence focused on clarifying that the team needed only to know the outgassing properties of the EPDM or at a minimum if the material had been tested for outgassing. Lee was able to acknowledge that the EPDM utilized had not been tested by the manufacture for outgassing. With that information, a new investigation into other seal materials (including low outgassing EPDMs) began.

The investigation revealed that another EPDM with low outgassing data was not available. Multiple low outgassing materials were discovered after the reviewing the EPDM option. Table 4.1 was constructed compiling the possible options and the outgassing properties. As delineated in the table, all materials possessed outgassing properties below the maximum 1% TML and 0.1% CVCM requirements. Many of the materials were designed to be manufactured into seals or gaskets which improved the chance Lee would be able to mold one of the materials.

Samples would need to be obtained to test the compatibility with R-134a. The test consists of immersing the samples in R-134a for a month. The dimensions, shape, texture, and color of the samples would be measured before and after immersion. Once a compatible material was determined, the plan was to have Lee try molding the seal in the new material. After determining additional options, the testing was turned over to the

other propulsion members upon the author's acceptance of the Program Manager position. No material testing was completed due to the primary need of system testing and thrust data collection.

Table 4.1. List of Possible Seal Materials for System Valves [25,26]

Name	Type	Mfg	TML%	CVCM%	# of Parts	Application
RTV142	Silicone Rubber	GE	0.002	0.05	One	Gasketing, Sealing, Electronic Adhesive
RTV566	Silicone Rubber	GE	0.0014	0.02	Two	Adhesive, Sealing
CV-2187	Silicone Elastomer	NuSil	0.26	0.04	Two	Potting Connectors, Cable Harness Breakouts, Molded High-Voltage Terminals, Seals and Gaskets
CV-2287	Silicone Elastomer	NuSil	0.27	0.06	Two	Potting Connectors, Cable Harness Breakouts, Molded High-Voltage Terminals, Seals and Gaskets
CV-2289	Silicone Elastomer	NuSil	0.35	0.05	Two	Potting Connectors, Cable Harness Breakouts, Molded High-Voltage Terminals, Seals and Gaskets

An immersion capsule was constructed that can be reused for any future testing. The immersion test capsule is illustrated in Figure 4.2. The capsule has been constructed to be simple to use. A sample is placed inside the tube and a can of R-134a is attached. The R-134a fills the capsule and once a sufficient amount has been added, the ball valve

is closed. The R-134a source is removed and a cap is tightened on to the end as a precaution should the valve be accidentally opened.



Figure 4.2. Immersion Capsule for R-134a Compatibility Testing

4.3. OUTGASSING TESTING

The outgassing of materials in the space environment has been researched for a number of years. The research began with testing at the Goddard Space Flight Center using equipment developed by the Stanford Research Institute (SRI). The SRI apparatus and data served as a foundation for low outgassing material research. After a series of tests and verification of procedures, the American Society of Testing and Materials (ASTM) established a standard test method for outgassing based on the SRI apparatus [27]. This method has been used to collect data for potential materials in space applications. This standard method is defined in the ASTM E-595 document.

The NASA-TM-109216 document outlines the vacuum stability requirements of polymeric materials for s/c application and incorporates the ASTM outgassing test method. The vacuum stability requirements are that the TML% and CVCM% are below 1.0% and 0.1% respectively. This stability is also defined by the UNP UG. The importance of the NASA and ASTM documents is significant to the team. The possibility exists that outgassing tests could be conducted on campus for materials with unknown outgassing properties.

Originally, neither the facility nor the equipment existed on campus to conduct the tests. Based on conversations with material specialists on campus and industry contacts, the opinions of the subsystem members were that industry tests would be costly

and that any testing on campus would require purchasing expensive equipment. As a result, the outgassing test was set as an option of last resort and alternative materials were researched instead. New vacuum facilities have been established on campus since the subsystem originally considered conducting outgassing tests. The only pieces missing from the tests would be the procedure and test apparatus. The discovery of the ASTM method opens up the possibility for testing.

4.3.1. Test Apparatus. The apparatus has been thoroughly detailed in the ASTM standard. The dimensions and finishes are critical for reproducibility and consistency between test data sources. The apparatus is simple in design consisting of five pieces: cover plate, heater bar, separator plate, cooling plate, and collector plate. Figure 4.3 illustrates the apparatus (limited to two specimen compartments). The left image is a cross section of the article and fully labeled. The right image is a mock up of the apparatus and shows the side vents.

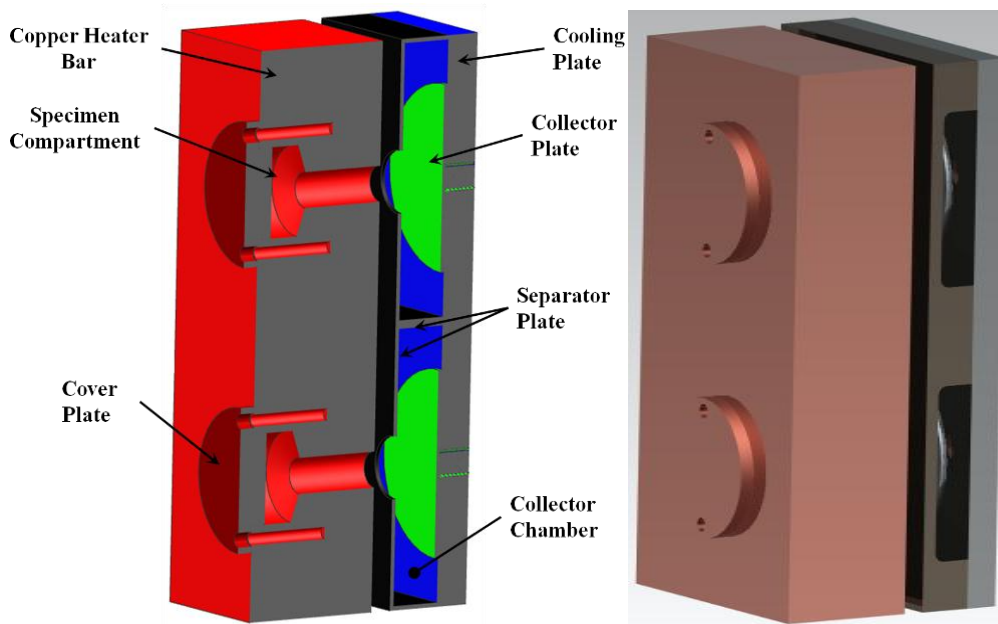


Figure 4.3. Outgassing Test Apparatus: Labeled Configuration (left), Mockup (right)

The primary component is the copper heater bar. Typically the heater bar is 650 mm (25.5 in.) in length, 25 mm (~1.0 in.) square cross section, and consists of 12 specimen chambers. The specimen chambers are sealed by cover plates so any vapor emitted from the samples are evacuated out the smaller exit aperture. The next component is the cooling plate. Fitted to the plate are the collector and separator plates. The collector plates mounts to the cooling plate while the separator plate sets against the cooling plate forming small collection chambers. The separator plate features side vents. The plate serves to prevent cross contamination between the multiple collector plates and samples. The separator plates should be plated with electroless nickel while the collector plates should be finished with electroplated chromium.

4.3.2. Test Procedure. The procedure that follows is only a summary of the full procedure. Further review of the standard is needed to perform the test. The first stage is to precondition the samples. This occurs by placing the samples in a suitable container that is held at 25 °C, 50% humidity for 24 hours. The container or boat is weighed before the preconditioning and then weighed with the sample after. The specimens are placed into the heater bar then sealed in using the cover plates. Typically 24 specimens are tested at a time for accuracy purposes, which means two 12-chambered heater bars are used.

The next stage is test operations. The apparatus and surrounding vacuum chamber must be lowered to a vacuum of at least 7×10^{-3} Pa (5×10^{-5} Torr). The heater bars are heated to bring the specimen chamber temperature to 125 °C and the cooling plate is chilled to 25 °C using whatever heat exchanging fluid desired. The heated specimens will release vapors into the specimen compartment. Some of the vapors will exit into the collector chamber through the apertures in the bar and separator plate. In the collector chamber, the vapor will condense on the collector plates due to the lower temperature. The collector plates will have been weighed independently beforehand. After 24 hours, the test article is cooled and the vacuum chamber is repressurized with a dry, inert gas.

The specimens (samples of seal material) must be cut into cubes on the order of 1.5 to 3.0 mm (1/16 to 1/8 in.). The specimen boats should be approximately 10 x 6 x 12 mm (3/8 x 1/4 x 1/2 in.) in size. The minimum masses of the specimens are on the order

of 200 mg, or else if any lower, the accuracy of the measurements may be impaired. Also the specimens should be handled appropriately (e.g. wear gloves). Contamination such as skin oil can skew results.

The calculations for TML% and CVCM% are simple. By collecting the weights of the boats, samples, and collector plates before and after testing, a simple percentage can be determined from the difference between the values. Equations 1 and 2 can be used to determine the values for TML% and CVCM% for each sample [28]. An average can be calculated as well. S_f and S_i are the final and initial mass of the sample. B_f and B_i are the final and initial mass of the container boat. C_f and C_i are the collector plate final and initial mass. All masses are typically measured in grams.

$$TML\% = \frac{(S_f + B_f) - (S_i + B_i)}{S_i} \times 100 \quad (1)$$

$$CVCM\% = \frac{(C_f - C_i)}{S_i} \times 100 \quad (2)$$

4.4. VACUUM BAKEOUT OF SEAL MATERIAL

The NASA-TM-109216 document regulates the outgassing of polymeric materials to be used for vacuum environments. In addition to specifying the ASTM E-595 test, the document also lists example considerations should a material fail to meet the TML or CVCM requirements. One of the considerations is the use of vacuum baking. The vacuum baking process places the material in a vacuum environment for typically 48 hour period. During that time, the material is heated to the maximum use temperature. The process has been known to bring desired materials back into the accepted vacuum stability as defined in the NASA document. Should the subsystem decide to use a seal material that violates the outgassing requirement, the valves could be vacuum baked for a 48 hour period at the maximum temperature of 70 °C. This temperature would be the maximum temperature expected during on-orbit operations of the propulsion system.

4.5. RECOMMENDATIONS

The propulsion subsystem has some options regarding the valve seal situation. One, a new low outgassing, R-134a compatible material could be selected and Lee Company could attempt to mold the seals. Two, select a material with known outgassing properties and vacuum bake to reduce the TML% and CVCM% to an acceptable level. Three, conduct outgassing tests as outlined by the ASTM E-595 document. Of the three options, the author recommends that the latter two options be pursued first. Since the valves are for university use in low quantities, Lee may not be willing to continue custom designing and manufacturing the seals to test which material is moldable. Lee currently has the valve designed to meet the outgassing requirement. The marketing benefits of an R-134a compatible valve is not in high demand at this point in time. The first options places a significant demand on Lee and offers little benefit beyond supplying the satellite team with valves. This option should be exploited as a last resort.

The recommended path would be to pursue the outgassing test first, then vacuum baking. The outgassing test is overall simple and easy to construct. The construction of the setup would repay the team's construction cost in the ability to test not only valve materials, but any future materials sought to be employed onboard a future s/c. The author recommends setting up the test for analyzing the standard EPDM used by Lee. Lee would benefit from having another material tested for outgassing and possibly a second option to the Viton[®] seal. The vacuum baking could be employed should the EPDM fail the outgassing test. Further baking may bring the material back into compliance with the vacuum stability requirement.

5. SPACECRAFT INTEGRATION AND PROPULSION PROCEDURES

5.1. INTRODUCTION

The final two stages of producing a functional satellite involving the propulsion system were assembly of the system and integration into the s/c, and operation of the system. This section discusses the process to integrate the propulsion system into the s/c, the assembly and operational procedures developed for the system, and finally the lessons learned.

5.2. INTEGRATION OF PROPULSION SYSTEM

The configured system is discussed as compared to the initially planned system, the CDR model, and the FCR final model. Following the overview of the system, assembly of the s/c is presented and integration of the core hardware and panel hardware into the s/c is discussed.

5.2.1. Configured System. As previously discussed, the propulsion system was primarily restricted by the design envelop for the s/c and the additional components such as the computer and battery boxes. The first step taken to integrate the system into the MR SAT s/c was to establish the location of each thrusters. As shown in Figure 5.1, eight thrusters were used for the propulsion system, which allowed for five degrees of freedom of control. A cluster of four thrusters were placed on a panel. A single thruster was placed on the opposite panel to the four thrusters. Three thrusters were placed at the corners of two panels. The selected corners were perpendicular to panels with the other five thrusters. This thruster placement was set by a former propulsion member.

Since the system type was determined to be a cold gas, an initial system configuration was formed as shown in Figure 5.2. All cold gas systems require a storage vessel connected to a series of valves, sensors, regulators, and thrusters. The only challenge for integrating the system into the s/c was to determine the route the propellant lines would need to take from the tank to the thrusters. By the time of CDR, a CAD model was developed illustrating the configured system. This configuration can be seen

in Figure 5.3. The striking feature of the system is that some components are routed along the bottom panel of the s/c and up a vertical section of tubing.

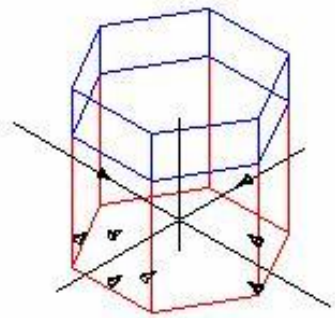


Figure 5.1. Thruster Placement on MR SAT

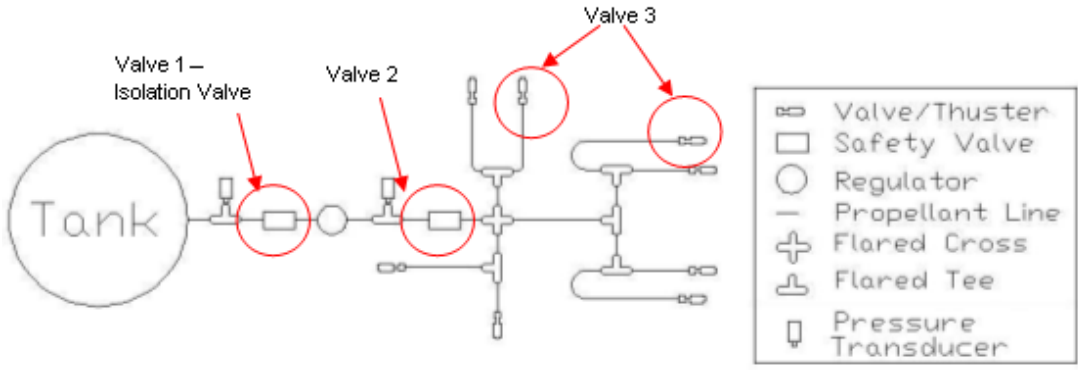


Figure 5.2. Initial Configuration of the Propulsion System

After CDR, it was realized that this configuration would not work. First, the location of the fittings and lines interfered with bolts and brackets holding all the side panels together inhibiting the assembly of the satellite. Second, the tank is held in place by friction. Such a fastening method was not recommended by the UNP. Finally, the

vertical segment of tubing was unsupported unless fastened to the nearby component boxes. To easily integrate and remove components from the boxes, no external components could be attached to boxes. Additionally, the boxes needed to be sealed to minimize electromagnetic interference. Thus no connection points could be added to the box exterior surface. Given the mass hanging on the vertical segment, structural support was needed to ensure the system survived the 20 g loading that could occur during launch. The components needed to be attached to a structural component. The preferred method for attachment was placing the components directly on a panel or support rod and securing with either bolts or zip-ties.

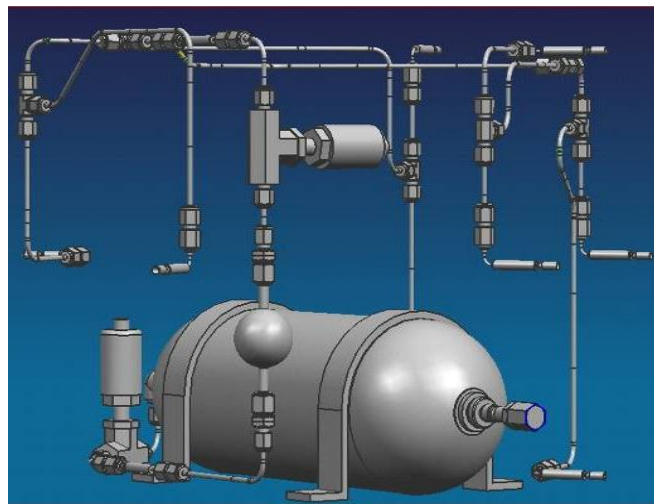


Figure 5.3. CDR Model of the Propulsion System

As the satellite was arranged, there was no room on a panel to place the regulator and transducers. Adding a vertical support rod would have been impossible given the planned assembly procedures. The only option was to add either a shelf or horizontal support above the tank. As can be seen in the FCR model of the system (Figure 5.4), a horizontal support was chosen. This decision is discussed in the next section. The final FCR model is compact to take advantage of the open space above the tank and minimize

the volume consumed by propulsion components. The lines and components wrap around the top of the tank. The tank mounts also serve supports and fastening locations for many of the other components. The NS-4 protoflight propulsion system was reproduced exactly to the specifications of this FCR model.

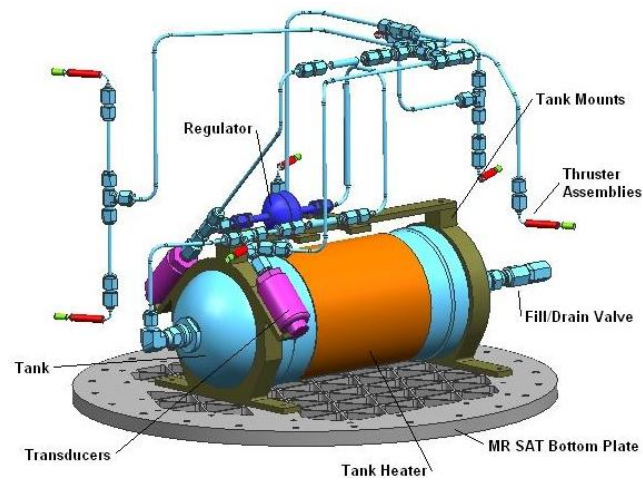


Figure 5.4. FCR Model of the Propulsion System

5.2.2. Assembly of MR SAT. The panels of the s/c were numerically labeled to facilitate integration. Components would be added to each panel first, then the panels would be bolted together completing the satellite. The propulsion system would require components to be placed on the top panel, bottom panel, Panels 1, 2, 4, and 6. Panels 3 and 5 would not have any components since these panels would have to remain off until last so all final connections of components could be made.

To assembly MR SAT, the core hardware would be attached to the bottom panel. The side panels would then have propulsion components added. The satellite assemblers would bolt Panels 1, 2, 4, and 6 to the bottom panel. The propulsion assembly of the top panel would be lowered into the satellite and all connections between lines and fittings would be tightened. Finally, the top panel would be added and bolted to the side panels.

The propulsion assembly of the top panel would be secured to the top panel using zip-ties and Arathane 5753. Figure 5.5 illustrates the satellite during assembly and the addition of the top panel propulsion assembly.

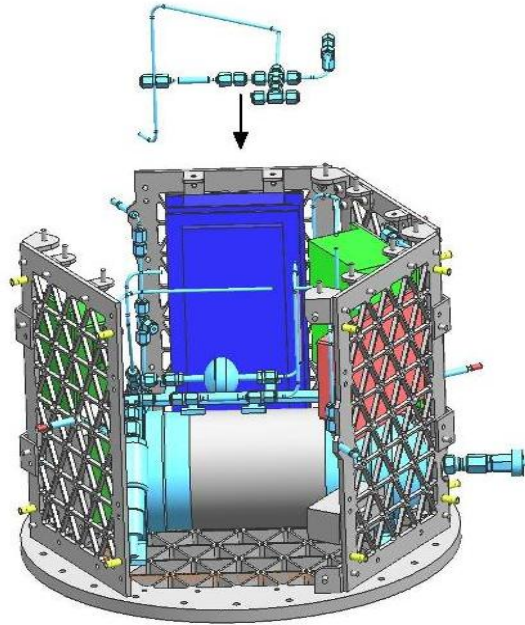


Figure 5.5. Final Propulsion Components Added to MR SAT

5.2.3. Core Hardware Integration. The core hardware assembly consisted of several components of the propulsion system. Specifically included were the tank, pressure transducers, regulator, and the first isolation valve. The plan for the core hardware was to create a module that could be integrated to the bottom panel and secured using only a few bolts. The assembly is illustrated in Figure 5.6. When the satellite was assembled, only a single connection point would be present in the module to tie the core hardware in with the web of tubing running out to the thrusters.

To integrate the tank into the s/c, the tank had to be oriented between the corners of adjoining panels as see in Figure 5.7. The length of tank and size of the battery and

computer boxes restricted the core hardware to this orientation. A custom 90° elbow for the tank outlet had to be designed by Swagelok to fit within the limited space of the corner. The elbow was designed to swivel to easily align the fitting with the tubing. Seubert discusses the design further in reference [13]. On other corner, the panels had to be notched to allow the fill/drain valve to project out. Once filled the valve is capped as seen in Figure 5.8.

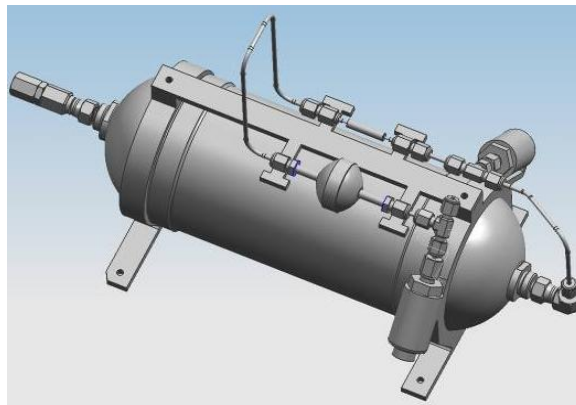


Figure 5.6. Core Hardware of the Propulsion System

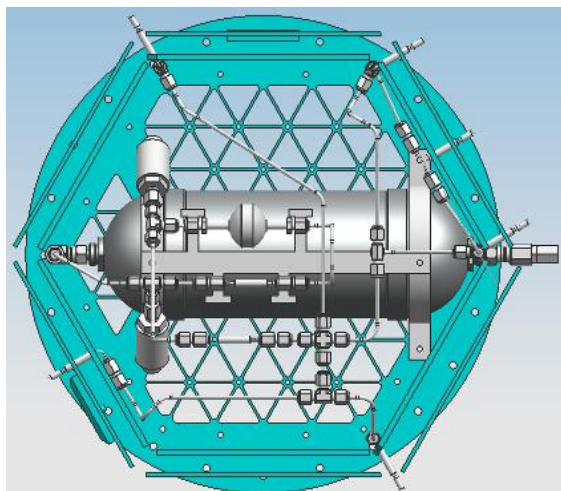


Figure 5.7. Orientation of the Propulsion System in MR SAT (top view)

Two factors influenced the core hardware assembly: compacting the volume of the system and supporting hardware that could not be integrated on a side panel. Figure 5.9 illustrates the fully integrated satellite excluding a side panel. Notice the large battery box (in red) and large computer box (in teal). These two components limited the methods to support components in center of the s/c. The components inside each box required a large volume of space. To integrate a shelf into the s/c would have required cutting those boxes in half, which was not an option. The only choice was to support a shelf or framework from the top or bottom panels.

The developed plan was to frame in the tank with a supporting structure that mounted to the bottom panel, held the tank in place, and carried the core components. The framework consists of two custom mounting brackets and a “mount bridge.” Figure 5.10 illustrates the mounting brackets which were manufactured from a 3/4 in. plate of aluminum 6061. The brackets feature wide feet for bolting to the bottom panel and a large pad on top for fastening the mount bridge using #10 bolts. The shape of the brackets was achieved through water-jetting. The centers were roughly cut to a small circular diameter then the edges of the centers were machined down to match the curvature of the tank’s hemispherical ends. The tank was manufactured with a thick lip where the electron beam weld jointed the hemispherical ends to the cylindrical center. The mounts were designed to mate with the tank at the lip to prevent any movement of the tank. This design eliminated the hazard of a friction hold as seen in the CDR version. The bracket mated to the outlet side of the tank features two large projections. These surfaces would be used to support and secure the pressure transducers.

To add rigidity to the top of the mounts and provide support for components, a bridging piece was added. This structure could have been a small isogrid panel or small plate of aluminum, but to minimize weight the structure was limited to a narrow strip of aluminum. The strip was water-jetted to have four tines projecting out at specific locations. The tines would be used to support the regulator and isolation valve at the Swagelok fittings. Zip-ties applied across the tines and Swageloks would secure the hardware. The mount bridge can be seen in Figure 5.6.



Figure 5.8. Panel Cut-out for Fill Valve

The last feature of the core hardware was the bent line. A 1W heater had to be integrated into the system before the regulator. The rectangular heater was 0.35 in. width and 3.5 in. long. The presence of a component box prevented routing the line straight for 3.5 in. then bending back to connect to the regulator. The only space to run a long segment of tubing was vertically. So, four 90° bends were required in the segment to fit in the heater. All the components except the tank, would be secured to the support brackets by zip-ties and potting compound Arathane 5753.

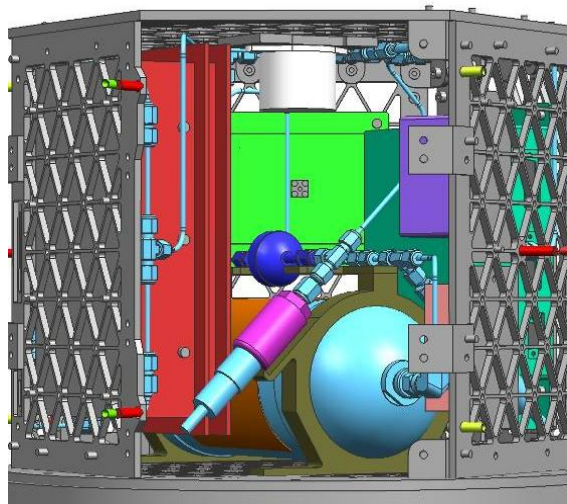


Figure 5.9. Propulsion System Integrated into MR SAT

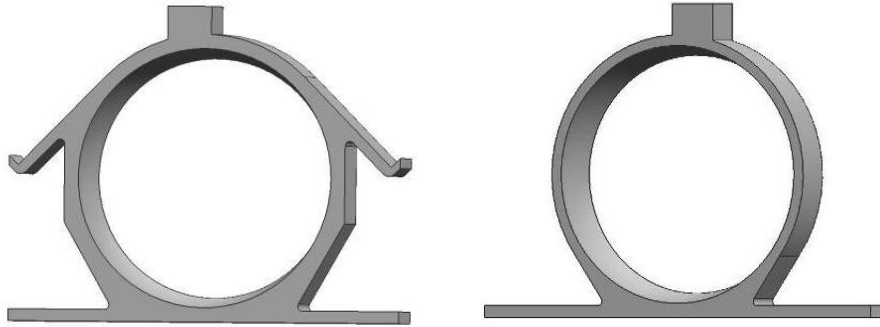


Figure 5.10. Tank Mounts of the Propulsion System

5.2.4. Panel Hardware Integration. Panel 1 featured the cluster of four thrusters, Panel 2 featured placements for two thrusters, and Panel 4 and Panel 6 featured single thrusters. The top panel of MR SAT featured a web of tubing distributing the propellant from the connection of the core hardware assembly to all side panels. Also integrated into the top panel was the second isolation valve. The plan was to have one connection point for each panel and one line running down from the top panel. Due to space limitations and integration steps, the plan had to be revised. For Panel 1, two connection points were necessary. Each connection would service two thrusters. For Panel 4 and Panel 6, a single tee fitting would be used to connect the single thrusters. However, this tee had to be placed on the top panel so that the fittings could be tightened with a wrench. Only Panel 2 would follow the original plan of a single connection point. Figure 5.11 shows the type connection point featured on Panels 1 and 2.

The main challenge of integrating onto the panels was avoiding boxes, bolts, and brackets while still maintaining the minimum bend radius and correctly connecting to the fittings. Figure 5.12 illustrates the limited space for the propellant lines on a panel. A significant amount of time was required to redraw the tubing to satisfy the Propulsion, Structures, and Integration subsystems.

To facilitate integration to the side panel, thruster supports had to be designed into the panels. Figure 5.13 shows all four supports for the thrusters. For the corner thrusters, tabs with a single hole were added to the panel. For the Panel 1 thrusters, the two side thrusters were supported by two slits while the other two thrusters were supported by a

corner of a isogrid triangle. For Panel 4, the thruster was positioned in the center of the panel and placed through the center circular cut-out of the isogrid. The thrusters would be secured in place by zip-ties and Arathane 5753.

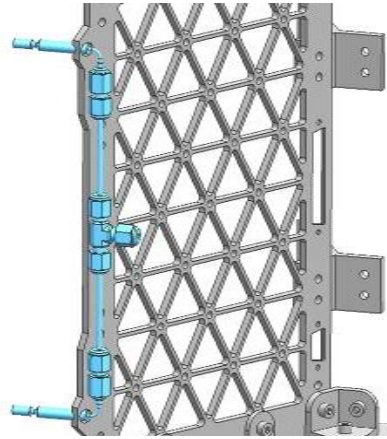


Figure 5.11. Connection Point of a Panel Assembly

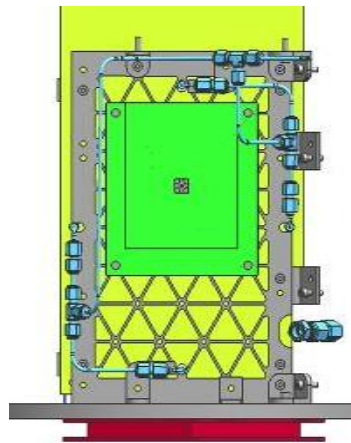


Figure 5.12. Propellants Lines Placed to Avoid Hardware and Connection Points

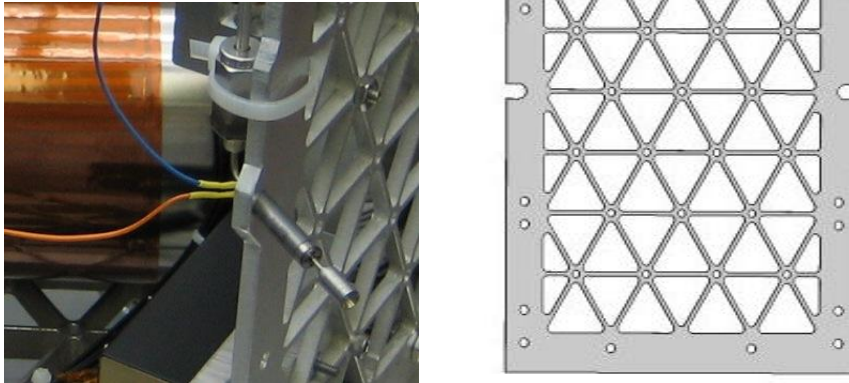


Figure 5.13. Panel Supports for Thrusters

5.3. ASSEMBLY PROCEDURES

Precise, repeatable, and detailed instructions are needed for the assembly and integration of the system into the s/c. Assembly procedures were constructed to accomplish this task. For the propulsion system, eight distinct documents were written to achieve the complete assembly of the propulsion system inside the s/c. Each document is briefly described. Appendix C contains samples of the line manufacturing, heater attachment, and module procedures for reference and illustration purposes. Ziegler illustrates the format of the procedures in reference [6].

5.3.1. Propellant Line Manufacturing Procedures. This procedure was established to ensure reproducibility of the multiple tube segments connecting the propulsion components. From testing to the final build, segments of tubing may need to be replaced due reaching the maximum constriction of opening of the stainless steel tubing. Reproducing the segments exactly is needed to ensure the system assembles and integrates identically.

The stainless steel tubing stock comes in 6 ft lengths. The procedure specifies the lengths to which each segment needs to be cut. The exact lengths of the tubing were determined using the CAD model of the system. The bends in the lines are produced by a tube bender. The bend radius was set by the radius of the bender. The tube bender must have a radius that meets the minimum radius recommended for 1/8 in stainless steel tubing by Swagelok. The structural integrity of the tubing must be preserved. The

procedure dictates that a tube bender is utilized for shaping the propellant lines. Without the bender, the tube segments could be kinked or a weak point formed that could rupture during pressurization of the system.

5.3.2. Heater Attachment Procedures. This procedure document directly follows the heater manufacturer's recommendations for attaching the heaters to a surface. The procedures however have been condensed and tailored for the application to the propulsion system. Two attachment processes are explained in the procedures: attachment with a pressure sensitive adhesive (PSA) backing and attachment with shrink bands. These procedures ensure that the heaters are attached properly, but most importantly that air pockets between the heater and the attachment surface are eliminated. Any air pockets can lead to hot spots and ultimately a failure point as a result of the concentration of heat. The PSA is the primary attachment method while the shrink band serves as a backup. This was done at the recommendation of the heater manufacturer. The shrink bands ensure that the heater does not curl up due to failure of the PSA at the edges of the heater.

5.3.3. Core Hardware Module Procedures. This procedure was written for the purpose of assembling the core propulsion components of the system into a module that would easily integrate into the MR SAT s/c. The module is built around the propulsion tank. A framework is formed around the tank for the purpose of supporting the other core components. These components wrap around the top of the framework.

5.3.4. Side Panel Module Procedures. These procedures specify the creation of modules consisting of lines and fittings for attachment to the side panels of the s/c. By constructing these modules, integration is easier than if each fitting and line were attached individually. In many cases, the fittings and lines simple could not be attached individually since the wrench could not fit in the space or fit adequately enough around the connections to do any turns.

5.3.5. Procedures for S/C Integration. In the overall MR SAT s/c assembly procedures, steps specific to the propulsion are stated. These steps cover how the various subassemblies for the panels and core hardware are finally connected to complete the propulsion system. The connection points were placed for ease of access and to ensure proper tightening. The order of assembly of the s/c can be reviewed in Section 5.2.2.

5.4. OPERATIONAL PROCEDURES

Two procedures documents were written by the end of the NS-4 competition to specify some of the ground operations involving the propulsion system. These procedures were the filling and draining of the propulsion tank procedures. Critical for filling of the propulsion system, the procedures dictated that pressure was to be monitored. Over pressurization could present a danger and safety violation. Draining the system recommends not to spray the R-134a on personnel as the liquid is a skin irritate. The important detail in both procedures is the use of the proper filler fitting. The fill/drain valve was designed to mate with a specific filler fitting. Any other device may damage the fill/drain valve.

5.5. LESSONS LEARNED AND FUTURE DEVELOPMENT

The lessons learned during assembly, integration, and operation of the propulsion system is detailed in this section. Included are recommendations that potentially could solve the challenges experienced.

5.5.1. Assembly and Integration. Within the Propulsion subsystem, integration involved tightening several fittings. While Propulsion had the most complete and accurate procedures developed for the assembly of the FCR protoflight satellites, inexperience with the hardware and tools hampered the assembly and integration of the system. No one on Propulsion had used Swagelok fittings before FCR. Based on instructional information from Swagelok documents, the tubing would stay in the fittings without having to apply any turns to the connections. By having loose connections, the tubing could be rotated to help with the alignment of the lines. Unfortunately, the subsystem discovered that the tubing would often slip out of the fittings. For the top panel assembly, all the connections needed to remain loose to align the lines with fittings. The assembly crumbled in the hands of the personnel assembling the s/c. The solution was to tighten the connections to hand tight, then apply a 1/4 turn with a wrench. This amount of turning tightens the connection enough to hold the tubing in place. The remainder of 1/2 a turn can be added later to fully tighten the connection resulting in an

equivalent 3/4 turn. Also to ensure a good seal, the tubing must be fully inserted into the fitting. Learning to identify when a tube has slipped out is a necessary skill.

Tightening the connection also had an unforeseen side effect. The torque applied to the fittings would cause bending to occur in the thin 1/8 in. tubing. The extra bending made it a challenge to secure components and almost destroyed hardware and fittings. The valves use very thin tubing. As a result, the added Swagelok fittings almost broke off. Better support for the valves needs to be designed into the system. The couplings for the transducers almost met a similar fate as the valves. Care should be taken not to press the couple end into the tank mounting bracket or else the coupling will bend and break. In general, the recommendation would be to work in Swagelok fittings with rotatable fittings periodically to prevent bending. This way the system would not be fully clamped and the tubing can freely rotate instead of bending.

Finalizing the design of the satellite promptly after CDR is critical. Having a s/c constantly changing hampers any decision on fitting counts, getting parts timely, and wastes resources on extra redesign work.

When conducting assembly and integration, a picture is helpful. As the saying goes, "A picture is worth a thousand words." While Propulsion did not necessary have an issue not having illustrations, the challenge the subsystem faced was inaccurate, not detailed enough, or completely wrong pictures. Practicing with procedures is recommended before actually assembling or integrating so the bugs can be worked out of the procedures. If detail is needed and cannot be achieved in the photo of the procedure list, include an appendix with the assembly procedure document and attach larger illustrations.

To minimize number of connections and leak points, adding a propellant distribution node is recommended. Instead of having a web of lines scattered through the s/c as was done in NS-4, a central distribution after the regulator would allow for a streamlined system. A node with seven connection could service six panels each with two thrusters. This would be the maximum number of thrusters needed to establish six degrees of freedom. If a distributor or manifold device cannot be promptly located, the recommendation is to discuss manufacturing a custom fitting with Swagelok. The company has worked with the team in the past to customize hardware. There would be

added cost and lead time, but if planned in advance there would be not significant impact to schedule or resources. A component could also be made in-house through the manufacturing abilities of the department machine shop. However, designing, testing, and verifying the component could consume valuable personnel resources when other critical tasks need to be completed. Figure 5.14 illustrates an example of the propulsion distributor.

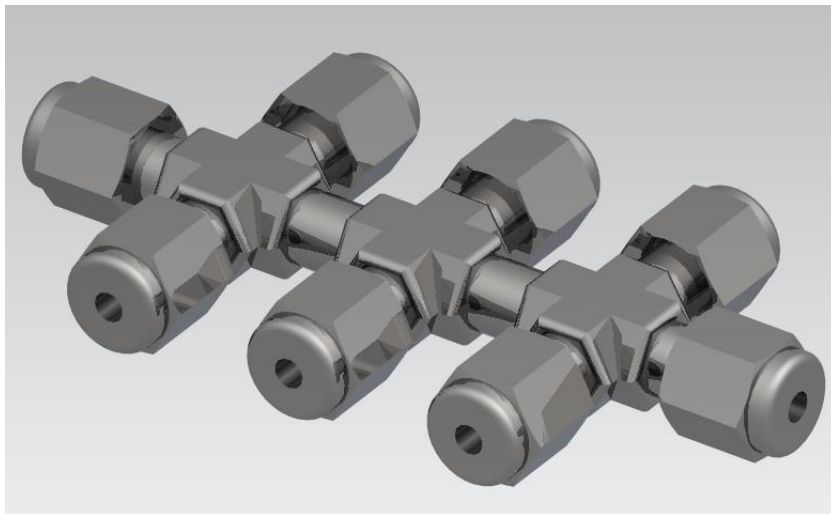


Figure 5.14. Example Propulsion Distributor

5.5.2. Operations. After NS-4, the subsystem had the opportunity to conduct some operations of the propulsion system. The challenge of the operating the system was the lack of documents and procedures. The author's participation in operations of the system was limited to pressurizing the system and attempt to conduct system tests. Three documents became apparent for operation of a cold gas system: a pressurization log, a connection turn count log, and a system leak check procedure. Examples of the two logs can be seen in Appendix B.

The pressurization log is needed to record how often the system is pressurized. A pressure vessel has a limited number of cycles before a retest is needed to verify that the

vessel has not reached the end of operation life. The turn count log is to establish the number of turns applied to a connection point and the amount of constriction a segment of tubing undergoes. Each time a connection is tightened, loosened, and retightened, an additional rotation of a turn is required to seal the connection. The added tightening compresses the stainless steel tubing and constricts the fluid flow further. Eventually, the tubing will not compress and the connection will leak. By logging the turns, the subsystem can keep record of when a segment of tubing needs to be replaced due to too many applied turns. The leak check procedures would aid in quickly determining leak locations systematically.

6. SUMMARY REMARKS

This thesis describes the management and organization used by the M-SAT team to develop a pair of satellites for the University Nanosat Program. The processes described pertain to the program management role, which when paired with the Systems Engineer, complete the student leadership of the team. The techniques discussed facilitate the successful completion of the project by providing the means to monitor and assess the progress of the project. The techniques were successfully implemented in the Propulsion subsystem, which started out behind schedule, but with proper management was able to produce a functional system for NS-4 and testing post-competition. Some of the management techniques were used in the NS-4 competition and enabled the team to take third place in the competition. The opportunity existed to finish the satellite design and construct a flight-ready s/c. However, the progress was marginal and achievement of the flight-ready s/c eluded the team. The failure originated from not utilizing all the management tools available (i.e. no work breakdown structure) and incorrectly or poor utilization of other tools. Established in this thesis are the management aspects that could be improved and lead to successful completion of a satellite from start to completion of the flight-ready unit.

The aspects of program management influence the progress of each subsystem of the developing s/c. Discussed in the remainder of the thesis was the development of the propulsion system for the MR SAT satellite. Specifically, the selection of the propellant R-134a and hardware are discussed in detailed. Further highlighted was the progress in determining improvement to the valves, a critical piece of hardware, for effective operation with R-134a and a vacuum environment. Should the valve not be able to operate in vacuum or with R-134a, new valves would need to be located and would require redesign of the propulsion system. An outgassing test is described which may facilitate the improvements establishing the outgassing characteristics of the potential valve seal materials. Finally, the integration of the system into MR SAT is reviewed.

APPENDIX A.
SAMPLE MANAGEMENT TECHNIQUES AND CONFIGURATION
MANAGEMENT DOCUMENTS

- Construct subsystem requirements
- Research types of propulsion systems
 - Electric options
 - Chemical options
 - Cold gas
- Determine system configuration
 - Determine thruster locations
 - Establish basic hardware list
 - Establish volume for system
- Research off-shelf hardware
 - Tank
 - Regulator
 - Valves
 - Fittings
 - Pressure transducer
 - Heaters
- Manufactured tank
 - Material trade study
 - Investigate aluminum
 - Investigate titanium
 - Investigate stainless steel
 - Design tank
 - Investigate optimal dimensions
 - Model in NX
- Integration of system
 - Construct initial assembly procedures
 - Divide system into subsystems
 - Plan tubing manufacturing procedures
 - Plan heater attachment procedures
 - Develop core hardware procedures
 - Develop panel procedures
 - Second iteration of procedures
 - Third iteration of procedures
 - Construct initial procedures for satellite integration

Figure A.1. Sample of Propulsion Work Breakdown Structure

155900-01 (PE) New Order

154800-00

OCI electronics corp. 200 NEWTON ROAD PLAINVIEW, N.Y. 11803-4381
 00/09/14 PHN 516-293-6630
 13.44.55 FAX 516-293-5192

OCI electronics corp. 200 NEWTON ROAD PLAINVIEW, N.Y. 11803-4381
 DUNS# 04-920-0231
 TWX 510-224-6550

UN00-270

JACKSON & TULL
 AIRFORCE RESEARCH LAB/BLDG 595
 1851 CHARLENE DR/ATT:MC CROREY
 KIRTLAND A.F.B., NM 87117

JACKSON & TULL
 AIRFORCE RESEARCH LAB/BLDG 595
 1851 CHARLENE DR/ATT:MC CROREY
 KIRTLAND A.F.B., NM 87117

TO VERBAL VERBAL

CUSTOMER'S ORDER NO. CUSTOMER'S ORDER NO.

DATE	PACKING SLIP NO.	TERMS	FOR	SHIPPED VIA	PART	COMP.	S
09/14	154800-01	CREDIT CARD	PLAINVIEW	FEDERAL EXPRESS			

ITEM	QTY. ORDERED	QTY. SHIPPED	DESCRIPTION	DATE CODE	INSPECT REINSPECT DATE	MFG.
1	10	10	1N5806JANTX DIODE ADD HANDLING FEE	0015		MSW
1	1	1	HANDLING FEE MISC SHIP TODAY - FEDX STD If shipping via Federal Express use Acct. [REDACTED]			ZZZ

CERTIFICATE OF COMPLIANCE

IT IS HEREBY CERTIFIED THAT ALL ARTICLES IN THE ABOVE SHIPMENT AND IN THE QUANTITIES AS CALLED FOR IN THE ABOVE CONTRACTORS PURCHASE ORDER ARE IN CONFORMANCE WITH THE REQUIREMENTS, SPECIFICATIONS, AND DRAWINGS APPLICABLE TO THAT ORDER.

Lay Stern
 Signature Quality Control

RECEIVED
 SEP 15 2007
K. McCreary
 9/15 C. U. Roy

JAN TRACEABILITY

I HEREBY CERTIFY THAT THE DEVICES SHIPPED AGAINST THE ABOVE REFERENCED ORDER ARE FROM THE SAME LOT/SHIPMENT AS THAT COVERED BY THE ATTACHED MANUFACTURER'S DOCUMENTATION. ORIGINAL DATE CODES AND LATEST INSPECTION/REINSPECTION DATES ARE SHOWN NEXT TO EACH LINE ITEM WHERE APPLICABLE.

SIGNATURE *Lay Stern*
 DATE 9/14/07

OCI electronics corp.

CLAIM FOR ANY SHORTAGE OR DEFECTIVE MATERIAL MUST BE MADE WITHIN 10 DAYS AFTER RECEIPT OF THIS MATERIAL. OUR CONSENT MUST BE OBTAINED BEFORE RETURNING ANY MATERIAL.

PACKING SLIP

Figure A.3. Sample Certificate of Compliance

REQUEST FOR DEVIATION/WAIVER		RFD/W NUMBER	REV.
APPLICABLE REQUIREMENT (DOC., PARA.)	SHEET 1 OF ____		
<p>APPLICABLE REQUIREMENT (DOC., PARA.) (Note: Most likely a NS-4 User's Guide and/or derivative requirement.)</p>		<p>WBS (Note: Univ. structure, if applicable.)</p>	
<p>REASON FOR WAIVER REQUEST: (Note: Include all relevant technical information, to include drawings, schematics, diagrams, photographs, test data, test reports, analysis reports, etc. Provide sufficient detail to completely describe the problem and proposed resolution.)</p>		<p>EFFECTIVITY</p>	
<p>PROPOSED REQUIREMENTS WAIVER / IMPACT ASSESSMENT (SYSTEMS & SCHEDULE): <input type="checkbox"/> CLASS I <input type="checkbox"/> CLASS II</p>		<p>REVIEW SIGNATURES (Univ.)</p> <p>ORIGINATOR / DATE _____</p> <p>REA / DISCIPLINE / DATE _____</p> <p>REA / DISCIPLINE / DATE _____</p> <p>REA / DISCIPLINE / DATE _____</p> <p>REA / DISCIPLINE / DATE _____</p> <p>IT MANAGER / DATE _____</p> <p>SAFETY / DATE _____</p> <p>SYSTEMS ENGINEER / DATE _____</p> <p>CONFIGURATION MANAGER / DATE _____</p> <p>PROGRAM MANAGER / DATE _____</p>	
<p>DISPOSITION (Completed by AFRL)</p> <ul style="list-style-type: none"> - CLASS I CHANGES-PROGRAM MANAGER APPROVAL/DISAPPROVAL REQUIRED - CLASS II CHANGES-REQUIREMENTS GOVERNING BODY APPROVAL/DISAPPROVAL REQUIRED <p>APPROVAL SIGNATURE _____ DATE _____</p> <p>DISAPPROVAL SIGNATURE _____ DATE _____</p>			

REV. 2/18/00

VSSV-FORM-RFDW-001

Figure A.4. Sample Request for Deviation/Wavier

CERTIFICATION LOG

CERT LOG NO.	PURPOSE OF LOG <input type="checkbox"/> FAB / ASSY <input type="checkbox"/> I&T	PROJECT NAME				DATE
PART NUMBER	NOMENCLATURE	QTY	S/N	H/W TYPE <input type="checkbox"/> FLT <input type="checkbox"/> FLT QUAL <input type="checkbox"/> NONFLT <input type="checkbox"/> ETU		
ASSY DWG NO.	REV	ASSY P/L NO	REV	ASSY W/L NO.	REV	
NEXT ASSY P/N		PREV ASSY CERT LOG NO..		NEXT ASSY CERT LOG NO.		
MFG APPROVAL/DATE²		QA APPROVAL/DATE²		ENGINEERING APPROVAL/DATE²		
UNINCORP ECR	REV	DWG/DOC AFFECTED	S/N AFFECTED	INCORP BY OPER/DATE²	QA VERIF/DATE²	
EVENT NO.	RESP.ORG	EVENT DESCRIPTION¹		INSP BY/DATE²	PROB RCD ITEM NO.	
	QC	FINAL QA ACCEPTANCE			CLOSE OUT BY/DATE	
RETROFIT IS NO.		PART NUMBER		NOMENCLATURE	SERIAL NUMBER	

Notes:
¹ For other events see continuation sheets
² Field must contain handwritten signature and date

Figure A.5. Certification Log

PROBLEM FAILURE REPORT

PFR NO.	PROJECT NAME				DATE
PART NUMBER	NOMENCLATURE	QTY	S/N	H/WTYPE <input type="checkbox"/> FLT <input type="checkbox"/> NONFLT <input type="checkbox"/> FLT QUAL <input type="checkbox"/> ETU	
TEST PROCEDURE NUMBER	PARAGRAPH NUMBER		FOUND DURING <input type="checkbox"/> TEST <input type="checkbox"/> INSPECTION		
ORIGINATOR / DATE¹	ASSIGNED TO / DATE				
DESCRIPTION OF FAILURE					
(Note: Include all relevant technical information, to include drawings, schematics, diagrams, photographs, test data, test reports, analysis reports, etc. Provide sufficient detail to completely describe the problem and proposed resolution.)					
CORRECTIVE ACTION TAKEN					
COST IMPACT			SCHEDULE IMPACT		
TRANSITIONED TO <input type="checkbox"/> PFR#	<input type="checkbox"/> ECN#	<input type="checkbox"/> STR#	<input type="checkbox"/> RFD/W#	<input type="checkbox"/> CERT LOG #	<input type="checkbox"/> MDN #
COGNIZANT ENGINEER / DATE¹	QA / DATE¹		CUSTOMER / DATE¹		APPROVAL / DATE¹

Notes:
¹ Field must contain handwritten signature and date

Figure A.6. Sample Problem Failure Report

	MANUFACTURING DEVIATION NOTICE	SHEET 1 OF ____	MDN NUMBER
PART DESCRIPTION: PART/ASSEMBLY NO.: _____ SIN _____ DRAWING NO.: _____ REV. _____			
MANUFACTURING COMPLIANCE RECORD			
IS A CHANGE FOR FUTURE UNITS REQUIRED? <input type="checkbox"/> YES <input type="checkbox"/> NO			
REASON FOR CHANGE: (Note: Include all relevant technical information, to include drawings, schematics, diagrams, photographs, test data, test reports, analysis reports, etc. Provide sufficient detail to completely describe the problem and proposed resolution.)			
CORRECTIVE ACTION TAKEN: <input type="checkbox"/> CLASS I <input type="checkbox"/> CLASS II			
REVIEW SIGNATURES ORGANIZATION / DATE REA / DISCIPLINE / DATE REA / DISCIPLINE / DATE REA / DISCIPLINE / DATE REA / DISCIPLINE / DATE SET MANAGER / DATE SAFETY / DATE SYSTEMS ENGINEER / DATE CONFIGURATION MANAGER / DATE PROGRAM MANAGER / DATE			
EFFECTIVITY			
WBS			
DISPOSITION - CLASS I CHANGES - PROGRAM MANAGER APPROVAL REQUIRED - CLASS II CHANGES - REQUIREMENTS GOVERNING BODY APPROVAL REQUIRED			
APPROVAL SIGNATURE _____		DATE _____	
DELAPPROVAL SIGNATURE _____		DATE _____	

REV. 02/18/00

VDSV-FORM-MDN-001

Figure A.7. Sample Manufacturing Deviation Notice



	<p>ENGINEERING CHANGE REQUEST</p>	<p>SHEET of</p>	<p>ECR NUMBER ECR-</p>	<p>REV.</p>
<p>REASON FOR CHANGE:</p>				
<p>AFFECTED DOCUMENTS (DOC. NUMBER, TITLE, REVISION):</p>				
<p>DISCUSSION OF CHANGES / IMPACT ASSESSMENT (SYSTEMS & SCHEDULE): <input type="checkbox"/> CLASS I <input type="checkbox"/> CLASS II</p>				
<p>ORIGINATOR / DATE</p>				
<p>REA / DISCIPLINE / DATE</p>				
<p>REA / DISCIPLINE / DATE</p>				
<p>REA / DISCIPLINE / DATE</p>				
<p>REA / DISCIPLINE / DATE</p>				
<p>INTEGRATION MANAGER / DATE</p>				
<p>CONFIGURATION MANAGER / DATE</p>				
<p>PROGRAM MANAGER / DATE</p>				
<p>SYSTEMS ENGINEER / DATE</p>				
<p>DISPOSITION (SYSTEMS ENGINEER)</p>				
<p>APPROVAL SIGNATURE _____ DATE _____</p>				
<p>DISSAPPROVAL SIGNATURE _____</p>				
<p>MSAT-FORM-ECR-001</p>				
<p>REV. 04/01/10</p>				

Figure A.8. Sample M-SAT Engineering Change Request

		QUALITY ASSURANCE DOCUMENT FOR MANUFACTURED PARTS		SHEET of	
DISCREPANCIES FOUND? <input type="checkbox"/> Y <input type="checkbox"/> N		MDN NEEDED? <input type="checkbox"/> Y <input type="checkbox"/> N		MDN APPROVED? <input type="checkbox"/> Y <input type="checkbox"/> N	
DRAWING NO.:			FILED MDN NO.:		
PART DESCRIPTION:					
DRAWN BY / DATE			MANUFACTURED BY / DATE		
/			/		
INFORMATION INCLUDED ON PART DRAWING					
MATERIAL	<input type="checkbox"/> Y <input type="checkbox"/> N	INSP BY / DATE	/		
SURFACE FINISH	<input type="checkbox"/> Y <input type="checkbox"/> N	INSP BY / DATE	/		
PROCESS	<input type="checkbox"/> Y <input type="checkbox"/> N	INSP BY / DATE	/		
2 PERSON CHECKED	<input type="checkbox"/> Y <input type="checkbox"/> N	INSP BY / DATE	/		
VISUAL & MEASUREMENT INSPECTION					
MEASUREMENTS W/IN TOLERANCE	<input type="checkbox"/> Y <input type="checkbox"/> N	INSP BY / DATE	/		
SURFACE FINISH	<input type="checkbox"/> Y <input type="checkbox"/> N	INSP BY / DATE	/		
LIST OF DISCREPANCIES: (IF A "NO" IS LISTED ABOVE, EXPLAIN HERE)					
QA / DATE			STRUCTURAL MANAGER / DATE		
/			/		
INTEGRATION MANAGER / DATE			SYSTEMS ENGINEER / DATE		
/			/		
PART APPROVAL / DATE			DOCUMENT NUMBER:		
/			12-QA- - (12-QA-DOC #-PART NAME)		

MSAT-FORM-QAD-001

REV. 04/01/10

Figure A.9. Sample M-SAT Quality Assurance Document

APPENDIX B.
PROPULSION TRADE STUDY AND SAMPLE LOGS

Criteria	Units	Score					Weight	Tank Design Materials									
		0	1	2	3	4		5	Titanium Ti-6Al-4V		Stainless Steel 304		Aluminum 5083 O				
		Value	Value	Value	Value	Value		Value	RS*	WS**	Value	RS*	WS**	Value	RS*	WS**	
Density	g/cm ³	>9.0	7.0-9.0	5.0-7.0	5.0-3.0	3.0-1.0	<1.0	3	5.0-3.0	3	9	7.0-9.0	1	3	3.0-1.0	4	12
Physical Property : σ	MPa	<100	100-300	300-500	500-700	700-1000	>1000	2	700-1000	4	8	500-700	3	6	100-300	1	2
Physical Property : σ_y	MPa	<100	100-300	300-500	500-700	700-1000	>1000	2	700-1000	4	8	100-300	1	2	100-300	1	2
Cost		Very High	High	Mod High	Significant	Mod Accept	Accept	4	High	1	4	Significant	3	12	Significant	3	12
Stress Corrosion Resistance to NaCl		No	Below	Low	Moderate	High	Highly	2	No	5	10	No	5	10	No	5	10
Thermal Conductivity	W/m-K	<10	10.0-30.0	30.0-60.0	60.0-80	80.0-100.0	>100	2	<10	0	0	10.0-30.0	1	2	>100	5	10
Fracture Toughness		n/a	n/a	n/a	n/a	n/a	n/a	2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Weighted Score Totals								39							35	48	

Figure B.1. Trade Study of Materials for Propellant Tank

Document Name:	Pressurization Log	Fitting Description	Fitting Name	Connection Pt.	Turn	Preparer	QA	Date	Turn	Preparer	QA	Date
Document Number:	04-030	Tee	TML01	ML01	3/4	S Miller	J Miner	7/25/2010	1/4	S Miller	J Miner	8/1/2010
Revision:	A			ML02	3/4	S Miller	J Miner	7/26/2010				
Created By:	Shawn Miller			CpML01	3/4	S Miller	J Miner	7/27/2010				
Date Created:	6/1/2010	Coupling	CpML01	PtML01	3/4	S Miller	J Miner	7/28/2010	1/4	S Miller	J Miner	8/1/2010
Date Modified:	6/20/2010 SM	Cross	CML01	ML06	3/4	S Miller	J Miner	7/29/2010				
				L1	3/4	S Miller	J Miner	7/30/2010				
				L2	3/4	S Miller	J Miner	7/31/2010	1/4	S Miller	J Miner	8/1/2010
				L3	3/4	S Miller	J Miner	8/1/2010				

Figure B.2. Sample Propulsion Connection Turn Count Log

Document Name:	Pressurization Log		Pressure (psi)	Preparer	QA	Date
Document Number:	04-030	1	50	S Miller	J Miner	6/20/2010
Revision:	A	2	50	S Miller	J Miner	6/20/2010
Created By:	Shawn Miller	3	60	S Miller	J Miner	6/21/2010
Date Created:	6/1/2010	4	148	S Miller	J Miner	6/29/2010
Date Modified:	6/20/2010 SM	5	150	S Miller	J Miner	7/6/2010
		6	208	S Miller	J Miner	8/1/2010
		7				
		8				
		9				
		10				

Figure B.3. Sample Propulsion Pressurization Log

APPENDIX C.
SAMPLE PROPULSION PROCEDURES





Step #	Activity	View	Performer Initials/Date	QA Initials/Date
PT-01	Cutting Procedures: Cut each tube segment to length L as specified in Table 5-1 using the Tube Cutter/Saw.			
PT-02	Deburr ends 1 and 2 using the Metal File.			
PT-03	Place tubing in bench vice.			
PT-04	Drill out center hole using drill bit (both ends).			
PT-05	For each tube segments (ML01, ML03, ML05, L1, L2, L2a, L2a2, L2b, L2b1, L3a, L3b), mark the starting point of each bend in each segment as specified in Table 5-2 using a Sharpie marker.			
PT-06	ML01 Tube: Lay Tube on flat surface (Table) with end 1 pointed toward the individual bending.			
PT-07	Place tube bender at first bend location making sure that the 0° marks on the tube bender are aligned.			
PT-08	Bend to a 90° angle as shown (end 2 will point to the right when lying on Table).			

Figure C.1. Sample Tube Manufacturing Procedures


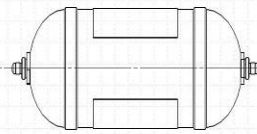


Step #	Activity	View	Performer Initials/Date	QA Initials/Date
PHA-02	Tank Heater HTk01: Attach Tank Heater HTk01 to the Tank Tk01 by following Steps 3-9 below which have been taken from Engineering Instructions 138 (EI 138).			
PHA-03	With the PSA release liner still intact, place the Heater HTk01 centered in the space between the raised rings on the Tank as shown. The short length of the heater will run axially along the tank. The heater ends will not touch as shown.			
PHA-04	Once the desired position is achieved, peel off the release liner from one corner of the Heater HTk01 while leaving the remaining release liner intact as shown. Tweezers may be helpful for lifting the liner. Avoid touching the exposed PSA.			
PHA-05	Apply the Heater HTk01 to the Tank in its correct position, beginning at the corner edge of the exposed PSA using firm, even hand pressure as shown.			
PHA-06	Slowly peel off the remaining release liner from the PSA while adhering exposed PSA to the Tank. Work from the adhered end outward to avoid trapping air.			
PHA-07	Use a metal roller 1 to press the Heater HTk01 onto the Tank. Roll from the center toward the edges in an effort to remove trapped air as shown.			
PHA-08	Place the installed Heater into a 100°C (212°F) vacuum oven for five to ten minutes. NOTE: The temperature should be set at least as high as the operating temperature, but not above 150°C (302°F) for polyimide insulation.			
PHA-09	Then, while the adhesive is still warm, repeat Step 7 above. A two to three day wet-out time will maximize adhesion.			

Figure C.2. Sample Heater Attachment Procedures

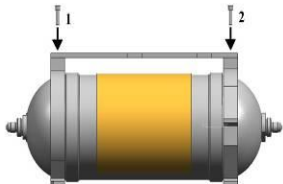
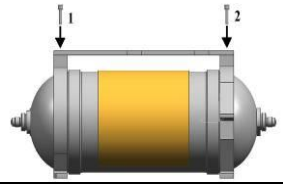
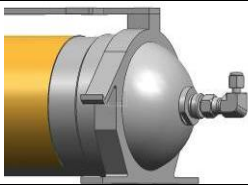
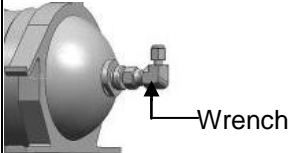

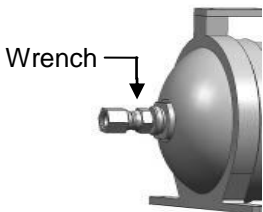
Step #	Activity	View	Performer Initials/Date	QA Initials/Date
PCHT-04	Insert 8-32 x 1/2" screw (Normal length) into first hole on top of mount bridge and torque to ### in-lb +- 1 in-lb. Record actual torque.			
PCHT-05	Insert 8-32 x 1/2" screw (Cut short length) into second hole on top of mount bridge and torque to ### in-lb +- 1 in-lb. Record actual torque.			
PCHT-06	Wrap Tank Tk01 in the MLI.			
PCHT-07	To join the two ends of the MLI, place a strip of MLI tape along the seam.			
PCHT-08	Connect side 1 of Tank Connector ESML01 to end 2 of Tank (outflow side of tank); tighten connector by hand until it stops.			
PCHT-09	Using the 5/8 in. wrench on side 1 of Tank Connector, apply a turn until connector stops.			
PCHT-10	Connect side 2 of Coupling CpFD to end 1 of Tank (inflow/fill side of tank); tighten connector by hand until it stops.			
PCHT-11	Using the 5/8 in. wrench on side 2 of Coupling CpFD, apply a turn until connector stops.			

Figure C.3. Sample Assembly Procedures

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VITA

Shawn Wayne Miller was born on December 13, 1983 in Poplar Bluff, Missouri. Shawn graduated from Rifle High School in Rifle, Colorado in May 2002. He then enrolled at the Missouri University of Science and Technology (formerly the University of Missouri – Rolla) to study Aerospace Engineering and earned a Bachelor of Science Degree in Aerospace Engineering in May 2006. Upon completion of this degree he remained at Missouri S&T to obtain a Master of Science Degree in Aerospace Engineering in December 2010.

While an undergraduate at Missouri S&T, Shawn was a member of the local American Institute of Aeronautics and Astronautics (AIAA) chapter and Sigma Gamma Tau (the Aerospace Engineering Honor Society). Over the past three and a half years, Shawn has been a member of the M-SAT satellite design team. He has been a member of the Propulsion and Structures subsystems as well as having served as a temporary Propulsion lead. His final position on the team was Program Manager with the responsibilities to be an overall team leader and director of the business aspects of the team.

