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INITIAL DESIGN, MANUFACTURE, AND TESTING OF A CUBELAB MODULE FRAME FOR BIOLOGICAL PAYLOADS ABOARD THE INTERNATIONAL SPACE STATION

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ABSTRACT OF THESIS

INITIAL DESIGN, MANUFACTURE, AND TESTING OF A CUBELAB MODULE
FRAME FOR BIOLOGICAL PAYLOADS ABOARD THE INTERNATIONAL
SPACE STATION

This thesis investigates the design of a CubeLab Module frame to facilitate biological research aboard the International Space Station (ISS). With the National Laboratory designation of the ISS by the United States Congress the barriers for use of the facility have been lowered for commercial and academic entities, allowing greater volume and diversity in the research that can be done. Researchers in biology and other areas could benefit from development and adoption of a plug-and-play payload containment system for use in the microgravity/space environment of the ISS. This research includes design and analysis of such a system. It also includes production and testing of a prototype. The relevant NASA requirements are documented, and they were considered during the design phase. Results from finite element analyses to predict performance of a proposed design under expected service conditions are reported. Results from functional testing of the prototype are also provided. A discussion of future work needed before the structure outlined in this thesis can become commercially viable is also presented.

KEYWORDS: Containment, CubeLabs Modules, International Space Station, Microgravity, NanoRacks Platform

Twyman Clements
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April 15th 2011
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INITIAL DESIGN, MANUFACTURE, AND TESTING OF A CUBELAB MODULE
FRAME FOR BIOLOGICAL PAYLOADS ABOARD THE INTERNATIONAL
SPACE STATION

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April 15th, 2011

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THESIS

Twyman Samuel Clements

The Graduate School

University of Kentucky

2011

INITIAL DESIGN, MANUFACTURE, AND TESTING OF A CUBELAB MODULE
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SPACE STATION

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THESIS

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A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Mechanical Engineering in the College of Engineering
at the University of Kentucky

By
Twyman Samuel Clements
Lexington, Kentucky
Director: Dr. John R. Baker
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Lexington, Kentucky
2011

To my Parents: Keene and Cathy Clements

ACKNOWLEDGEMENTS

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1   INTRODUCTION

This chapter begins with a history of the Kentucky Space Consortium, which serves as a common thread linking together all the components discussed throughout this thesis. An introduction to the CubeSat standard, its history, previous missions, and the community which has formed around this standard of satellites will also be discussed. As well, an introduction to the NanoRacks Platform, hardware that facilitates the use of micro gravity to a diverse pool of researchers, will be presented. The problem statement and scope of this thesis will be outlined to better define the design that this research will address. Finally, a section concerning the units used during the design and analysis portions will conclude the introduction.

1.1 History of Kentucky Space

Kentucky Space began in 2006 as a non-profit enterprise between universities, public organizations, and private companies within the commonwealth of Kentucky. The goal of Kentucky Space is to train students in the dynamics of spacecraft design, construction, testing and operation as a means of extending science and technology education, R&D, innovation and economic development in the state. The managing partner of this consortium is the Kentucky Science and Technology Corporation (KSTC), a private non-profit based in Lexington, Kentucky which seeks to increase technology research, commercialization, and economic development within the state. All missions undertaken by Kentucky Space are student led and student designed from concept to completion, with input from engineers and professionals in both academia and industry [1]. These missions are categorized into four areas: near space, sub-orbital, orbital, and International Space Station (ISS). All missions undertaken are multidisciplinary which allows students to gain knowledge and experience in a wide range of areas including systems engineering and project management.

1.1.1 Missions Profile

Previous Kentucky Space missions include Balloon-1, the consortiums first high altitude balloon, which included a GPS, environmental measurement sensors, and digital cameras. This mission also served as an outreach opportunity to grade school children who were able to fly "PearlSats", which are halved ping pong balls in which personal objects can be flown inside and retrieved later [1]. With regard to the sub orbital flights the consortium has developed three payloads for flights aboard experimental launch vehicles. Of these, the most successful was the deployment of a Kentucky Space payload out of the Hall 12.067 terrier-improved malamute sounding rocket launched from Wallops, Virginia, on March 27, 2010, shown in Figure 1-2 [2]. This event marked the first time a payload designed, built, and tested within the Commonwealth of Kentucky reached space. With this mission, Kentucky Space acted not only as payload developer, but as mission manager and integrator, further maturing the capabilities of the program. The payload for the mission, AdamaSat, tested the antenna deployment system for orbital satellites while additionally confirming the feasibility of ejecting CubeSat standard satellites from the 17" diameter sounding rockets typically used at the NASA Wallops flight facility [3].
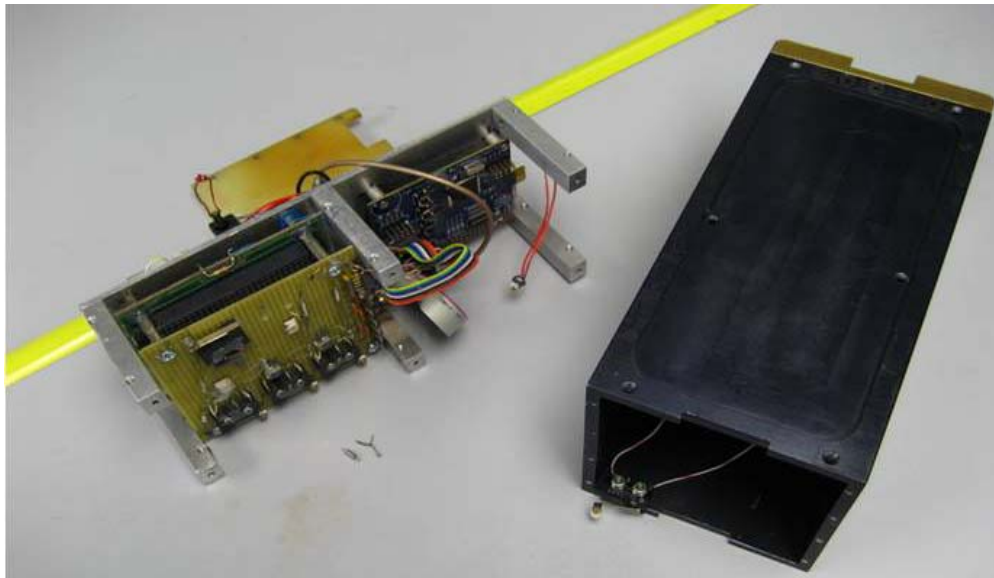
Figure 1-1: AdamaSat Deconstructed

Figure 1-2: Hall 12.067 Launch carrying AdamaSat

The flagship mission of Kentucky Space since its inception has been KySat-1, a 1U CubeSat. Adhering to the CubeSat standard constrains KySat-1 to a volume of 1 liter within which communication, power, structural, attitude control, and payload systems must be included. The primary mission of KySat-1 is to serve as an educational outreach mechanism to the university students designing the spacecraft and to the K-12 students and teachers, who can use the spacecraft, once in orbit, as a teaching platform in Science, Technology, Engineering, and Math (STEM) applications [4]. In January 2010, NASA announced that KySat-1 was one of three university built CubeSats manifested to be launched as part of the ELaNa (Educational Launch of Nanosatellite) program, which serves as a secondary payload of the NASA GLORY mission scheduled for launch in March 2011 [5]. This achievement marks the first NASA mission carrying student built satellites to orbit. With the ELaNa program expanding to become Project ELaNa, KySat-1 hopes to be the first of many NASA missions ferrying student satellites to Low Earth Orbit. Figure 1-3 shows the flight model of KySat-1 just before delivery for launch.

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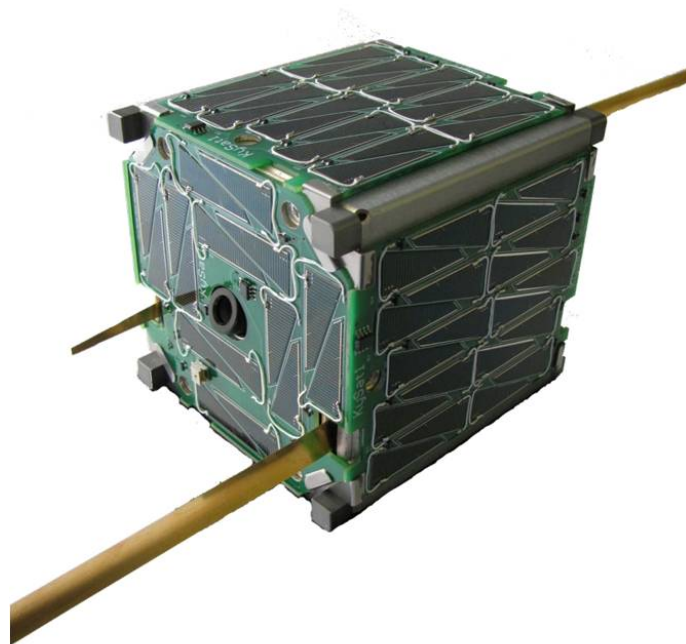
Figure 1-3: KySat-1 Flight Model

The final category of missions involves payloads built for use aboard the International Space Station (ISS). The ISS has been, to date, a 12 year international effort to build a fully functional space station and research laboratory orbiting 240 miles (386 km) above the surface of the earth moving at 17,500 miles per hour (32,410 km/s) [6]. With construction nearing completion ISS managers have turned their attention to broadening its capabilities for experimentation and allowing a wider range of developer's access. Under these circumstances, aerospace start-up NanoRacks LLC developed the NanoRack Platforms to accomplish these goals [7]. The NanoRack Platforms serve as an interface between small cube shaped experiments (CubeLab Modules) and existing space aboard the ISS dedicated for experimentation and research.

1.2   The NanoRack Platform

The NanoRack Platform serves as the first commercial means to have standard, miniaturize payloads aboard the ISS allowing for affordable and rapid access to a microgravity environment. The Platform, shown in Figure 1-4,

supplies power and data connectivity for up to 16 1U CubeLab Modules (explained below). NanoRacks Platforms were developed in the Space Systems Lab (SSL) at the University of Kentucky from October 2009 to January 2010. All engineering design, manufacturing, and flight verification of the two Platforms occurred during this time period. The Platforms were flown to orbit on STS-131, which launched on April 5, 2010, and STS-132 launched on May 14th, 2010. Installation and activation of the two Platforms occurred on July 12th and August 23rd 2010, respectively [8] [9].

Astronaut Shannon Walker is shown in Figure 1-5 giving a successful "thumbs up" sign after installation. Both NanoRacks Platforms can be seen behind her as well. The connection between the individual modules and the platforms uses the USB standard, allowing data transfer from the experiments to the earth. Retrieving data from the modules on orbit involves downloading the information through a USB cable to a laptop computer on station, then down linking the data through satellite constellations to the earth where the information is disseminated to the appropriate parties. As of March 2011, the combined NanoRacks Platforms allow up to 32 kg of research mass aboard the ISS.

Figure 1-4: Fully Assembled NanoRacks Platform

Figure 1-5: Astronaut Shannon Walker after NanoRack Installation

1.3 The CubeSat & CubeLab Standards

The CubeLab standard is a set of requirements to which payload developers must adhere for use with the NanoRack Platforms. The particulars of this standard are heavily based on the CubeSat standard, which has heritage and familiarity within the small satellite community. The following section outlines the history, requirements, and mission varieties that these two standards provide.

1.3.1 The CubeSat Standard

The CubeSat standard was developed in 1999 in a collaboration between Stanford University's Space Systems Development Lab (SSDL) and California Polytechnic State University as a means for students to develop hands-on experience in spacecraft design [10]. A secondary goal of the CubeSat standard was to decrease launch costs to allow more academic institutions access to fly spacecraft. CubeSats can be broadly defined as 10 cm x 10 cm x 10 cm cubes with a mass no greater than 1 kg, and additional constraints outlined in the CubeSat Design Specification (CDS) [11]. While 1U volumes are the most commonly used, larger 2U (10 cm x 10cm x 20cm) and 3U (10cm x 10cm x 30cm) CubeSats can be built when additional volume is needed.

1.3.2 The CubeSat Developers Community

Since the CubeSat Standards development, a diverse community including high school, collegiate and government entities, along with commercial companies, has formed around the use of CubeSat satellites for a variety of aerospace applications. This CubeSat community holds three developer's conferences a year where ideas are exchange, potential missions are presented, and discussion between developers allows for sharing of ideas. CubeSats have gained traction internationally as well, having been built by students in Japan, the Netherlands, and New Zealand [12] [13]. Similarly, large aerospace companies have taken notice, such as Boeing and Lockheed Martin, as well as a range of national research labs, which have flown missions for flight heritage, component testing, and scientific research [14]. With this combination of industry input and a small engaged community, CubeSats have become a widely accepted standard with a mission profile that includes payloads for space weather characterization, communications testing, and biological research, to name a few [15] [16].

1.3.3 The CubeLab Standard

The CubeLab Standard is an extension of the knowledge and standardization with which many students and industry engineers are familiar through CubeSats. The CubeLab Standard constrains developers to similar dimensions as CubeSats, and requires a USB type B port for power and data transfer. Since CubeLab Modules interface with the NanoRack Platforms inside the ISS, more volume within the structure is available for the payload as there is no need for thermal control, communications systems, or structural systems [17]. Also CubeLab Modules requiring greater volume can use 2U, 4U, and up to 2U x 4U configurations if needed as shown in Figure 1-6.
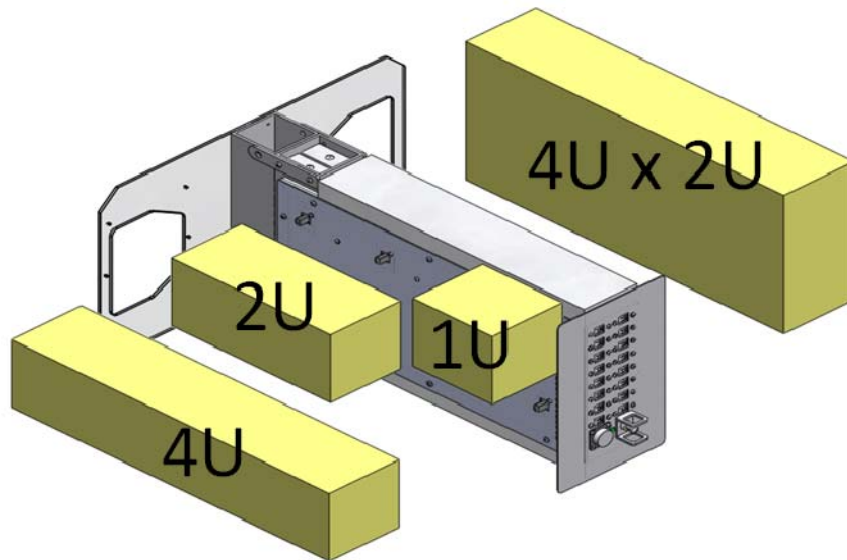
Figure 1-6: CubeLab Volume Options with a NanoRack Platform

As long as exposure to the space environment is not essential, any CubeSat payload can be converted to a CubeLab Module and used with the NanoRack Platform. This method would avoid the launch opportunity bottle neck that occurs with many student satellites. Additionally, CubeLab Modules can be manifested to fly to the ISS aboard the Russian unmanned Progress and manned Soyuz, the Japanese ATV, the European HTV, and the United States' Space Shuttle, as well as SpaceX's Falcon 9 and Orbital's Taurus II launch vehicles. The customizability of CubeLab Modules has allowed for a wide variety of development from high schools, universities, and industrial partners, with experiments including fluid mixing, plant growth, cancer research, and educational outreach initiatives [9].

1.4 Problem Statement

The work outlined in this thesis details the design, analysis, and testing, of a 1U CubeLab structure to facilitate biological related research aboard the ISS. With such a containment design future CubeLab Modules could host a variety of biological payloads and bring a generation of more complex CubeLab Module payloads to foster greater scientific research. Success of the design will be judged by its containment capability, customizability, and manufacturability.

1.5 Scope of Thesis

This thesis research is restricted to topics associated with successful completion of the problem statement. The numerous requirements and constraints relevant to the design process will be outlined in Chapter 3 before any design work or prototyping is described. A prototype has been designed, analyzed, built, and tested and is reported in Chapters 4 and 5. Design modifications for a flight model are presented in Chapter 6. This thesis concludes over viewing both the work completed and the verifications that the prototype structure did and did not meet, and discusses future research to be conducted.

1.6 Units

Due to a blend between the English and metric unit systems within the documentation used to create the containment CubeLab requirements, this thesis will not entirely conform to either system. To prevent confusion, the units used for various parameters are outlined in Table 1-1. This hybrid approach is attributed to the fact that the mechanical dimensions of the design adhere to the CubeLab Standard which uses metric units, while pressures outlined in NASA requirements use pounds per square inch (PSI). In addition, pressures will be stated in atmospheres in brackets () after psi readings, as a normalized comparison to standard atmospheric pressure. Finally stress analysis results will be listed in a form of Pascal's (e.g. MPa, KPa).

Table 1-1: Unit Systems Used

Metric	System Used	Units Used	Reasoning
Dimensions	Metric	mm	CubeLab Standard outlines maximum volumetric envelopes and USB placement in millimeters
Pressure	English	Psi (atm)	NASA requirements are stated in PSI for continuity. Atmospheres are included in parentheses as a normalized comparison.
Stress	Metric	Pascal's	Material property values and analysis results are listed in Pascal's.

2   BACKGROUND AND PREVIOUS WORK

A review of previous work related to this research, along with additional background information, will be presented in this chapter as an introduction to basic concepts that this thesis addresses. Explanations of the microgravity environment and why it cultivates unique results in scientific research will be provided. A brief history of microgravity research in space will be laid out as well. Overviews of three CubeSats built by NASA's Ames research center will be presented, as these missions proved that useful space biological research can be done within small satellites. Concluding this chapter is an explanation of the National Laboratory designation of the International Space Station and the importance of such recognition and how it affects research opportunities.

2.1   Importance of the Microgravity Environment for Research

The environment of the ISS resembles that of an ordinary research laboratory in terms of temperature, pressure, and humidity. However, absent from this environment is the most common force encountered on earth; gravity. This fundamental force is nearly impossible to escape for researchers other than very specific opportunities and only for short durations (parabolic flight paths, free fall chambers). To achieve a ground based microgravity environment, researchers may use a Rotating-Wall Vessel (RWV) which rotates a biological medium about an axis orthogonal to the gravitational vector, as shown Figure 2-1. This configuration allows suspended particles within the contained medium to be maintained in suspension as the RWV is rotated and a sustained low-shear environment for growth is achieved [18]. RWV devices have been used for initial microgravity studies, such as one done in Cologne, Germany, which showed Human Melanoma cancer cells with weakened levels of cancer gene chemicals tied to the "metastatic" spread of the cancer after subjected to a RWV environment for durations of 6 and 24 hours [19] [20].
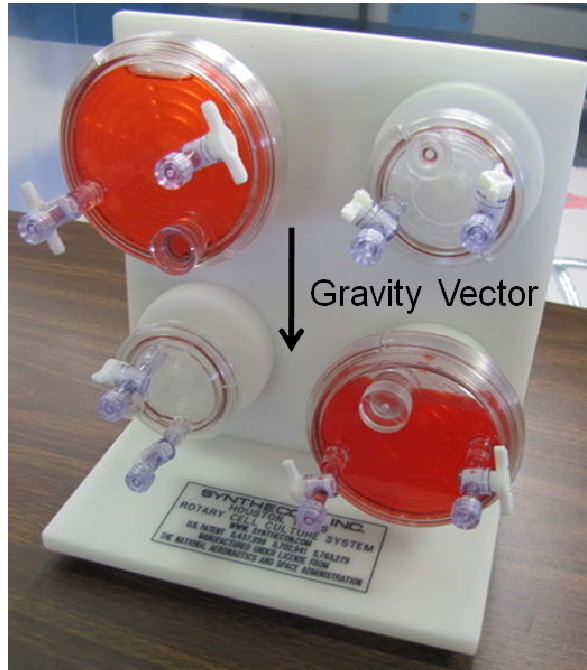
Figure 2-1: Example of a Rotating-Wall Vessel (RWV)

While the use of a RWV system gives only a proxy to a true microgravity environment, the effect of this environment has shown potential within the biotech industry. Previous microbial experimentation in microgravity has shown increased virulence, reduced antibiotic effect, and the regulation of gene expression [21]. The range of ecological environments microbes inhabit displays their ability to adapt to changing environmental factors, such as temperature, pH, osmotic pressure gradients, oxygen levels, and nutrient availability. The response of a cell to mechanical stimulation is called mechanotransduction, and it is the potential of this response that microgravity research seeks to understand [22].

A full understanding of the effects of microgravity on microbial specimens has been limited by three main constraints; low experimentation volume, the inherent rigorous engineering needs, and a lack of communication between the parties who seek new environments for microbial experimentation (researcher) and those with the knowledge to design and build the hardware necessary for use aboard spacecraft (engineering) [18] [21]. The work of this thesis hopes to in some way alleviate aspects of all three of these constraints.

2.2 Biological Research in Microgravity: Past, Present, and Future

The first microgravity microbial growth experiments occurred in 1957 aboard the USSR's orbital satellite, Sputnik [18]. Since that time technological achievements, such as kidney dialysis machines, salmonella vaccines, and wireless communications, have been fostered through research in microgravity [23] [24]. The sections below explain both past and potential biological payloads flown in Low Earth Orbit (LEO). Three of these payloads were CubeSats built by the small spacecraft division at the NASA Ames Research Center in Mountain View, California. The last mission concerns brain cancer research using a CubeLab Module currently under development by Kentucky Space and students and faculty at the University of Rome in Italy.

2.2.1 GeneSat-1

GeneSat-1 was the first CubeSat built by the Small Satellite Office of NASA's Ames Research Center. The program objectives of the mission were to use the advantages of small satellites to develop an autonomous technology demonstration platform with sensor capable of characterizing the behavior of cellular and microscopic organisms in space [16]. To accomplish this, E. coli strains were housed in a fluidic card which supplied nutrients and hydration. Once initiated, the growth rate and density of the E. coli was measured with an LED driven optical device during a 96 hour testing period.

GeneSat-1 was launched as a secondary payload on December 16th, 2006, out of the NASA Wallops Flight Facility on a Minotaur II launch vehicle. The payload experiment was initiated within two days of orbital insertion and all mission objectives were accomplished within a month. The containment of the E. coli payload included a pressure vessel in which the fluidic cards, temperature control system, and sensing devices were installed. The assembled GeneSat-1 spacecraft with the payload module, wrapped in gold thermal sheeting, where the biological medium was contained is shown in Figure 2-2 [25].
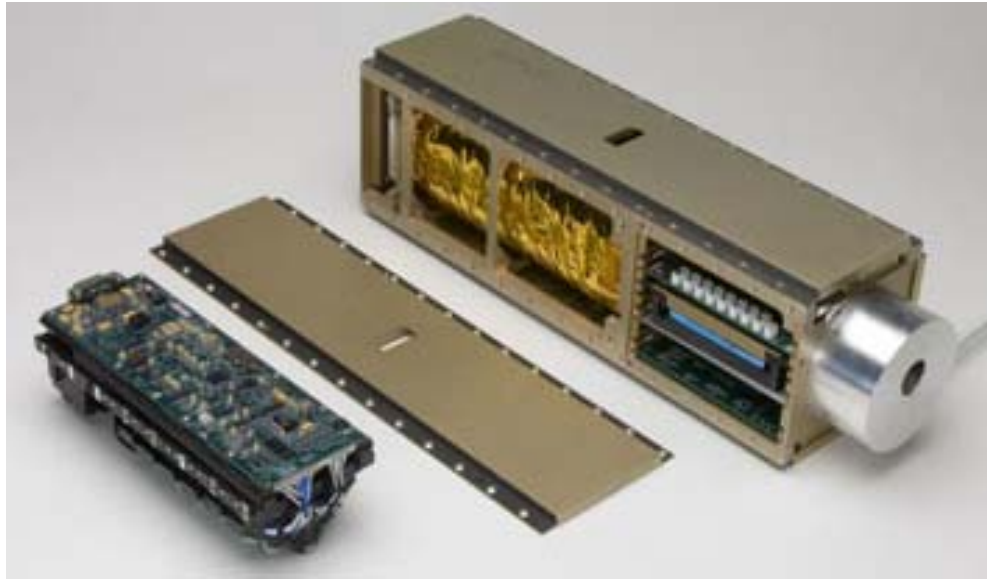
Figure 2-2: GeneSat-1 Spacecraft

2.2.2 PharmaSat

With the success of GeneSat-1, the Ames Small Satellite Office then developed PharmaSat as the next step in using CubeSat Standard satellites for biological research. Many of the technologies of GeneSat-1 were leveraged in the design of PharmaSat, whose mission objective was to investigate the efficacy of anti-fungal agents in the spaceflight environment [26]. This mission profile included dosing independent segments of yeast strains with three different quantities of an anti-fungal solution and then optically measuring the density of each well before and after dosing.

As with its predecessor, GeneSat-1, PharmaSat was a 3U CubeSat consisting of a 1U bus module and a 2U payload module. The payload module differed from GeneSat-1 in that the pressure vessel was rectangular and not cylindrical to accommodate the figure of the payload. PharmaSat was launched out of the Wallops Flight Facility on May 19, 2009 as a secondary payload with the Air Force's TacSat-3 satellite aboard a Minotaur I launch vehicle. With the short timeline of the biological experiment, the experiment was initiated early and mission success was achieved within the first week after reaching orbit [26].

2.2.3 O/OREOS

The next line of biological microgravity experimentation lead by NASA Ames was the O/OREOS (Organism / Organic Exposure to Orbital Stresses) spacecraft. O/OREOS was split into two different payloads, each occupying a 1U volume. The first was the Space Environment Survivability of Living Organisms (SESLO) which activated two strains each of two biological organisms at different points during the mission (Figure 2-3 L). Data was collected using optical density measurement similar to those flown on GeneSat-1 and PharmaSat to measure the effect of the space environment on biological strains after prolonged exposure [27].

The second payload was the Space Environment Viability of Organics (SEVO) experiment, which investigated the growth rates of four different organic molecules in thin-film form in a variety of modeled environments (Figure 2-3 R). These environments include interplanetary, interstellar space, lunar surface, wet/salty environments, and a Martian atmosphere. To house all these experiments, a carousel with 24 micro wells was built that could rotate to align with the optical measurement device [27]. The O/OREOS mission flew to orbit as a secondary payload on the STP-S26 Space Test Program launched out of Kodiak Island, Alaska, on November 19th 2010 [28]. After deployment, the spacecraft's mission lifetime is expected to be much longer than its Ames predecessors and nominally operate for six month.
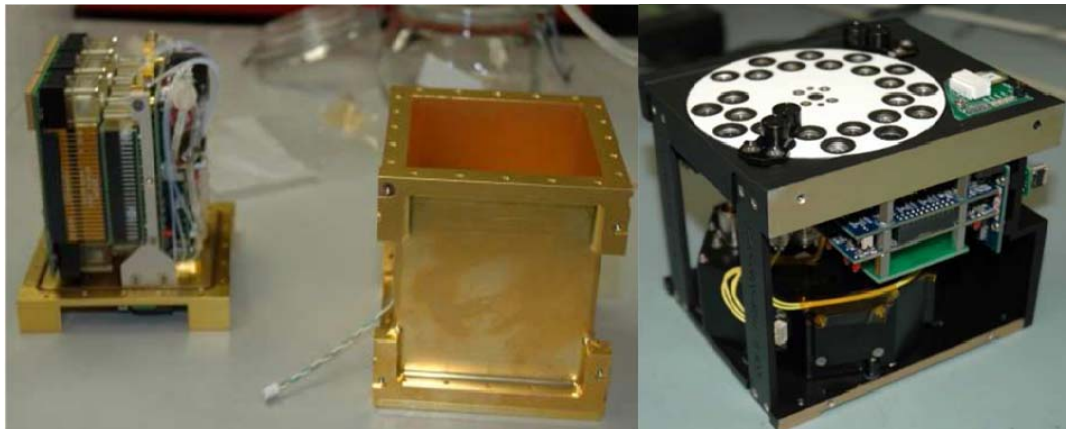
Figure 2-3: SESLO (L) and SEVO (R) Payloads

2.2.4 GlioLab

GlioLab is a proposed CubeLab Module which seeks to study the effects of the combined microgravity and ionizing radiation environments of Low Earth Orbit (LEO) on a strain of glioblastoma cancer cells. This experiment is a joint venture between the GAUS-Group of Astrodynamics at the "Sapienza" University of Roma, Kentucky Space, and the NASA Ames Research Center. The design of GlioLab presents many limitations and will require the equipment needed for a similar experiment on the earth to be shrunk into the volume of a 2U CubeLab Module.

The cell line under investigation, Glioblastoma Multiforme (GBM), is the most common, aggressive, and deadly type of primary brain tumor accounting for 52% of all primary brain tumor cases with a < 5% five year survival rate [29]. The payload will include a CubeLab Module containment structure for the GBM vials, actuation mechanisms which will intermittently feed the medium during the duration of the experiment, and a full electronics bus. Actuation can be controlled by uploading input files through the NanoRack Platform to the GlioLab Module allowing the possibility for changes in the mission profile after launch and installation.

This mission will leverage much of the research of this thesis along with other projects within Kentucky Space and the Space Systems Laboratory. Once in orbit the operational life of GlioLab will be 30 days upon which it will return to earth for RNA transcription analysis. Furthermore this mission will test the capability of CubeLab Modules for biomedical research and potentially could pave the way for affordable and rapid experiments in the microgravity / high radiation environment of low earth orbit.

2.3 The Orbiting National Lab: The International Space Station

With construction of the ISS slated for completion somewhere between late 2011 to early 2012 with the installation of the Russian module Nauka, the vision of a fully functioning manned research laboratory in the micro gravity low

earth orbit environment will be reached. Furthermore, the addition of three crewmembers, bringing the crew to six, aboard the station provides additional time for science, as duties aboard the spacecraft can be split among more inhabitants. Realizing this, the U.S. Congress designated the United States portion a National Laboratory in 2005, with the goal "to increase the utilization of the ISS by other federal entities and the private sector [30]." This title was done to foster the innovation potential of the ISS to all from the scientific and technology communities within the country.

While the National Lab title formally opens the ISS for research uses, NASA's effort to bring new collaborators into the arena of micro gravity research aboard the ISS has proven difficult. The difficulties are due to the inherent obstacles in operating a payload aboard a manned spacecraft. Previous experiments have shown an average of 20 months between initiation and launch. This is much too long a timeline for developers who face budgetary and scheduling constraints. In response to these issues, a new lean integration process has been developed to reduce the time between initiation and launch to 6 months. This new procedure includes "Ship and Shoot" testing, which determines requirements by a per payload basis, streamlining the process and eliminating unnecessary testing. While decreasing timelines is a main objective to increase ISS research, diversity, crew safety, and procedure verification have remained unchanged. This new method of payload integration was first used on the NanoRack Platforms / CubeLab Standard development by the University of Kentucky's Space System Lab in which seven months passed between the time a space act agreement was signed to delivery of hardware to the ISS [9].

3 DESIGN REQUIREMENTS

The initial step in the development process was to determine design requirements that the prototype must meet. All requirements are discussed within this section then are consolidated into a single checklist for later reference. Each table includes the section number where the requirement is stated in its original document. These requirements and testing procedures are provided through NASA design standards as well as the CubeLab Module ICD. Many specifications are repeated between documents, and the most aggressive requirement/test found is the one listed within the following tables. All requirements summarized in this section either involve structural integrity, materials, or the sealing capacity of the CubeLab structure. Since no electronics are considered in this research, testing relating to electronics is not included.

3.1 CubeLab Module ICD: 8400-NRP-ICD-1

The first series of requirements to consider are those set by the CubeLab Standard and are listed in Table 3-1. Requirements 2-1 through 2-7 deal only with mechanical and material portions of the document and are taken from Revision-1 of the *Interface Control Document Between CubeLab Modules and the NanoRacks Platform (8400-NRP-ICD-1)* [17].

Table 3-1: CubeLab ICD Applicable Requirements

Number	Requirement	Section #
2-1	Dimensioning for CubeLab Modules shall be centered off of the USB connector (table 1)	3.1 Table 1
2-2	External CubeLab Dimensions shall be no greater than 110 mm x 100 mm x 100 mm for a 1U Module	3.2 Table 2
2-3	1U CubeLab Module shall not exceed a mass of 1 kg	3.3 Table 3
2-4	Shall adhere to applicable standards listed in ISS IDD*	3.5.1
2-5	Shall use materials approved by NASA-STD-6016*	3.7.1
2-6	CubeLab Modules shall use low offgassing materials per NASA-STD-(I)-6001A*	3.7.3
2-7	CubeLab Module shall contain at least one USB type B female connector	3.8.4

*Standards explained in section 3.2

3.2   NASA Requirements

The sections below summarize NASA design and procedural standards which are used as references for aerospace hardware. The adherence of containment CubeLab Modules to these standards would be required for flight verification in the future.

3.2.1   Standard Materials and Processes: NASA-STD-6016

The Standard Materials and Process Requirements for Spacecraft states the requirements for "materials and processes (M&P) used in the design, fabrication and testing of flight components for all NASA manned, unmanned, robotic, launch vehicle, lander, in-space and surface systems, and spacecraft program/project hardware elements [31]." Table 3-2 includes the requirements of this standard to be considered for the designs of this thesis.

Table 3-2: NASA-STD-6016 Applicable Requirements

Number	Requirement	Section #
3-1	RTV silicones that liberate acetic acid shall not be used since they can cause corrosion	4.2.3.1 c
3-2	Natural Rubbers shall not be used	4.2.3.1 e
3-3	Organic materials used in the pressurized environment shall be evaluated for fungus resistance prior to selection and qualification	4.2.3.8 a

3.2.2   Flammability and Offgassing: NASA-STD-(I)-6001B

The *NASA-STD-(I)-6001A* document outlines the requirements "for evaluation, testing, and selection of materials to preclude unsafe conditions related to flammability, offgassing, and fluid compatibility [32]." This document is a supplement of requirements from the *NASA-STD-6016* document.

Table 3-3: NASA-STD-(I)-6001A Applicable Requirements

Number	Requirement	Section #
4-1	Materials used in habitable area of spacecraft, including the materials of the spacecraft, stowed equipment, and experiment, shall be evaluated for flammability and offgassing.	4.1 a
4-2	A) Specimens shall be placed into certified-clean containers and thermally conditioned for 72 (±1) hr at 50 (±3) ˚C [122 (±5) ˚F] B) After thermal conditioning the atmosphere inside the specimen container shall be analyzed for offgassed compounds C) Using the SMAC for each offgassed compound the overall toxicity rating shall be determined	7.7

3.2.3 EXPRESS Rack Payloads IDD: SSP 52000-IDD-ERP

The *EXPRESS Rack Payloads IDD* outlines in its preface that the document "provides a single source of design and interface compliance requirements which must be satisfied in order to certify the EXPRESS Rack payload for integration into an applicable EXPRESS Rack [33]." Adherence to this document is pivotal as EXPRESS Racks are the location of CubeLab Modules when installed with the NanoRacks Platform. Table 3-4 outlines each requirement from this document below.

Table 3-4: EXPRESS Rack IDD Applicable Requirements

Number	Requirement	Section #
5-1	Payloads shall protect crew member from sharp edges and corners	3.6.3
5-2	Exposed surfaces shall be free of burrs	3.6.3.4
5-3	Hard mounted payloads to EXPRESS Rack shall have a first primary natural frequency equal to or exceeding 35 Hertz (Hz)	4.1.1.1
5-4	Payloads stored within the Space Shuttle middeck shall have a first primary natural frequency equal to or exceeding 30 Hertz (Hz)	4.1.1.2
5-5	Payloads shall maintain a positive factor of safety during launch conditions outlined in table 4.1.2.1-1	Table 4.1.2.1-1

Table 3-4 (Continued)

5-6	Shall maintain a Factor of Safety above 1.5 for worst case loading scenarios	Table 4.1.3.1-1
5-7	Load factors shall survive emergency landing load factors of table 4.2.2-1	Table 4.2.2-1
5-8	Shall maintain positive factor of safety for random vibration profile shown in table 4.3.1-1	Table 4.3.1-1
5-9	Payloads shall maintain a positive factor of safety when exposed to the loads outlined in table 4.5.1-1	Table 4.5.1-1
5-10	Payloads shall maintain a positive factor of safety when exposed to orbital loads of 0.2 g's in any direction. This is due to accelerations from spacecraft docking procedures	4.5.2
5-11$	Payloads shall maintain a positive Factor of Safety during maximum depressurization and repressurization of 8.4 psi/min. The initial pressure should be 15.2 psi and final pressure 3.95 psi	4.8.3
5-12	All fasteners planned to be installed and/or removed on orbit shall be captive when disengaged	12.12.4
5-13	Only right-handed threads shall be used	12.12.6

$ 4-11 most rigorous test when compared to similar requirements

3.2.4 Safety Requirements Document -ISS Program: SSP 50021

The SSP 50021 document outlines safety requirements "to be used by all international partners involved in the design, development, production, test, and operation of the ISS" [34]. Table 3-5 displays those requirements from this document concerning the containment of a CubeLab Module and more specifically those which state that the containment vessel should have triple containment of the biological medium for safety.

Table 3-5: ISS IDD Applicable Requirements

Number	Requirement	Section #
6-1	The **\<CubeLab Prototype\>** shall be designed such that no combination of two failures, or two operator errors, or one of each can result in a disabling or fatal personnel injury, or loss of the Orbiter of ISS. Compliance with this requirement may be accomplished at the End Item level or through a combination of hazard controls at the Segment/Systems levels	3.3.6.1.1
6-2	**\<CubeLab Prototype\>** equipment located in pressurized volumes shall be capable of withstanding the differential pressure of depressurization, repressurization, and the depressurized condition without resulting in a hazard	3.3.6.11.2.1

3.2.5 Payload Test Requirements: NASA-STD-7002A

The NASA-STD-7002A standard outlines selected environmental exposure tests for hardware operating in earth orbit and serves as a NASA wide common basis from which test programs shall be developed for NASA payloads [35]. The requirements of Table 3-6 are baseline tests which shall be performed on flight hardware with specific levels determined by launch vehicle, payload location, or other factors. The random vibration profiles and sine sweep accelerations will be taken from the NASA GEVS (General Environmental Verification Specification) document [36].

Table 3-6: NASA Payload Testing Applicable Requirements

Number	Requirement	Section #
7-1	Sinusoidal Sweep from 5 to 50 Hz at a rate of 8 octaves a minute at levels 1.25 times the flight-limit levels	4.2.2
7-2	Random Vibration Analysis shall be performed to ensure positive margins of safety during loading	4.2.3
7-3	A report of the natural frequencies and mode shapes of the flight hardware shall be performed	4.2.5

3.3 Final Checklist

The aggregate of the applicable requirements throughout Chapter 3 are listed below in Table 3-7. Specific requirements which are met by other more aggressive requirements were omitted along with testing that could not be completed at the SSL or other University of Kentucky engineering facilities (e.g. flammability, out gassing). The requirements within Table 3-7 will be used as a checklist against the final CubeLab containment structure to ensure compatibility with the CubeLab Standard, the EXPRESS Rack, and the ISS.

Table 3-7: Final Containment CubeLab Requirements Checklist

-	Requirement
8-1	USB placement and volume dimensions shall follow tables 1 and 2 of the CubeLab ICD
8-2	1U CubeLab Module shall not exceed a mass of 1 kg
8-3	CubeLab Module shall contain at least one USB type B female connector
8-4	Natural Rubbers shall not be used
8-5	Payloads shall protect crew member from sharp edges and corners
8-6	Payloads stored within the Space Shuttle middeck shall have a first primary natural frequency equal to or exceeding 30 Hertz (Hz)
8-7	Payloads shall maintain a positive factor of safety during launch and landing conditions outlined in table 4.1.2.1-1
8-8	Payloads shall maintain a Factor of Safety above 1.5 for worst case loading scenarios outlined in table 4.1.3.1-1
8-9	Payloads shall maintain a positive factor of safety when exposed to the loads outlined in table 4.5.1-1
8-10	Payloads shall maintain a positive factor of safety when exposed to orbital loads of 0.2 g's in any direction. This is due to accelerations from spacecraft docking procedures
8-11	Payloads shall maintain a positive Factor of Safety during maximum depressurization and repressurization of 8.4 psi/min. The initial pressure should be 15.2 psi and final pressure 3.95 psi
8-12	All fasteners planned to be installed and/or removed on orbit shall be captive when disengaged
8-13	Only right-handed threads shall be used
8-14	The **<CubeLab Prototype>** shall be designed such that no combination of two failures, or two operator errors, or one of each can results in a disabling or fatal personnel injury, or loss of the Orbiter of ISS. Compliance with this requirement may be accomplished at the End Item level or through a combination of hazard controls at the Segment/Systems levels
8-15	Random Vibration Analysis shall be performed to ensure positive margins of safety during loading
8-16	A report of the natural frequencies and mode shapes of the flight hardware shall be performed

4 PROTOTYPE DEVELOPMENT: DESIGN AND ANALYSIS

This section outlines the design and analysis process for the Containment CubeLab prototype. Initial concepts and designs are explained as well as the subsequent refinement of the designs. A discussion of the materials selected to produce the prototype is detailed, in addition to explanations of the different analysis performed to ensure the article can withstand expected environments.

4.1 Preliminary Designs

Before the decision to formally research this topic was made, several rough designs had been considered for a CubeLab to contain biological payloads. These initial designs were all based around a 3U sized CubeLab made from sheet metal, which would contain the electronics, the payload, and the sensing device. An access panel was included to allow quick and easy placement of the biological specimen before launch. Figure 4-1 shows these preliminary designs in assembled and exploded views.
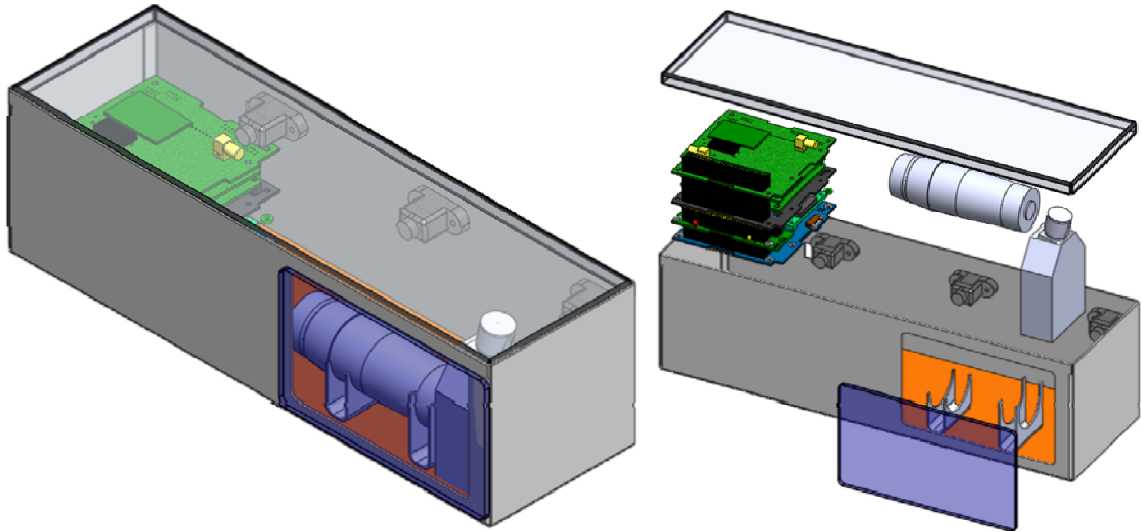
Figure 4-1: Preliminary Architecture of a Containment CubeLab

Upon review of these designs it was determined that several features and specifications could be altered to simplify both the design process for developers and production of the hardware. These alterations included forgoing the access

panel after realizing the difficulty of achieving proper sealing and that only creating one entrance (the top) would simplify the assembly. Building the CubeLab out of sheet metal was quickly dismissed because a dip brazing or comparable process would be needed to seal the gaps created during the bending of the aluminum. Instead, it was decided that using a plastic material would be preferred for this application. Using plastic, it should be easier to design a continuous single part which would be more conducive to containment. These design suggestions were taken into account to create a first prototype design.

4.2   First Prototype Design

The starting point for the initial design of a 1U containment CubeLab structure was the CubeLab standard itself. From the ICD the dimensions of the volume envelope for a 1U were set as constraints. The initial prototype CubeLab design included three major components: the body of the CubeLab, the top, and the sealing gasket. All design work was done using the SolidWorks 2008 CAD software package. Since maintaining a seal between the outside and inside environments of the CubeLab is the most important feature of the design, a cross section of all components was used to determine their profile. The first of these cross section designs is shown in Figure 4-2. The design leveraged several features to ensure a seal between the internal and external environments of the CubeLab. The first of these were two areas of interferences between components, as shown with red rectangles of Figure 4-2. Additionally, a knife edge was placed on the top to bite down into gasket 2 as an additional seal. While this initial design seems to provide multiple layers to prevent air from escaping, problems with the design were raised after consultation with machinists and fellow engineers within the Space Systems Lab.
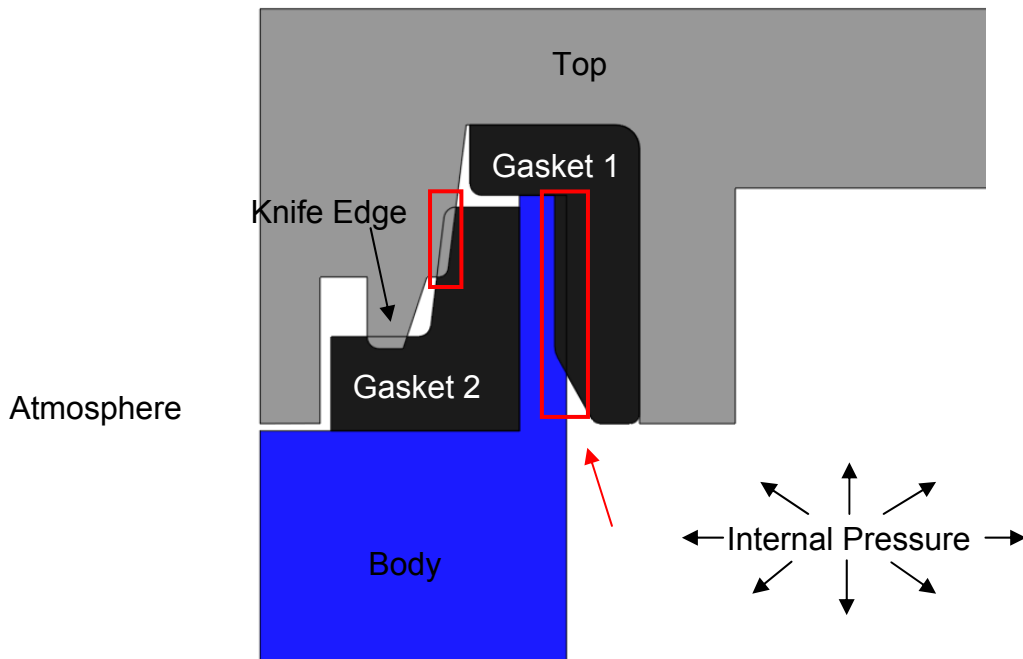
Figure 4-2: Cross Section of First Seal Design

The first of these problems comes from the angled section of gasket 1 (red arrow) which would allow air to work into the wedge between the gasket and body during a circumstance of greater internal pressure, allowing air to escape. Second, the complexity to fabricate the top would increase cost along with the fact that a similar sealing capacity could be achieve by one gasket instead of two.

4.3   Final Prototype Design

With the lessons learned from the first design, the cross section was modified to alleviate problems exposed through its scrutiny. The two separate gaskets were replaced with one much simpler design which was U shaped to fit around a "male" section of the body and a "female" section of the top. Also, the angled section of gasket 2 from the first design was replaced with a semi circle shape (red arrows) on the internal CubeLab side face of the gasket. This feature was added to use the internal pressure within the CubeLab to seal the semi circle against the adjacent top and body sections. Figure 4-3 displays this cross section design.
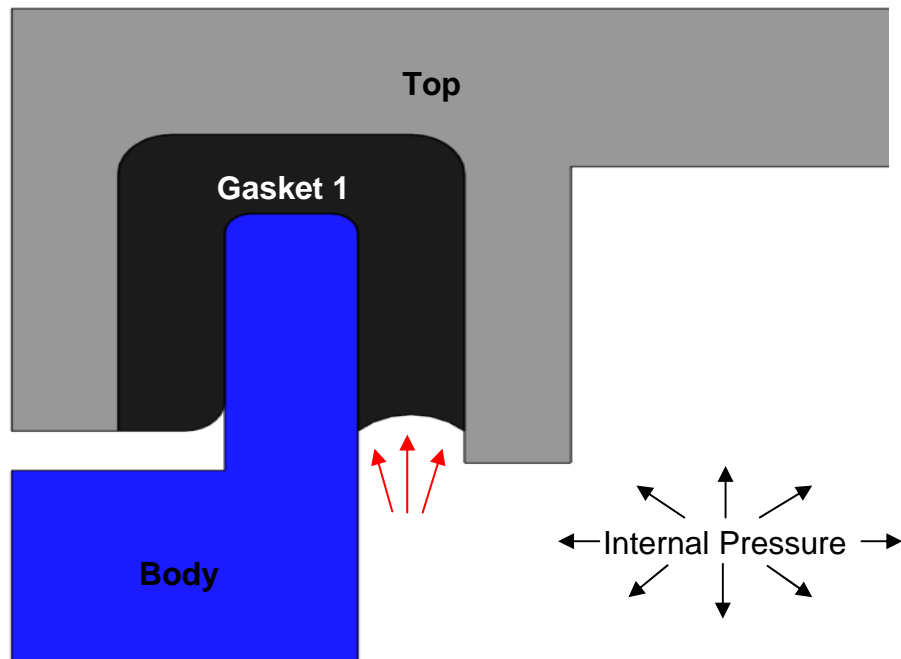
Figure 4-3: Cross Section of Final Seal Design

With the profile design of the components determined, the 2D models were expanded to 3D models in SolidWorks for further examination. The top and body 3D models are shown in Figure 4-4.
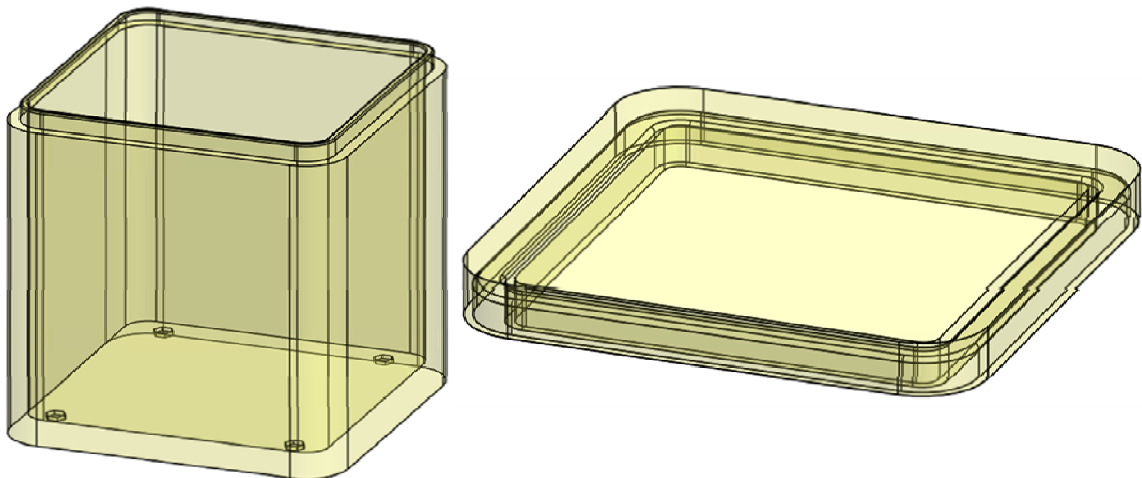
Figure 4-4: Top and Bottom Prototype Designs

At this point in the design process, features were added to attach the top component to the body with the gasket held in between. Case latches, attached to the body which holds down the top on opposing sides, were initially considered. However, machine bolts which pass through the top then thread into the body were determined to be better suited. This decision was due to the negatives of added volume and potential sharp edges the latches would give the module. With this, four features were added to the design, shown in Figure 4-5, to accommodate these bolts on both the body and top. Finally, four hexagonal holes were added for standoff tie-ins allowing electronics to be installed within the structure during testing. The final assembled design of all components with added features is shown in Figure 4-5.
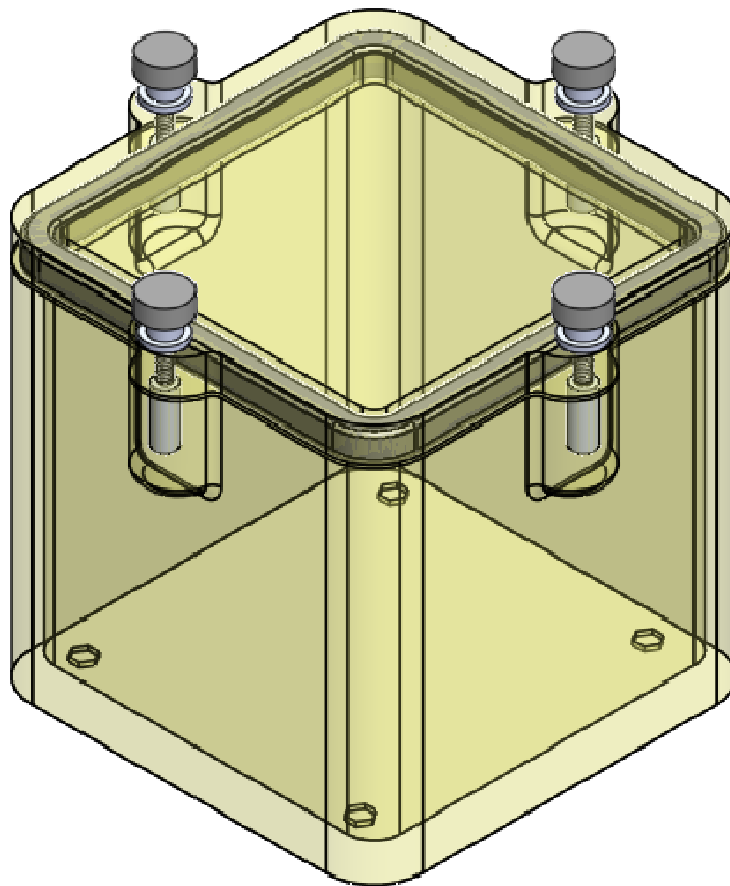
Figure 4-5: Assembled Containment CubeLab Design

4.4   Additional Hardware

Originally, it was planned to use hex bolts to hold the components together. However, it was decided that thumb screws would work best as the top would be removed several times a day during testing. Additionally, spacers were used to prevent the thumb screws from digging into the top and damaging it. The bolts selected were 1" in length 6-32 thumb screws. The spacers selected were 5/16 diameter plastic sleeve bearings.

4.5   Material Selection

Several material options were compared before structural analysis of the prototype began. Concerning the top and body, this decision was simplified as these components were made with a 3D systems SLA-3500 machine located in the Rapid Prototyping Lab at the University of Kentucky which uses DSM SOMOS WaterShed 11120 photo sensitive resin for stereolithography. These material properties are listed in Table 4-1 [37].

The material decision for the gasket was made after discussions with technicians and machinists in the College of Engineering who suggested a urethane compound would be best suited for the gasket application. This decision was based upon the familiarity with the material by those who were manufacturing the part, the 1:1 mixing ratio, which would create less variance between pours, and the pliability of urethane. Three different urethanes were considered, with durometer readings of 30A, 42A, and 70A [38][39][40][41]. The material properties of these urethanes are shown in Table 4-2. The Poisson's Ratios for the urethane's were not provided in their material data sheets and are required for accurate structural analysis. The Poisson's Ratio for rubber is listed at values approaching 0.50, which was used during subsequent ANSYS analysis [42][43].

Table 4-1: SLA Material Properties

Material	Density (g/cm^3)	Young's Modulus	Yield Strength	Poisson's Ration
SOMOS WaterShed 11120 (SLA)	1.12	2700 MPa	55 MPa	0.23

Table 4-2: Urethane Material Properties

Material	Density (g/cm^3)	Young's Modulus	Viscosity	Poisson's Ration
Urethane PMC-121/30	1.04	2 MPa	1200 cp	0.50
Urethane F-42 A/B	1.09	0.76 MPa	850 cp	0.50
Urethane F-70 A/B	1.11	2 MPa	1500 cp	0.50

4.6   Analysis

With the prototype design completed, structural analysis was undertaken to ensure sufficient structural support existed during worst case loadings and to ensure adequate clamping force is applied to the gasket to achieve the proper sealing capacity. This analysis was done using ANSYS, SolidWorks COSMOSXpress Analysis Wizard, and ANSYS/Workbench software packages. ANSYS was used for initial design validation using a 2D cross section of the prototype design in static situations. The SolidWorks COSMOSXpress Analysis Wizard was used to analyze the deformation of the top component when clamped to the body to validate that excess deformation would not compromise sealing capacity. Finally, ANSYS/Workbench was used to model the entire assembly for stress, deformation, and factor of safety for a variety of loading scenarios. All the analyses outlined in this section are done assuming a gasket made from 42A urethane, which subsequently preformed best in testing.

4.6.1 ANSYS 2D Modeling

The ANSYS software was used for initial calculations of a 2D model of the prototype design related to expected deformations and stresses during worst case scenarios. Additionally, the modeling was done to verify sufficient wall thicknesses for later pressure testing. The analysis utilized text input files which modeled the gasket, body, and top components as Plane 82 elements and the bolts used for clamping the assembly together as Pipe 16 elements. Interactions between the components were modeled using surface-to-surface contact pairs and the solution was solved under a plain strain assumption. The model was constrained by both the USB connector, mimicking its attachment to the NanoRack Platform on orbit (shown in Figure 4-6 by yellow triangles in lower right hand corner), and the bottom face of the assembly which allows the loading of the bolts to be properly represented. The input file used for this analysis is included in Appendix A.

Figure 4-6 shows an element plot of the assembly cross section. These sections are expanded versions of the designs shown in Figure 4-2 and Figure 4-3. In ANSYS, full cross-section of the top and body components were modeled to better estimate deformation over these areas and the effect of the deformation on the gasket. The material properties for this analysis were taken from Table 4-1 and Table 4-2. This 2D analysis was done as a baseline to ensure no significant design defects existed. The results from the subsequent 3D stress analysis, discussed later, are expected to be more accurate, as the entire assembly is modeled and the 3D analysis is not based on the plane strain assumption.
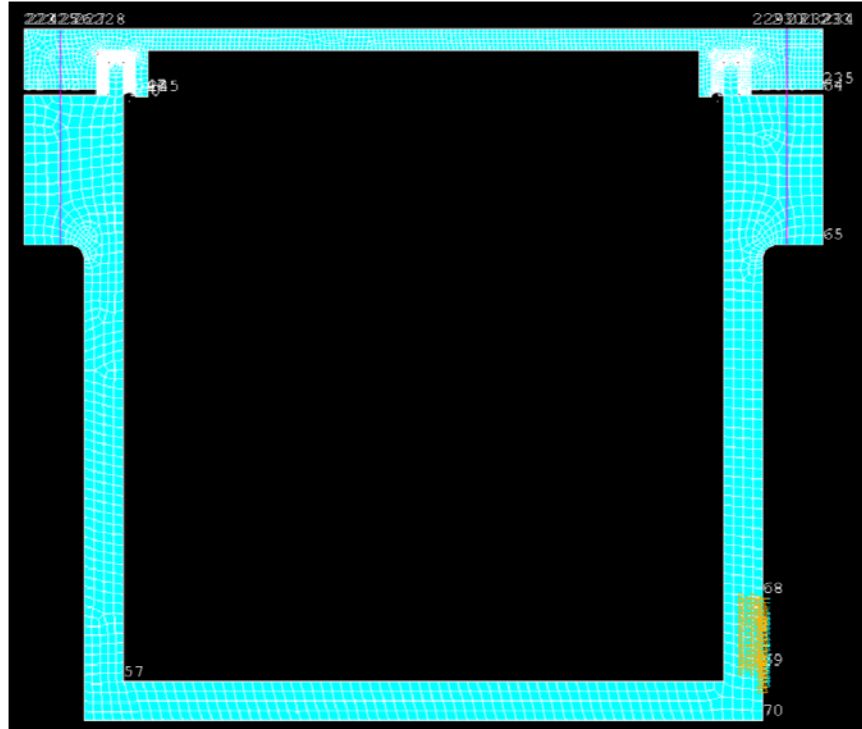
Figure 4-6: ANSYS Cross Section Rendering of Prototype Design

The urethane used in the gasket component presented a challenge in the analysis due to the nonlinear characteristics of the material under tension and shear loading circumstances. For an accurate model, the Mooney Rivlin technique was researched to adequately represent the gasket during loading [44]. This technique is quite extensive in theory as shown by equation 1. However, the equation can be simplified when entered into ANSYS to four constants determined by material testing.

$$\sigma = \frac{2}{J}\left[\frac{1}{J^{2/3}}(C_1 + I_1 C_2)B - \frac{1}{J^{4/3}}C_2 B \cdot B\right] + \left[2D_1(J-1) - \frac{2}{3J}(C_1 I_1 + 2C_2 I_2)\right] \qquad (1)$$

Where: σ = Stress
J = Compressibility Factor (e.g. Incompressible Material J = 1)
C1 = Material Constant
C2 = Material Constant
D1= Material Constant
I1 = 1st Invariant from Cauchy-Green Deformation Tensor
I2 = Second Invariant from Cauchy-Green Deformation Tensor
B = Left Cauchy-Green Deformation Tensor

After initial analysis was performed using Mooney-Rivlin constants provided by the urethane manufacturer it was determined that since the majority of forces acting upon the gasket in this application produce compression of the gasket, the nonlinear Mooney-Rivlin material model is not be necessary, as urethanes do not compress nonlinearly [45].

In determining the test loads for the analysis outlined in this section, an atmospheric pressure of 15.2 psi was used as opposed to 14.7 psi, the commonly used atmospheric pressure. This was done because requirement 8-11 uses a 15.2 psi pressure. The static analysis considered the worst possible scenario of a pressure differential (between the spacecraft and the interior of the CubeLab) of 11.35 psi, per requirement 8-11. Figure 4-7 shows the deformation plot from this analysis.

Figure 4-7 ANSYS Static Analysis -Deformation Plot

From this simplified analysis the maximum total deflection was calculated to be 2.32 mm with a maximum Von Mises stress of 36.7 MPa and a minimum factor of safety was 1.5. These metrics indicate the design could survive worst case pressure differen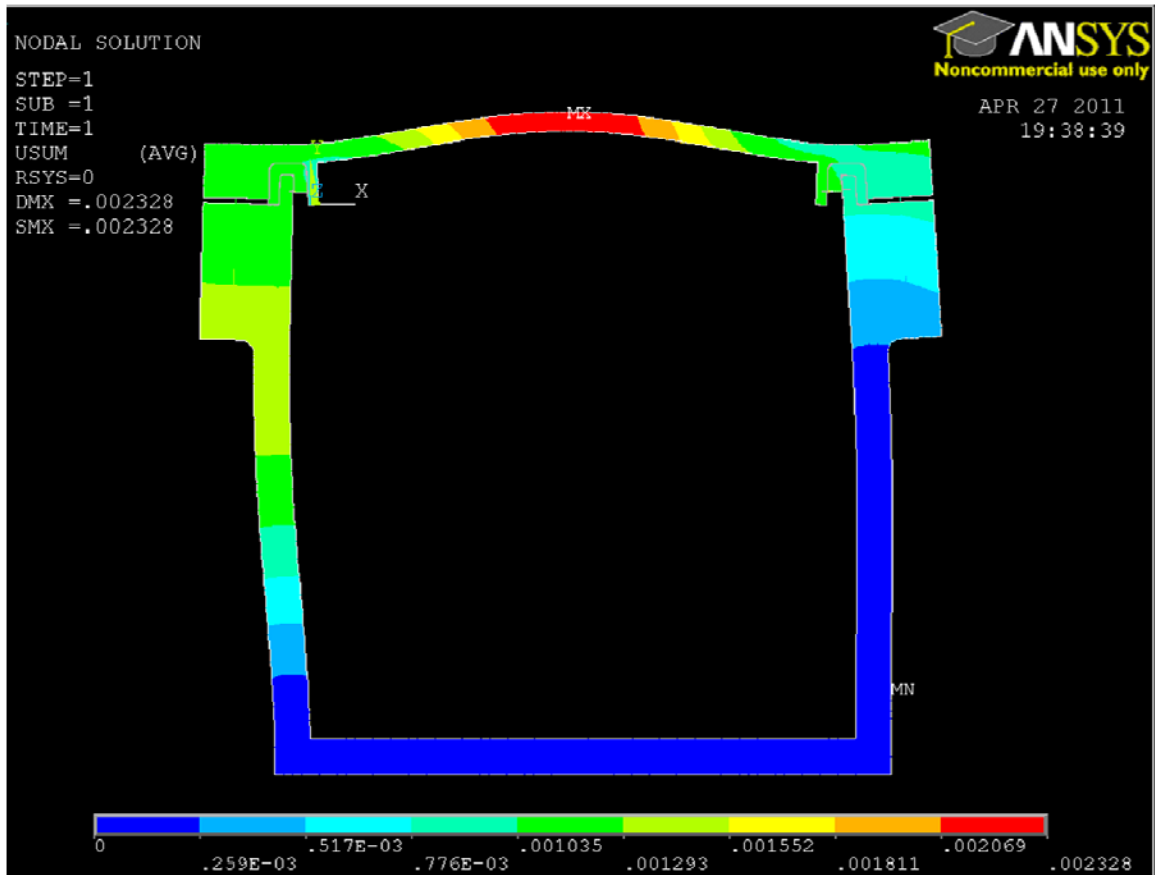tial scenarios with a safety factor above one. With these acceptable results a more accurate and detailed 3D analysis was undertaken to confirm the design could survive all testing with appropriate factors of safety.

4.6.2 Top Component Deflection under Loading

A concern that arose during discussions with fellow engineers and machinists during the design process was to ensure that the bolt formation used to connect the top component did not cause enough deflection to deform the gasket and compromise sealing capacity. To address this concern, the COSMOSXpress Analysis Wizard, which serves as the Finite Element Analysis (FEA) package of the SolidWorks CAD software, was used to analyze the deflection of the top during the loading expected from the tightening of the bolts combined with worst case pressure profiles.

An important figure needed to complete this analysis is the force exerted by each bolt on the top component. This force was calculated using equation 2. This equation takes into account the coefficient of friction, the pitch angle, the bolt length, bolt diameter and torque used to tighten the bolts. The bolts used for this application were 6-32 1" long stainless steel with a half angle from the bolt pitch of 60 degrees. A 0.15 coefficient of friction was used as a baseline value as suggested by Shigley and Mischke. Using these parameter values for these specific bolts and a 452 N-mm (5 in-lbs) torque, measured from a calibrated torque wrench, the calculated force per bolt is shown below [46].

$$F = \frac{T}{\frac{d_m}{2}\left(\frac{L + \pi\mu d_m \sec\alpha}{\pi d_m - L\mu \sec\alpha}\right) + \frac{\mu d_c}{2}}$$

$$= \frac{452\ mm - N}{\frac{3.11}{2}\left(\frac{25.4 + (\pi \times 0.125 \times 3.11 \times \sec\pi/6)}{(\pi \times 3.11) - (25.4 \times 0.125 \times \sec\pi/6)}\right) + \frac{0.125 \times 7.94}{2}} = 61.68\ N \tag{2}$$

Where: F = Force (N)
         T = Applied Torque (N-mm)
         L = Bolt Length (mm)
         d_m = Mean Diameter (mm)
         μ = Coefficient of Friction
         d_c = Mean Diameter of Spacer (mm)
         α = Half Angle of Bolt Pitch (radians)

Two loading cases were considered for this analysis. The first accounted for only the force exerted by the bolts on the top. This was done by selecting the gasket path as the restraint then distributing the load calculated in equation 2 over the area of each of the spacers. The deformation plot from this scenario can be seen in the top portion of Figure 4-8. The maximum deflection and Von Mises stress calculated were 0.078 mm and 5.82 MPa, respectively, with a minimum Factor of Safety of 8.58. Additionally, minimum deflection was calculated in the corners of the gasket path, which was the area of greatest concern for separation between the gasket and body.
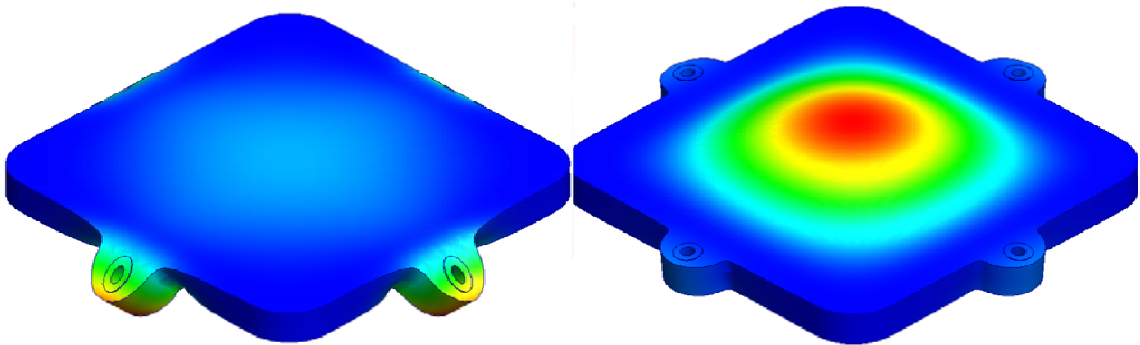
Figure 4-8: COSMOSXpress Deflection Plots

The second case included the force of the bolts plus the maximum pressure differential of 11.25 psi (0.77 atm) and was set up in the same method as the first. The maximum Von Mises stress and deformation were calculated as 13.57 MPa and 0.93 mm, respectively, with a minimum factor of safety of 3.68. The lower portion of Figure 4-8 displays the deformation plot for this case. Again, deformation of the gasket profile was not a cause of concern due to minimal deflection in the corners.

4.6.3 3D Stress Analysis

As mentioned earlier, for deformation and stress analysis of the entire 3D assembly, the ANSYS/Workbench software was used as it is well suited for such assessments. The original SolidWorks CAD models were imported to Workbench, contacts between components specified, and the material properties shown Table 4-1 and Table 4-2 were applied. Constraints and loads were applied for each particular case, and solutions were obtained.

The first case considered the loading due to the force of the bolts when torqued. The USB connector and bottom face of the assembly were again used as restraints. The loading was derived from the force of each bolt as calculated from equation 2 and distributed over the area of the spacers. The left side of Figure 4-9 is the deformation plot for this case, which shows a maximum deformation of 0.012 mm. The maximum Von Mises stress and corresponding factor of safety were calculated to be 1.69 MPa and 32.5.

Upon comparison of the factors of safety when only the top was stressed in section 4.6.2 (8.58) and the entire assembly in this section (32.5) the 3D analysis provided much safer results. This can be attributed to the fact that in the assembly scenario the areas of greatest deflection of the top hit the body component and transfer their load and lessen its deformation, stress, and increasing the factor of safety. When analyzing the top independently these areas of deflection were not constrained and allowed to deform to a greater extent.

As with the analysis of just the top component in section 4.6.2 the case of the maximum pressure load combined with the bolt force was analyzed in Workbench. The maximum deflections, shown on the right side of Figure 4-9, and Von Mises stress were 1.32 mm and 14.6 MPa, respectively, with a minimum safety factor of 3.43.
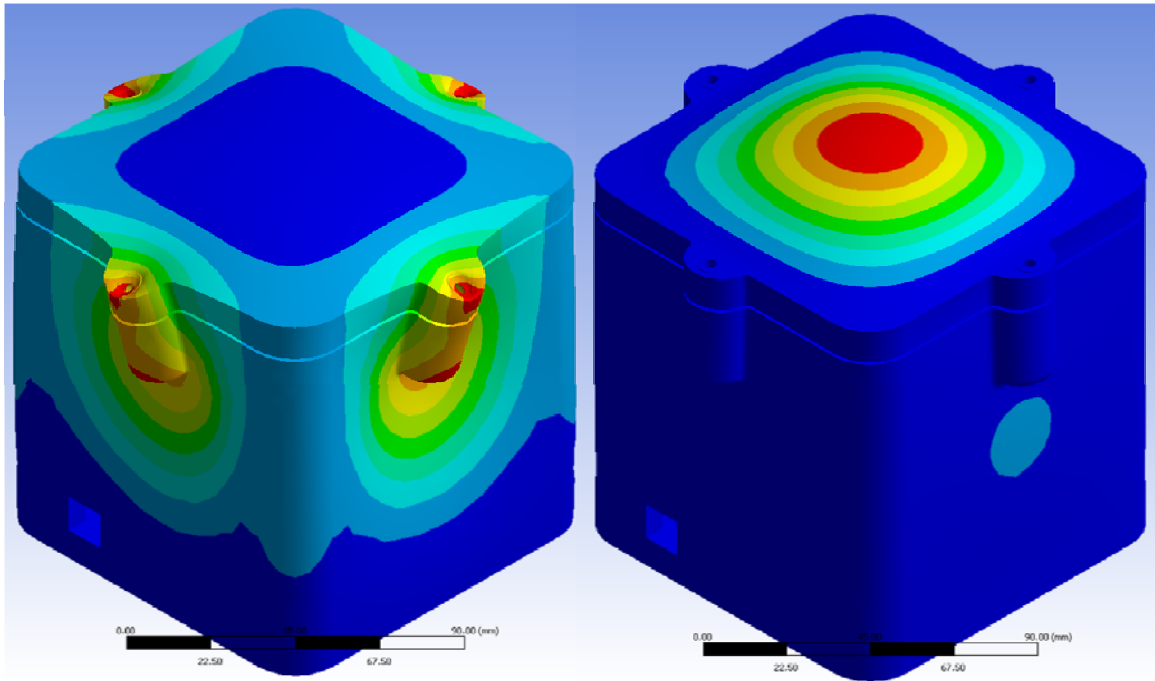
Figure 4-9: Deformation Plot -Bolt Force (L) and Pressure (R)

4.6.4 Rapid Depressurization / Repressurization Analysis

The dynamic pressure environment was modeled in ANSYS/Workbench to validate the design for a scenario of a rapid loss or reacquisition of pressure inside the spacecraft. The depressurization analysis assumed an initial pressure of 15.2 psi, with the pressure decreased to 3.95 psi at a rate of 8.4 psi/min, as specified in requirement 8-11. Constraints were applied the same as for the 2D and 3D analysis. Individually, the depressurization and repressurization analyses produced very similar results, as the pressure profiles were identical, just input in reverse of one another. The deformation and Von Mises stress plots are shown in Figure 4-10. Maximum deformation was 1.32 millimeters with a calculated maximum Von Mises stress of 14.6 MPa, and a minimum factor of safety of 3.43.
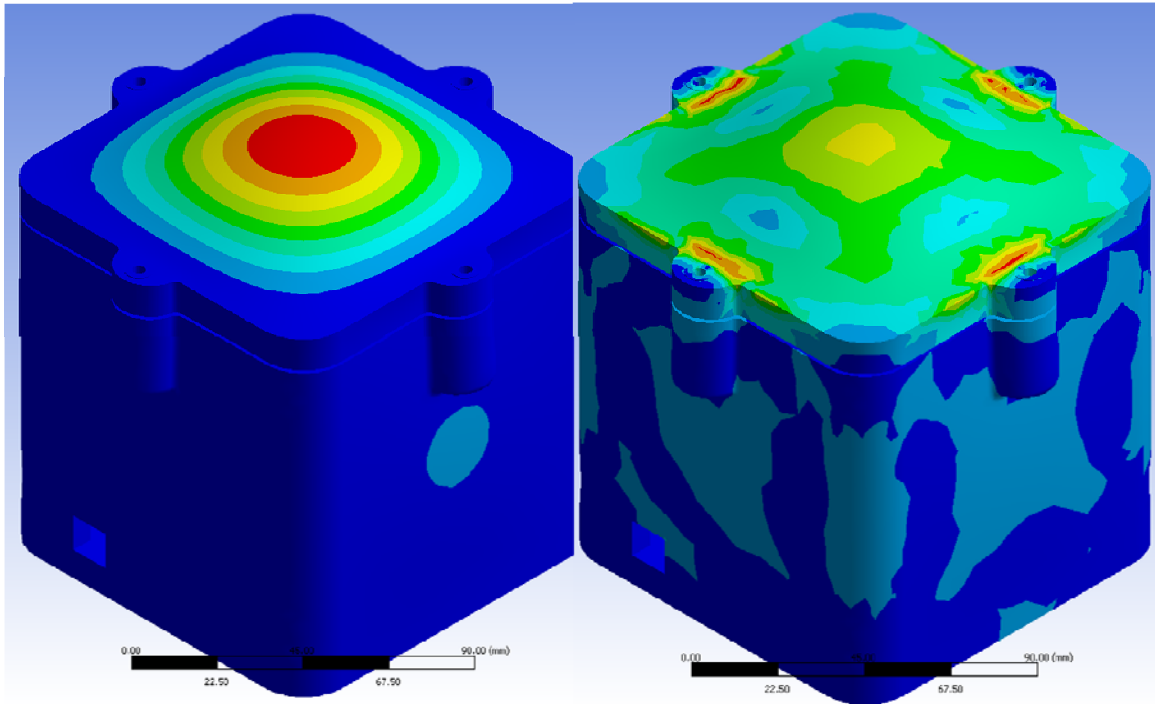
Figure 4-10: Depress. / Repress. Deformation (L) and Von Mises Stress (R)

4.6.5 Modal Analysis

To determine the natural frequencies and corresponding mode shapes for the prototype design, a modal analysis was run to verify the design could meet requirements 8-6 and 8-16. The first requirement concerns the first fundamental frequency and states that "payloads shall have a first fundamental frequency above 30 Hz." The second requirement states that a modal analysis shall be completed to determine mode shapes and natural frequencies of the hardware. Table 4-3 shows the first four natural frequencies calculated which are well above the 8-6 requirement. The models were constrained by their bottom face mimicking their soft stowage packing configuration during ascent to orbit in which resonance between the payload (CubeLab) and the vehicle is of most concern. Figure 4-11 and Figure 4-12 show the mode shapes corresponding to the first our natural frequencies. This modal analysis included only the pre-stress effects of the tightened bolts. When the maximum pressure differential is considered the natural frequencies are increased slightly above those listed in Table 4-3.

Table 4-3: Four Primary Natural Frequencies

Mode #	Frequency (Hz)	Mode #	Frequency (Hz)
1	725.55	3	903.62
2	902.16	4	955.71
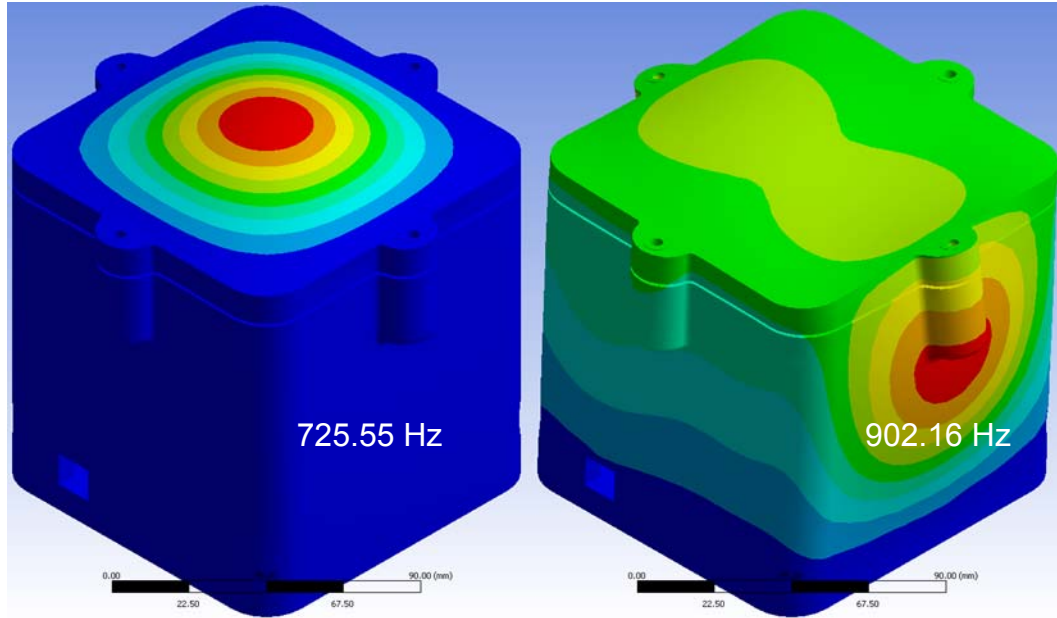
Figure 4-11: Mode Shapes at 726.36 Hz (L) and 904.90 Hz (R)
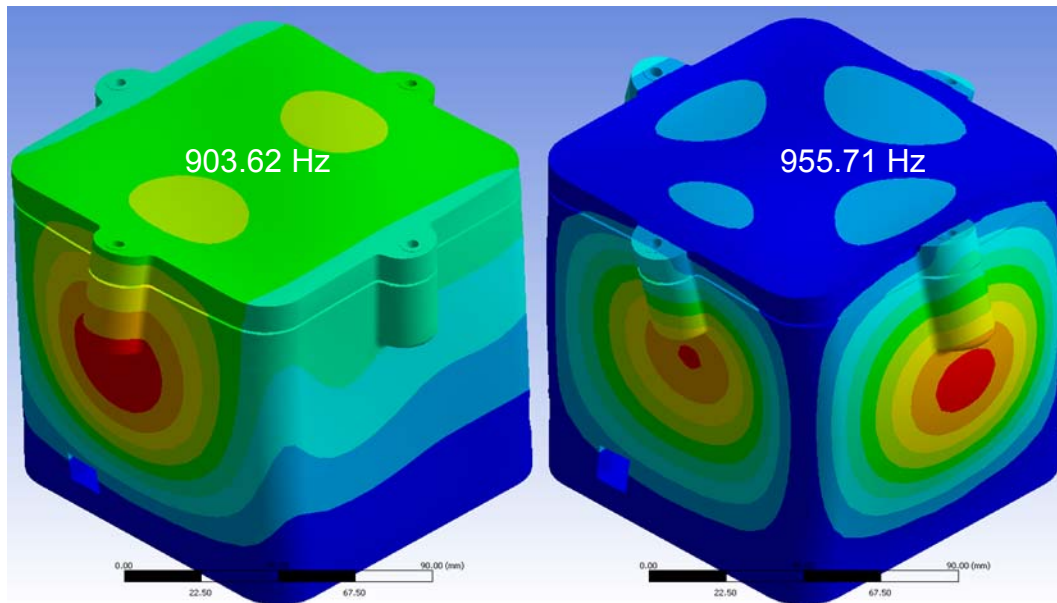
Figure 4-12: Mode Shapes at 905.90 Hz (L) and 958.67Hz (R)

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4.6.6 Random Vibration

This section documents the calculated response of the design to the random vibration profile taken from NASA GEVS (General Environmental Verification Specification) and outlined in requirement 8-9 of Table 3-7. This testing ensures survival of the payload during the ascent to orbit, and the levels used are much more severe than a similar requirement from the EXPRESS Rack IDD. The loading is specified through a power spectral density plot (PSD) of which the PSD table for requirement 8-9 is shown in Table 4-4. The composite value is the square root of the area under the PSD plot curve and is the rms value of the acceleration over the frequency range. For this analysis the model was constrained in the two axes the model was not be exited in. This analysis ran the vibration profile in all three axes independently to see which responded the greatest.

Table 4-4: Random Vibration PSD Plot

Frequency (Hz)	PSD (G^2/Hz)
20	0.026
20-50	+6 dB/oct
50-800	0.16
800-2000	-6 dB/oct
2000	0.026
Composite	14.1 g_{rms}

The maximum deformation and Von Mises Stress (Figure 4-13) were calculated during loading of the X axis to be 0.362 mm and 3.46 MPa, respectively, with a minimum safety factor of 15.9.
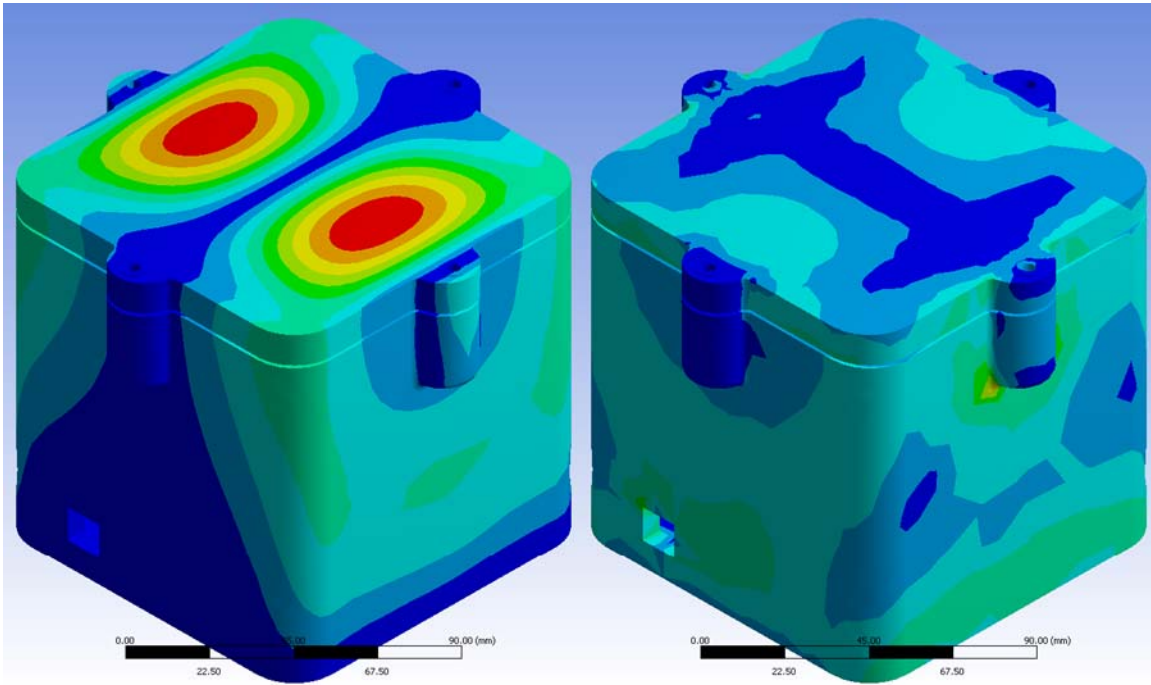
Figure 4-13: Random Vibration Deformation (L) and Von Mises Stress (R)

4.6.7   Liftoff and Landing Loading

The final analysis involved the expected inertial loading during liftoff and landing of the spacecraft. This loading is outlined in requirement 8-7 with the magnitude specified in g's as shown below in Table 4-5.   Additionally, this analysis fulfills requirement 8-10, which states that the CubeLab shall maintain positive factors of safety for accelerations in any direction of 0.2 g's. The analysis shown below was run with the loading at 11.6 g's in each direction, as a CubeLab Module could be oriented in a variety of ways with respect to the launch vehicle coordinate system and this circumstance verified the prototype could survive the worst case loading. The maximum deflection was calculated as 0.016 mm, while Von Mises stress was 1.7 MPa, with a safety factor of 29.4 as shown in Figure 4-14.

Table 4-5: Liftoff and Landing Inertial Loadings

Flight Event	Design Limit Loading Factors, G's		
	X-Axis	Y-Axis	Z-Axis
Liftoff	+7.70	+11.60	+9.90
Landing	+5.40	+7.70	+8.80
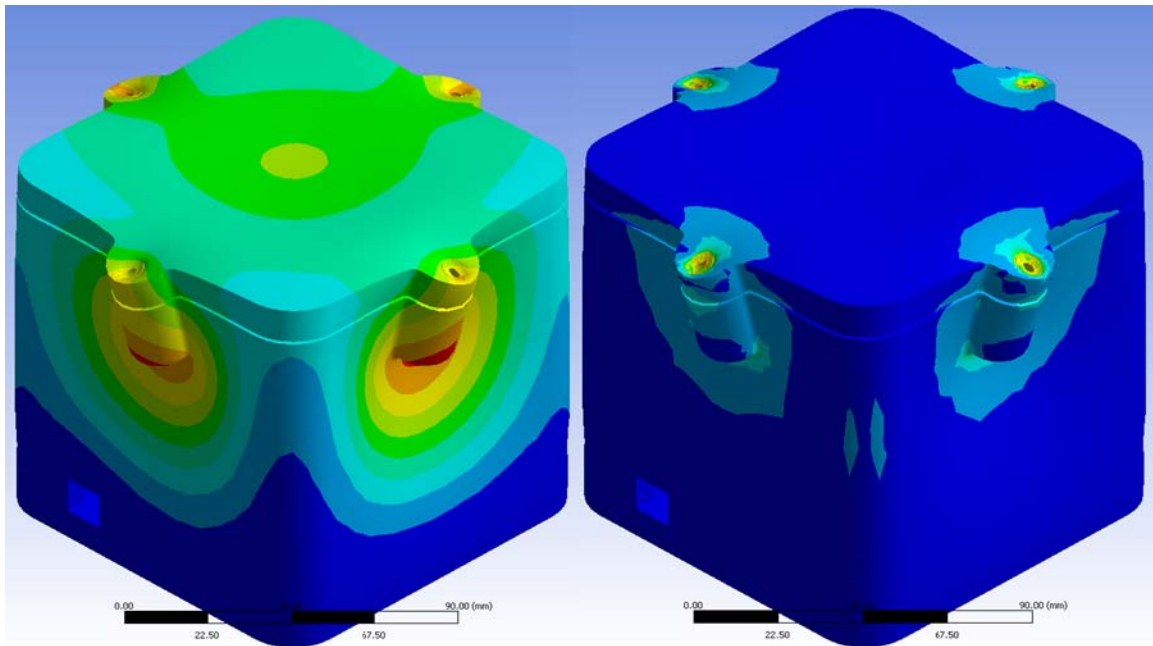
Figure 4-14: Inertial Loading Deformation (L) and Von Mises Stress (R)

5   PROTOTYPE MANUFACTURING AND TESTING

The following section outlines the manufacture of the prototype containment CubeLab design along with results from testing of the article to fulfill the requirements of Table 3-7.

5.1   Manufacture of Prototype

After finite element analysis of the design showed no failure modes from expected environments, a prototype of the Containment CubeLab design was created for testing and requirement verification. The CAD files of the top and body components, along with the gasket molds, were submitted to the Rapid Prototyping Lab at the University of Kentucky. The top and body were built on a *3D systems SLA-3500* machine using the DSM SOMOS WaterShed 11120 resin, as outlined in Table 4-1. This technique produced prototype parts with tight tolerances in less than 48 hours and required only drilling and threading the holes needed for the tightening bolts after UV curing of the SLA resin.

The gasket manufacturing was also carried out in the Rapid Prototyping Lab on a *MCP PLC 004* vacuum casting system. Using molds created from the SLA machine, the urethane was poured under vacuum to minimize air bubbles within the part. A problem was encountered with initial 30A and 50A urethane choices due to their high viscosity, coupled with the small area of the gasket profile which prevented proper flow of the urethane, resulting in gaskets void of material. The material flow was not an issue with the 70A urethane, which has a much lower viscosity (see Table 4-1), allowing the liquid urethane to flow and produce higher quality gaskets without air bubbles. However, the higher stiffness of the 70A urethane prevented desirable sealing during later static pressure tests. Finally, gaskets were poured from a 42A stiffness urethane which had low viscosity and desirable pliability. A 42A gasket was used for all testing in this thesis due to its higher quality. A comparison between a 30A (with flash still attached) and 70A gaskets is shown in Figure 5-1.

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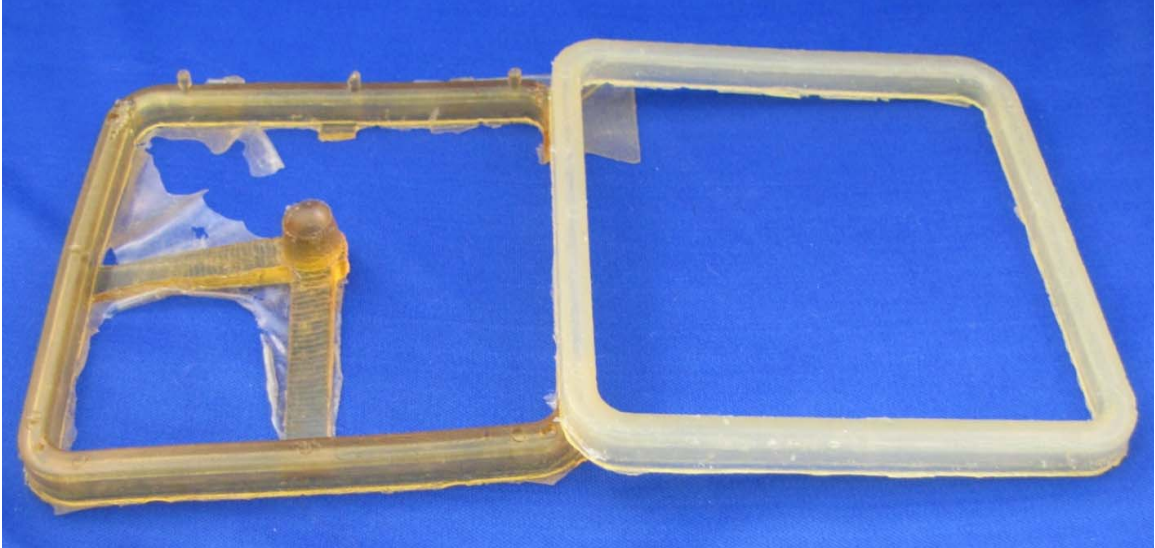
Figure 5-1: Comparison of Gaskets

After the components were manufactured, it was decided to glue the gasket into the top to ensure better sealing and eliminate one component from the assembly. The adhesive used was the original 30A urethane which proved to be too viscous for use as the gasket. However the viscosity proved to be beneficial as an adhesive and sealant as the urethane held its location. A bead of the urethane was laid into the top then the gasket placed on top, providing a seal between the components. After a drying period, held under vacuum, the standoff tie ins were epoxied in place and a PCD board was mounted for DAQ placement. Figure 5-2 shows the entire assembly after construction.

Figure 5-2: Entire Containment CubeLab Structure

5.2 Prototype Testing

The list of tests a new design must pass to meet full qualification for a manned spaceflight mission is exhaustive. The tests outlined in this section are those that could be accomplished with available equipment in the Space Systems Laboratory at the University of Kentucky that involve requirements from Table 3-7. Pressure tests were conducted under both static and dynamic conditions to measure the sealing capacity of the design. Also, human factors' tests were completed to ensure that no feature of the hardware could hurt personnel while handling it. A comprehensive table listing which requirements were met and which need further work is presented at the end of this chapter.

5.2.1 Static Pressure Tests: Light / Medium Vacuum

The static pressure tests are critical in validating the sealing capabilities of the design and were conducted to measure how well the structure held its internal pressure during light to medium vacuum pressure differentials. The atmospheric pressure for these tests ranged from 12.5 psi (0.85 atm) down to 3 psi (0.2 atm). The durations ranged from 10 minutes to 4 hours. The setup of this testing included a bell jar with a small electronic pump which could be throttled to create

and maintain the low pressure environments and provide accurate pumping rates. Two Data Acquisition Systems (DAQs) were used to measure the pressure both internally (CubeLab Sensor) and externally (Bell Jar Sensor) as shown in Figure 5-3, which displays the testing setup. These DAQ's used the MPX4250A (Case 867B-04) Series pressure transducers capable of measuring pressures down to 2.9 psi (0.19 atm) [47].

Figure 5-3: Static Pressure Testing Setup

The first of these vacuum tests was conducted with a 3 psi (0.2 atm) differential for ten minutes. The results are shown in Figure 5-4 with no pressure loss measured with the CubeLab sensor. The second of these tests used a pressure differential of 7.35 psi (0.5 atm) and a period of twenty minutes. The results are shown in Figure 5-5, and again no pressure loss was detected. The varying pressure reading of the Bell Jar Sensor for both tests was due to the back pressure of the pump on the bell jar.
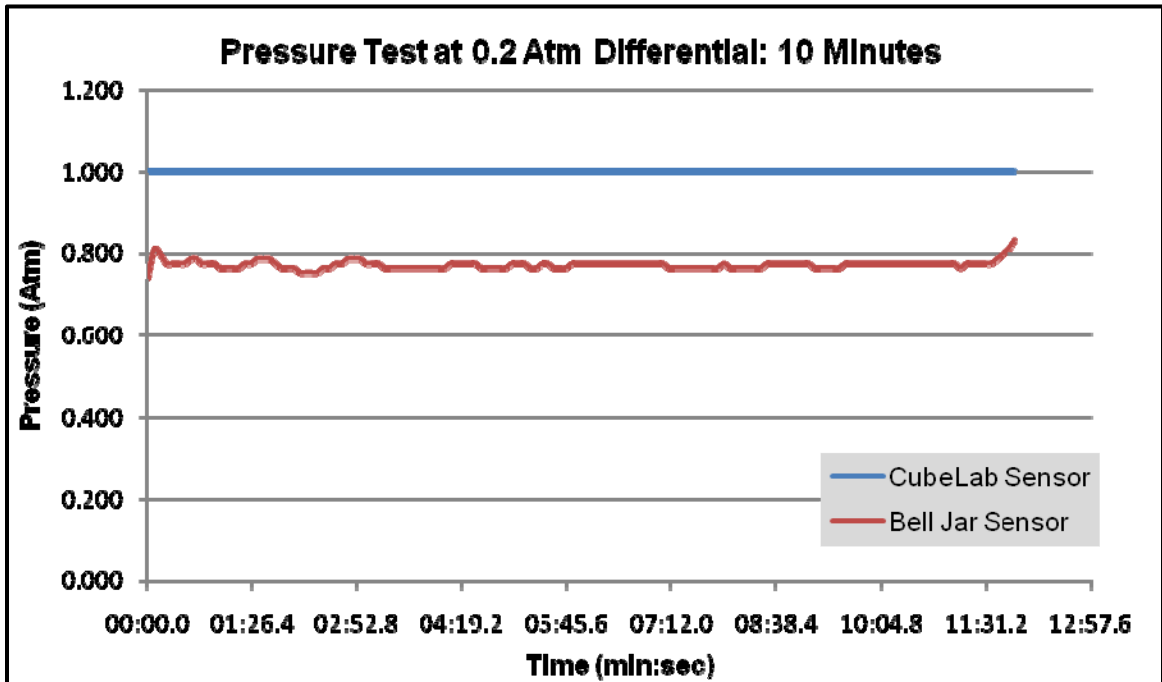
Figure 5-4: Static Pressure Test – 0.2 atm Differential for 10 minutes
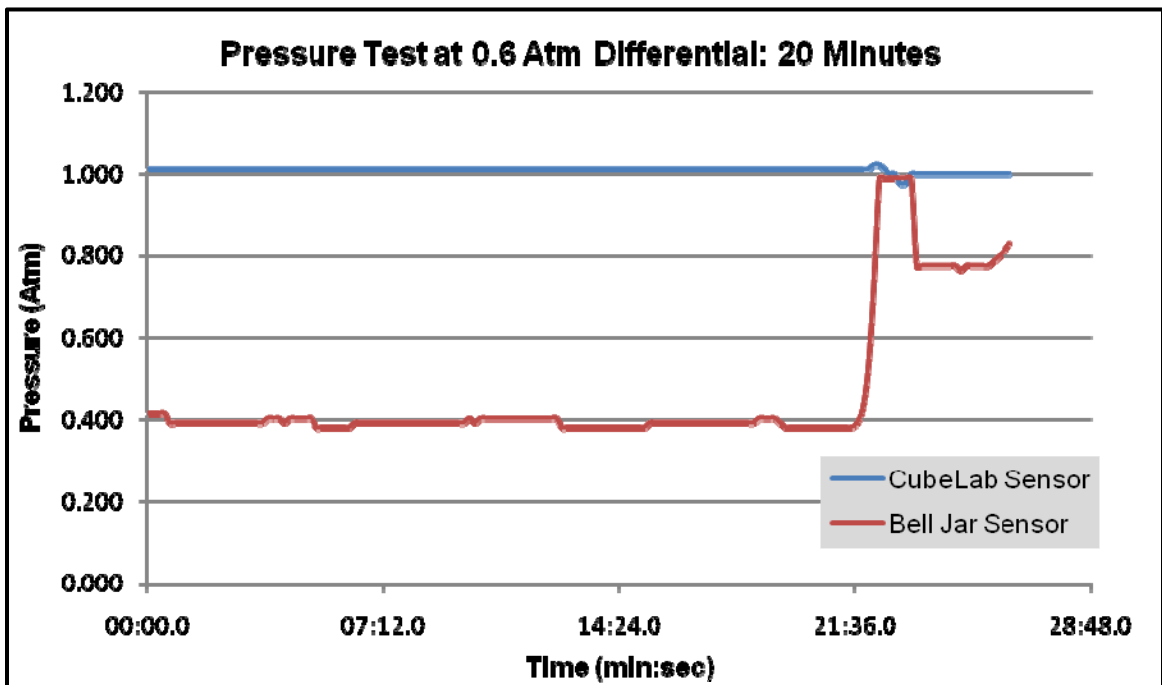
Figure 5-5: Static Pressure Test – 0.6 atm Differential for 20 minutes

Numerous tests were run with increasing pressure differential and duration. The longest and highest differential tests, using the configuration of Figure 5-3 was for four hours at a differential of 0.85 atm. The results of this test are shown in Figure 5-6.
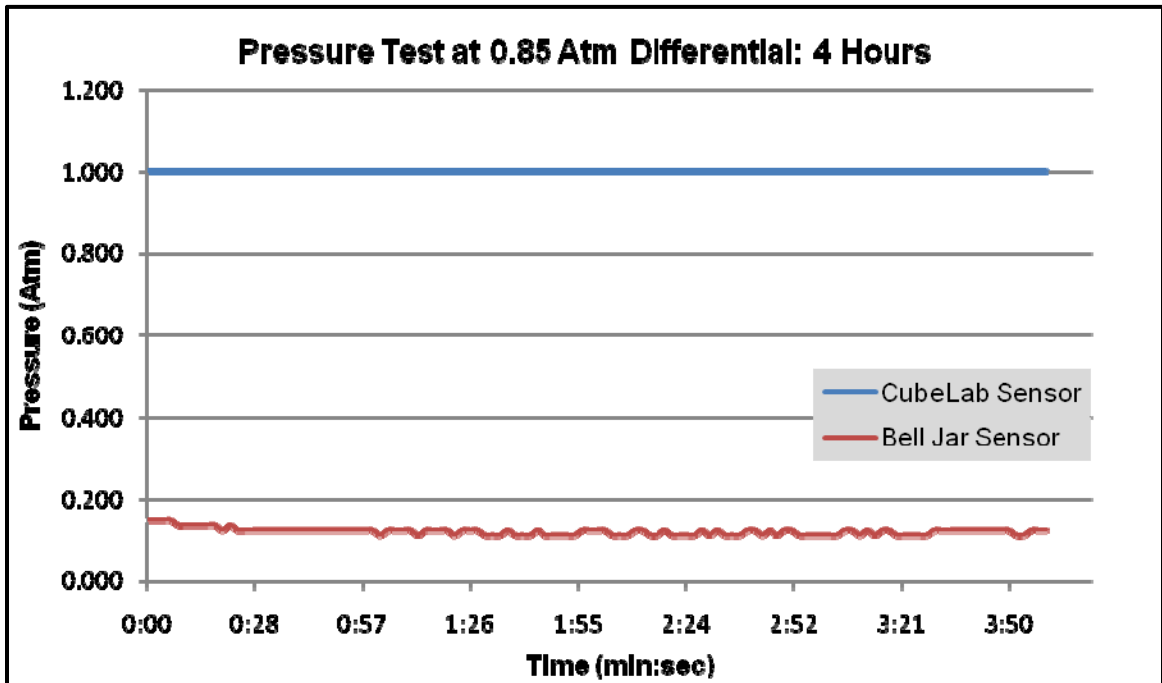
Figure 5-6: Static Pressure Test – Maximum Differential for 4 Hours

The comparison between the external and internal pressures of Figure 5-6 shows that the design holds up nominally for a long duration under medium vacuum situation, as the prototype lost no discernable pressure.

5.2.2 Dynamic Pressure Tests: Depressurization / Repressurization

Testing to determine if the prototype could handle both the rapid loss and reacquisition of pressure in its environment was conducted to fulfill requirement 8-11. Specifically, to meet this requirement, the structure must maintain a positive safety factor for a depressurization/repressurization rate of 8.4 psi/min, with an initial pressure of 15.2 psi down to a minimum pressure of 3.95 psi. To

accomplish this, the test setup shown in Figure 5-3 was used with a power supply used to throttle the pump to meet the pressure gradient rates. One portion of the requirement was not completely met as the initial pressure was measured at 14.7 psi instead of the required 15.2. Figure 5-7 shows the depressurization portion of this testing. The black line shows the gradient and minimum pressure requirement with the shaded area representing pressures outside the requirements specification. The testing shows the prototype maintained its seal during a rapid loss of pressure.
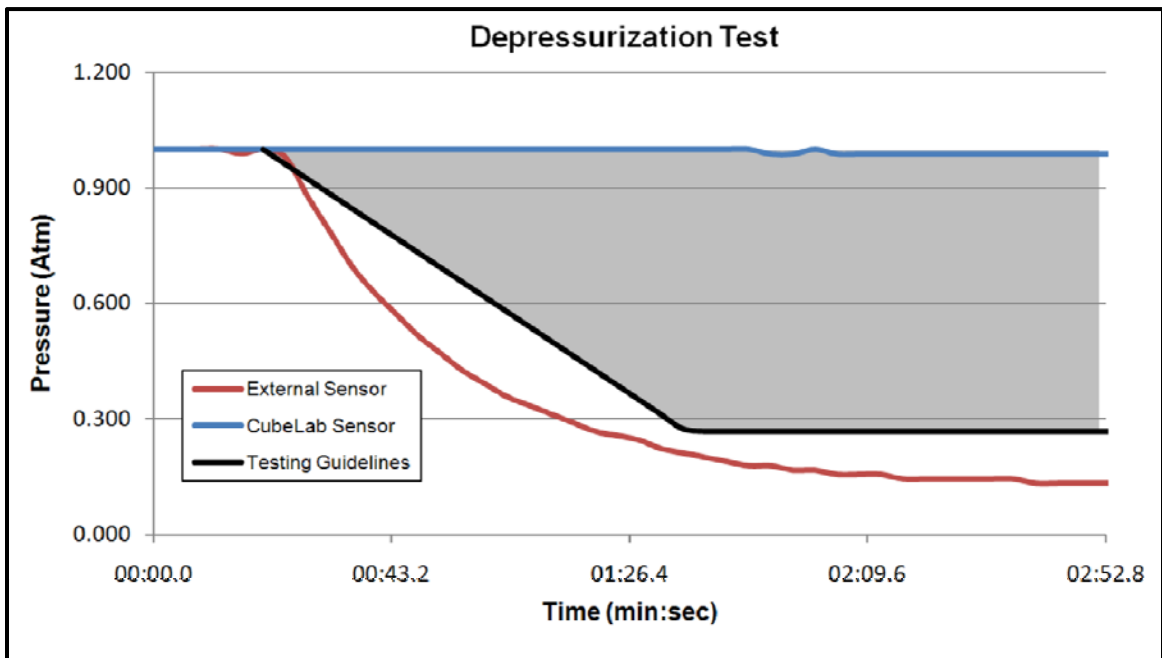
Figure 5-7: Depressurization Pressure Plot

Figure 5-8 shows the repressurization portion of the test with the same areas shaded indicating pressures outside the requirement. This test as well showed the prototype can withstand the repressurization in addition to maintaining its structural integrity as predicted by the analysis of this situation in section 4.6.4.
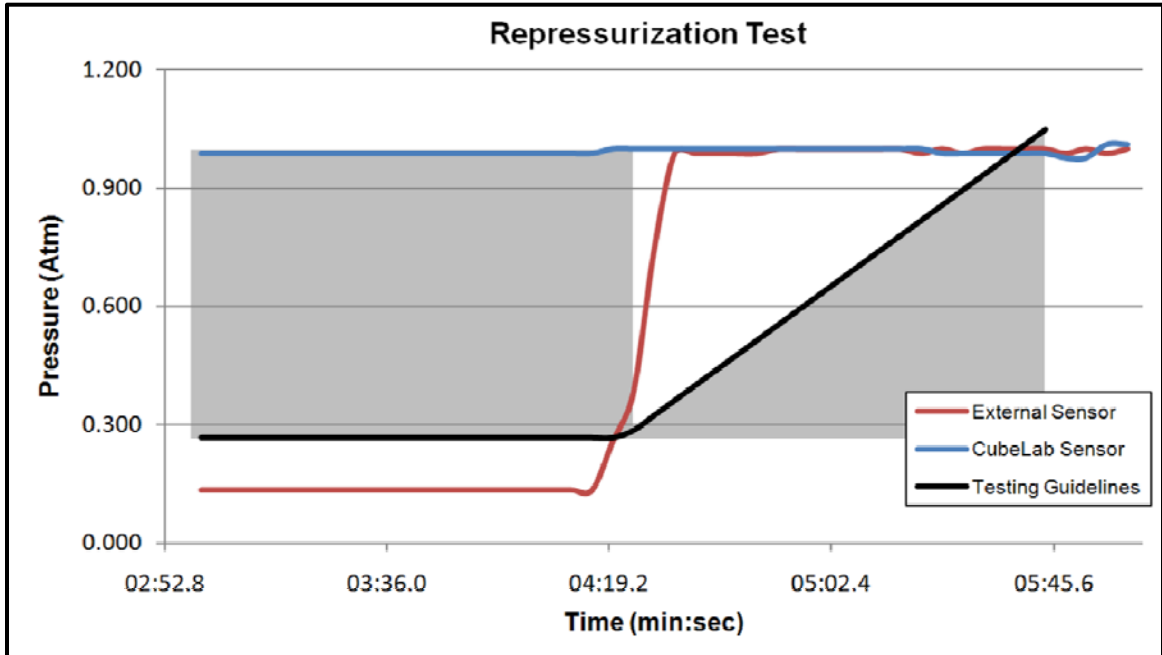
Figure 5-8: Repressurization Pressure Plot

5.2.3 Human Factors

Human Factors testing, or HFIT, is done to ensure proper ergonomics and safety for the astronauts on orbit when handling a payload. The only major HFIT requirement for which compliance needed to be verified was the sharp edge requirement listed as 8-5 in Table 3-7. To accomplish this, cotton gloves were worn and passed over the hardware to see if they catch on any edges. If this does occur, the hardware fails and needs to be modified.

No areas from the top, body, or gasket components violated the glove test, as these components were designed with rounded edges and made from smooth SLA and urethane materials. However, the hold down bolts did snag the cotton gloves. This was expected, as thumb bolts are used to achieve easy access to the interior during testing along with applying an even clamping force on the gasket. Additionally this design violates requirement 8-12 stating that all fasteners shall be captive to prevent floating away. A new design which satisfies both the sharp edge and 8-12 requirements is overviewed in section 6.2.

5.2.4 Requirements Check

The checklist of design requirements for the containment CubeLab prototype are shown in Table 5-1 and are marked in green, yellow, or red depending on whether requirements were met, partially met, or require additional design work for a flight model design.

Table 5-1: Final CubeLab Checklist Comparison

Req. #	Status	Requirement Name	Requirement Description
8-1	🟨	Volume and USB Placement	USB placement and volume dimensions shall follow tables 1 and 2 of the CubeLab ICD
8-2	🟩	Mass	1U CubeLab Module shall not exceed a mass of 1 kg
8-3	🟥	USB Connection	CubeLab Module shall contain at least one USB type B female connector
8-4	🟩	Materials	Natural Rubbers shall not be used
8-5	🟨	Sharp Edge	Payloads shall protect crew member from sharp edges and corners
8-6	🟩	Natural Frequencies	Payloads stored within the Space Shuttle middeck shall have a first primary natural frequency equal to or exceeding 30 Hertz (Hz)
8-7	🟩	Launch and Landing Loading	Payloads shall maintain a positive factor of safety during launch and landing conditions outlined in table 4.1.2.1-1
8-8	🟩	Safety Factor	Shall maintain a Factor of Safety above 1.5 for worst case loading scenarios outlined in table 4.1.3.1-1
8-9	🟩	Random Vibration	Payloads shall maintain a positive factor of safety when exposed to the loads outlined in table 4.5.1-1
8-10	🟩	Inertial Loading	Payloads shall maintain a positive factor of safety when exposed to orbits loads of 0.2 g's in any direction. This is due to accelerations from spacecraft docking procedures

Table 5-1 (Continued)

8-11		Depressurization / Repressurization	Payloads shall maintain a positive Factor of Safety during maximum depressurization and repressurization of 8.4 psi/min. The initial pressure should be 15.2 psi and final pressure 3.95 psi
8-12		Captive Fasteners	All fasteners planned to be installed and/or removed on orbit shall be captive when disengaged
8-13		Fasteners	Only right-handed threads shall be used
8-14		Triple Containment	The <END ITEM> shall be designed such that no combination of two failures, or two operator errors, or one of each can results in a disabling or fatal personnel injury, or loss of the Orbiter of ISS. Compliance with this requirement may be accomplished at the End Item level or through a combination of hazard controls at the Segment/Systems levels
8-15		Random Vibration Analysis	Random Vibration Analysis shall be performed to ensure positive margins of safety during loading
8-16		Modal Analysis	A report of the natural frequencies and mode shapes of the flight hardware shall be performed

Of the requirements listed in Table 5-1, eleven were verified by either testing or analysis, while five were not fully met. Those which were not fully addressed dealt with the placement of the USB connector, the lack of captive fasteners, and triple containment for hazardous payloads. The only requirement given red status was 8-3 which stated that the prototype required a USB type B female connector for consideration as a CubeLab Module. Potential solutions for these requirements are discussed in sections 6.1 – 6.3.

6   MODIFICATIONS FOR FLIGHT MODEL

With testing completed, this section outlines the lessons learned through the development process, modifications that need to be made to the current design to fulfill all the requirements of Table 5-1, and initial designs for those modifications. Also, potential features to be used for future CubeLabs are introduced to further their capabilities.

6.1   USB Connector

The only requirement to receive a red status in Table 5-1 dealt with the exclusion of a USB connector to the prototype. These connections are a requirement from the CubeLab Standard that allow power and data transfer from individual CubeLab Modules to the NanoRack Platform. The design of a connection system was omitted as this was beyond the scope of this research. These components would, themselves, need to seal between the interior and exterior environments. However, a sealed USB connector or electronics umbilical would be necessary for a CubeLab Module carrying a biological payload

Research into the hardware and processes necessary for USB connectors to achieve the same sealing capacity as the rest of the Containment CubeLab design of this thesis will be pivotal before any biological or hazardous payload can use the CubeLab Standard for research. Several possibilities exist, such as using ribbon cable USB connectors epoxied to the containment structure which would minimize volume and achieve the necessary sealing capacity. Another approach would be to use the configuration discussed in section 6.4.1 utilizing separate biological and electronics sections.

6.2   Improved Bolt Design

As explained in section 5.2.3, the bolt design used for prototype testing would not be allowed for flight due to failure of both the sharp edge (8-5) and captive bolt (8-12) requirements. To resolve these problems, a preliminary modified bolt configuration shown in Figure 6-1   was designed. This design uses shoulder

bolts which have two different diameters along their length, with only the shorter diameter towards the end only being threaded. Captive springs are also used to straighten and tension the bolts when loosed from the body component, and retaining washers are used to prevent the bolt assembly from separating from the top. This combination of hardware changes would require a modified design of the top component, but would eliminate sharp edges and the problem of bolts separating.
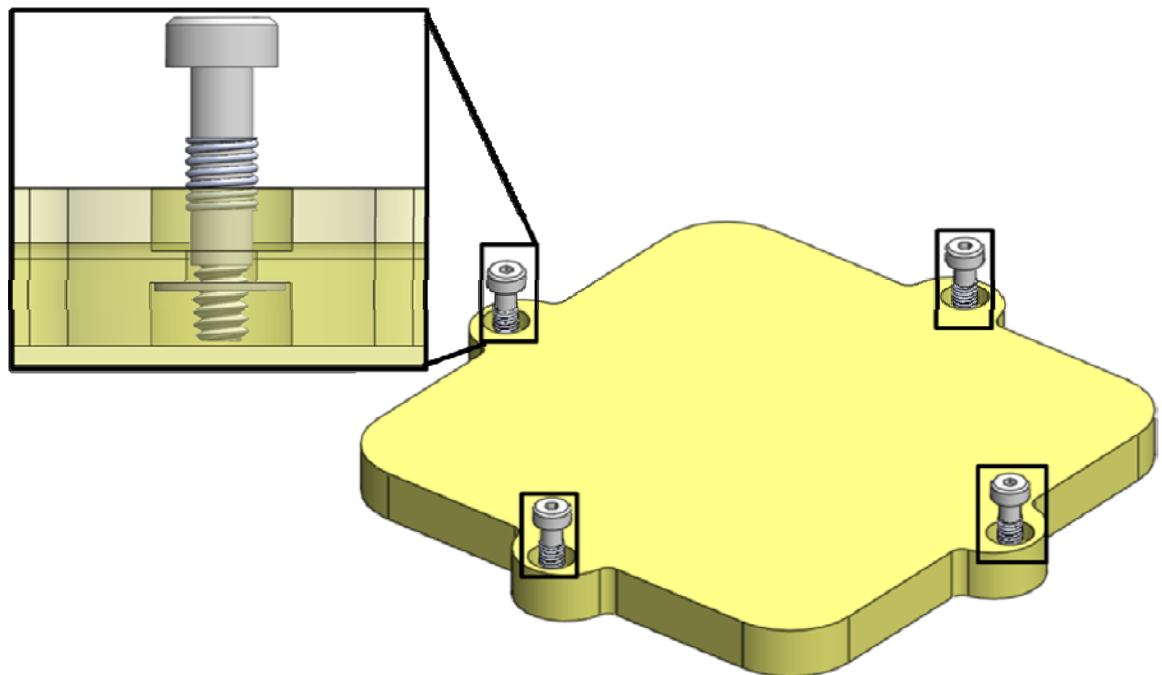
Figure 6-1: Shoulder Bolt Configuration

6.3 Triple Containment

For payloads which include biology that is categorized as hazardous, the structure of the CubeLab must adhere to requirement 8-14 which states:

"The <END ITEM> shall be designed such that no combination of two failures, or two operator errors, or one of each can results in a disabling or fatal personnel injury, or loss of the Orbiter of ISS. Compliance with this requirement may be accomplished at the End Item level or through a combination of hazard controls at the Segment/Systems levels."

Adherence to this double failure containment, requirement would entail expanding the design of this thesis to create a double walled assembly which would account for two levels of containment with the third being the vial which holds the medium (biological, hazardous liquids, etc.). This double walled design would include two similar structures being able to fit within the other. Such a configuration would create several design problems and will require further research to include both structures within the dimensions of the CubeLab Standard. Figure 6-2 displays a preliminary representation of such an assembly.
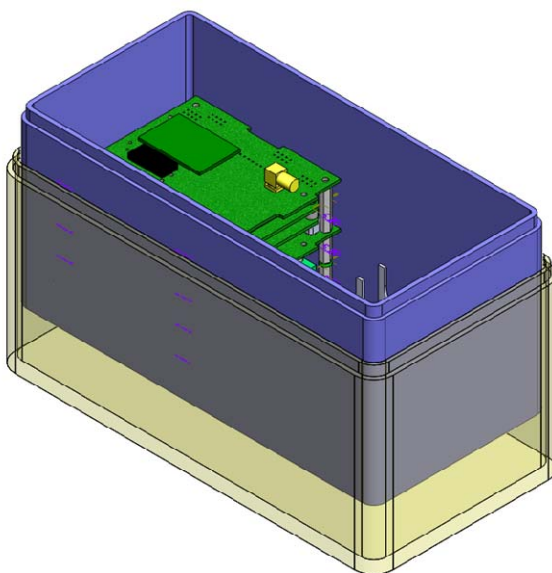
Figure 6-2: Preliminary Double Walled Configuration

6.4 Additional Features and Configurations

Considering the increased complexity of a CubeLab Module design which integrates both the triple containment and bolt designs outlined in sections 6.2 and 6.3, additional features could be considered, some of which are outlined below. The design features explained add additional safety measures or increase the variety of future CubeLab Modules.

6.4.1 1U Containment / 1U Electronics Bus

A potential configuration to be considered, shown in Figure 6-3, separates the biological and electronics portions of a CubeLab Module. Doing so would leave only the hardware which needs to be contained within the structure, while electronics, data handling, and power systems could be housed in a simpler structure. The USB port could then be placed in the electronics section with an umbilical between the two transferring data and telemetry. Such an arrangement would be beneficial in any mission were precise thermal control is necessary as the electronics would not be included in the volume which would need to be regulated.
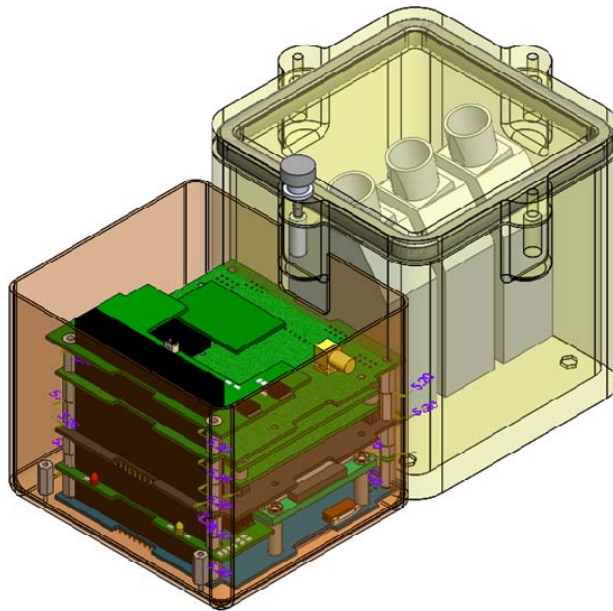
Figure 6-3: 1U Containment / 1U Electronic Bus Configuration

6.4.2 UV Safety Light

A safety measure in case of loss of the first level of containment (medium / biological vial) within a CubeLab Module could use UV lighting which would be activated by internal sensors (humidity, pressure, etc.) to turn on and kill the biological payload to ensure no harm is done. Such a feature would only be applicable with certain payloads, as only particular categories of bacteria and biological mediums are susceptible to UV sterilization [48].

7   CONCLUSIONS & FUTURE WORK

In this research, a thorough design process for containment structures aboard the ISS has been completed. This research lays the groundwork for a generation of more complex CubeLabs Modules. This thesis has documented the design requirements, initial designs, revisions to those designs, results of engineering analyses performed to predict design performance, production of a prototype, and testing under expected service conditions, which validated the work. The constraints of the CubeLab Standard were used as the starting point for a design which then evolved as different materials and manufacturing techniques were considered.

Primary achievements in this work were:

- A design, including body, top, gasket, and fasteners, was developed. The design was dimensioned to a 1U CubeLab Standard volume.

- The design of the gasket, which provides the sealing mechanism of the assembly, was greatly simplified from preliminary sketches after achieving a better understanding of the mechanical design of such a component.

- Engineering calculations were performed to determine the appropriate torque for the screws that fasten the top to the body.

- Finite element analysis was performed to predict the sealing capability for the fully-assembled design.

- Finite element analyses was also performed to predict deflections and stresses under expected loading conditions and verify that positive safety factors are expected during worse than expected loading scenarios.

- Modal analysis was performed with the finite element method to ensure the natural frequencies of the assembly are expected to be

well above the minimum frequency requirements concerning launch vehicles and stowage.

- A prototype of the full assembly was built. The body and top components were produced using the rapid prototyping method of stereolithography. A gasket mold was built, and several gaskets were produced from different urethane materials.

- The sealing capacity of the assembly was tested. From this testing, a urethane with a durometer hardness of 42A was found to produce the most desirable results.

The most critical tests in the validation of the containment CubeLab structure were pressure tests which verified that the prototype sealed its internal environment. In these tests, the external pressure was reduced at stepped intervals for increasing durations to stress the limits of the design. Such pressure tests included light and medium vacuum along with rapid depressurization and repressurization tests. These tests confirmed the seal design meets requirements.

Much preliminary work with regard to the structure of a CubeLab Module which can accommodate biological payloads, which requires containment, has been undertaken within this thesis's research. No specific payload was considered and no electronic component designs were developed. However, the integration of such systems was a constant concern during development. Several mission options which would leverage a containment CubeLab Module are currently under development with the most promising of these being the GlioLab mission mentioned in section 2.2.4.

While this research was limited to initial designs and structural analysis, many systems remain which would require further development before a biologically related payload, leveraging the CubeLab Standard, could be certified for flight. Such future research could include areas such as the following:

- Precise Thermal Control

- In Situ Environmental Measurement

- Electro-Mechanical Actuation

- Command & Data Handling Bus

- Automated Fluid Mixing System

- Micro Valve Characterization

The possibilities for CubeLab Modules are greatly enhanced by the designation of the ISS as a national laboratory and the greater role of commercial enterprises in space flight. With the barriers of entry for developers being lowered researchers in a variety of fields now have the opportunity to use the microgravity / low earth orbit environment. To fully utilize these opportunities future development of CubeLab Modules would benefit from the work discussed in this thesis.

APPENDIX A - ANSYS 2D Static Analysis Input Code

```
! ANSYS Input file for Static Analysis of
!CubeLab Containment Prototype using a 42A
!hardness Gasket with a maximum pressure
!differential of 15.2 psi

/filnam,ap1-example1
/prep7
et,1,82
keyopt,1,3,2

!Material Properties for 42A Gasket
mp,ex,1,0.74e6
mp,dens,1,1090
mp,prxy,1,.49

!Material Properties for SLA
mp,ex,2,2700e6
mp,dens,2,1120
mp,prxy,2,.23

!Key points and Lines for Gasket Left
k,1,-0.0045,0
k,2,-0.0045,0.0075
k,3,0.002,0.0075
k,4,0.002,0
k,5,0,0
k,6,0,0.0055
k,7,-0.0025,0.0055
k,8,-0.0025,0
l,1,2
*repeat,7,1,1
l,8,1

!Fillet Callouts for Left Gasket
ksel,s,kp,,1,2
lslk,s,1
*get,line1,line,0,num,max
ksel,s,kp,,2,3
lslk,s,1
*get,line2,line,0,num,max
ksel,s,kp,,3,4
lslk,s,1
*get,line3,line,0,num,max
```

```
ksel,s,kp,,5,6
lslk,s,1
*get,line4,line,0,num,max
ksel,s,kp,,6,7
lslk,s,1
*get,line5,line,0,num,max
ksel,s,kp,,7,8
lslk,s,1
*get,line6,line,0,num,max
ksel,s,kp,,1
ksel,a,kp,,8
lslk,s,1
*get,line7,line,0,num,max
allsel
lfillt,line1,line2,0.001
lfillt,line2,line3,0.001
lfillt,line4,line5,0.0005
lfillt,line5,line6,0.0005
lfillt,line6,line7,0.00075
allsel

!Semi Circle for Left Gasket
ksel,s,kp,,4,5
lslk,s,1
ldel,all
k,100,0.001,-0.001
larc,4,5,100,0.0014142
allsel
al,all

!Mesh For Left Gasket
smrtsize,1
amesh,all

!Key points and Lines for Right Gasket
k,211,0.098,0
k,212,0.098,0.0075
k,213,0.1045,0.0075
k,214,0.1045,0
k,215,0.1025,0
k,216,0.1025,0.0055
k,217,0.100,0.0055
k,218,0.100,0
l,211,212
*repeat,7,1,1
```

```
l,218,211

!Fillet Callouts for Right Gasket
ksel,s,kp,,211,212
lslk,s,1
*get,line71,line,0,num,max
ksel,s,kp,,212,213
lslk,s,1
*get,line72,line,0,num,max
ksel,s,kp,,213,214
lslk,s,1
*get,line73,line,0,num,max
ksel,s,kp,,214,215
lslk,s,1
*get,line74,line,0,num,max
ksel,s,kp,,215,216
lslk,s,1
*get,line75,line,0,num,max
ksel,s,kp,,216,217
lslk,s,1
*get,line76,line,0,num,max
ksel,s,kp,,217
ksel,a,kp,,218
lslk,s,1
*get,line77,line,0,num,max
allsel
lfillt,line71,line72,0.001
lfillt,line72,line73,0.001
lfillt,line74,line75,0.00075
lfillt,line75,line76,0.0005
lfillt,line76,line77,0.0005
allsel

!Semi Circle for Right Gasket
ksel,s,kp,,211,218
lslk,s,1
ldel,all
k,250,0.099,-0.001
larc,211,218,250,0.0014142
allsel
!al,all

!Mesh For Right Gasket
allsel
lsla,s
```

66

```
lsel,inve
al,all
allsel

!Urethane Material Callout for Gaskets
mat,1
smrtsize,1
amesh,all

!Key points and Lines for Top
k,221,-0.0105,0.001
k,222,-0.0165,0.001
k,223,-0.0165,0.011
k,224,-0.01606,0.011
k,225,-0.01288,0.011
k,226,-0.0105,0.011
k,227,-0.00812,0.011
k,228,-0.00494,0.011
k,229,0.10494,0.011
k,230,0.10812,0.011
k,231,0.1105,0.011
k,232,0.11288,0.011
k,233,0.11606,0.011
k,234,0.1165,0.011
k,235,0.1165,0.001
k,236,0.1105,0.001
k,237,0.1045,0.001
k,238,0.1045,0.0075
k,239,0.098,0.0075
k,240,0.098,0
k,241,0.098,-0.00025
k,242,0.096,-0.00025
k,243,0.096,0.0075
k,244,0.004,0.0075
k,245,0.004,-0.00025
k,246,0.002,-0.00025
k,247,0.002,0
k,248,0.002,0.0075
k,249,-0.0045,0.0075
k,250,-0.0045,0.001
l,221,222
*repeat,29,1,1
l,250,221
```

```
!Fillet Callouts for Top Left
ksel,s,kp,,247,248
lslk,s,1
*get,line10,line,0,num,max
ksel,s,kp,,248,249
lslk,s,1
*get,line11,line,0,num,max
ksel,s,kp,,249
ksel,a,kp,,250
lslk,s,1
*get,line12,line,0,num,max

!Fillet Callouts for Top Right
ksel,s,kp,,237,238
lslk,s,1
*get,line13,line,0,num,max
ksel,s,kp,,238,239
lslk,s,1
*get,line14,line,0,num,max
ksel,s,kp,,239
ksel,a,kp,,240
lslk,s,1
*get,line15,line,0,num,max
allsel

!Fillet Callouts for Top
lfillt,line10,line11,0.001
lfillt,line11,line12,0.001
lfillt,line13,line14,0.001
lfillt,line14,line15,0.001

allsel
lsla,s
lsel,inve
al,all
allsel

!SLA Material Callout for Top Component
mat,2
smrtsize,1
amesh,all

!Key points and Lines for Body
k,51,-0.0165,0
k,52,-0.0105,0
```

```
k,53,-0.0025,0
k,54,-0.0025,0.0055
k,55,0,0.0055
k,56,0,0
k,57,0,-0.098
k,58,0.100,-0.098
k,59,0.100,0
k,60,0.100,0.0055
k,61,0.1025,0.0055
k,62,0.1025,0
k,63,0.1105,0
k,64,0.1165,0
k,65,0.1165,-0.025
k,66,0.1105,-0.025
k,67,0.1065,-0.025
k,68,0.1065,-0.084
k,69,0.1065,-0.096
k,70,0.1065,-0.1045
k,71,-0.0065,-0.1045
k,72,-0.0065,-0.025
k,73,-0.0105,-0.025
k,74,-0.0165,-0.025
l,51,52
*repeat,23,1,1
l,74,51

!Fillet Callouts for Body
!Line Selection for Left Side
ksel,s,kp,,53,54
lslk,s,1
*get,line21,line,0,num,max
ksel,s,kp,,54,55
lslk,s,1
*get,line22,line,0,num,max
ksel,s,kp,,55
ksel,a,kp,,56
lslk,s,1
*get,line23,line,0,num,max

!Line Selection for Right Side
ksel,s,kp,,59,60
lslk,s,1
*get,line24,line,0,num,max
ksel,s,kp,,60,61
lslk,s,1
```

```
*get,line25,line,0,num,max
ksel,s,kp,,61
ksel,a,kp,,62
lslk,s,1
*get,line26,line,0,num,max
allsel

!Line Selection for Bolt Section Left
ksel,s,kp,,71,72
lslk,s,1
*get,line27,line,0,num,max
ksel,s,kp,,72
ksel,a,kp,,73
lslk,s,1
*get,line28,line,0,num,max
allsel

!Line Selection for Bolt Section Right
ksel,s,kp,,66,67
lslk,s,1
*get,line29,line,0,num,max
ksel,s,kp,,67
ksel,a,kp,,68
lslk,s,1
*get,line30,line,0,num,max
allsel

!Fillet Callouts for Body
lfillt,line21,line22,0.0005
lfillt,line22,line23,0.0005
lfillt,line24,line25,0.0005
lfillt,line25,line26,0.0005
lfillt,line27,line28,0.0025
lfillt,line29,line30,0.0025

allsel
lsla,s
lsel,inve
al,all
allsel

!SLA Material Callout for Body Component
mat,2
smrtsize,1
amesh,all
```

```
!*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
et,8,16
r,8,0.0035,0.00175

!Material Properties Bolts
mp,ex,8,193e9
mp,dens,8,8030
mp,prxy,8,.3

l,221,226
l,52,221
l,52,73

l,231,236
l,63,236
l,63,66

ksel,s,kp,,221
ksel,a,kp,,226
ksel,a,kp,,52
ksel,a,kp,,73
ksel,a,kp,,231
ksel,a,kp,,236
ksel,a,kp,,63
ksel,a,kp,,66
lslk,s,1

!SS Material Callout for Bolts
real,8
type,8
mat,8
smrtsize,1
lmesh,all
!*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-

!Contact Wizard Section
!_____
!Specifying friction between components etc.
mp,mu,1,.4
et,2,targe169
et,3,conta172
r,3,0,0,0,0,0,0
rmore,0,0,0,0,0,0
rmore,0,0,0,0,0,0
```

```
rmore,0,0,0,0,0,0
r,4,0,0,0,0,0,0
rmore,0,0,0,0,0,0
rmore,0,0,0,0,0,0
rmore,0,0,0,0,0,0
r,5,0,0,0,0,0,0
rmore,0,0,0,0,0,0
rmore,0,0,0,0,0,0
rmore,0,0,0,0,0,0


!Contact between Outside of Gasket Left and Inside of Top
real,3
lsel,s,line,,1
lsel,a,line,,2
lsel,a,line,,3
lsel,a,line,,9
lsel,a,line,,10
nsll,s,1
esln,s
type,2
esurf
lsel,s,line,,52
lsel,a,line,,53
lsel,a,line,,54
lsel,a,line,,55
lsel,a,line,,57
lsel,a,line,,58
nsll,s,1
esln,s
type,3
esurf
allsel

!Contact between Inside of Gasket Left and Inside of Body
real,3
lsel,s,line,,5
lsel,a,line,,6
lsel,a,line,,7
lsel,a,line,,8
lsel,a,line,,11
lsel,a,line,,12
lsel,a,line,,13
nsll,s,1
esln,s
```

type,2
esurf
lsel,s,line,,62
lsel,a,line,,63
lsel,a,line,,64
lsel,a,line,,65
lsel,a,line,,85
lsel,a,line,,86
nsll,s,1
esln,s
type,3
esurf
allsel

!Contact between Outside of Gasket Right and Inside of Top
real,4
lsel,s,line,,14
lsel,a,line,,15
lsel,a,line,,16
lsel,a,line,,22
lsel,a,line,,23
nsll,s,1
esln,s
type,2
esurf
lsel,s,line,,42
lsel,a,line,,43
lsel,a,line,,44
lsel,a,line,,45
lsel,a,line,,46
lsel,a,line,,47
lsel,a,line,,59
lsel,a,line,,60
nsll,s,1
esln,s
type,3
esurf
allsel

!Contact between Inside of Gasket Right and Inside of Body
real,5
lsel,s,line,,17
lsel,a,line,,18
lsel,a,line,,19

```
lsel,a,line,,20
lsel,a,line,,24
lsel,a,line,,25
lsel,a,line,,26
nsll,s,1
esln,s
type,2
esurf
lsel,s,line,,69
lsel,a,line,,70
lsel,a,line,,71
lsel,a,line,,72
lsel,a,line,,87
lsel,a,line,,88
nsll,s,1
esln,s
type,3
esurf
allsel

!Contact between of Top to Body
real,6

lsel,s,line,,27
lsel,a,line,,41
lsel,a,line,,42
lsel,a,line,,43
lsel,a,line,,44
lsel,a,line,,45
lsel,a,line,,46
lsel,a,line,,47
lsel,a,line,,51
lsel,a,line,,52
lsel,a,line,,53
lsel,a,line,,54
lsel,a,line,,55
lsel,a,line,,56
lsel,a,line,,57
lsel,a,line,,58
lsel,a,line,,59
lsel,a,line,,60
nsll,s,1
esln,s
type,2
esurf
```

```
lsel,s,line,,62
lsel,a,line,,63
lsel,a,line,,64
lsel,a,line,,65
lsel,a,line,,69
lsel,a,line,,70
lsel,a,line,,71
lsel,a,line,,85
lsel,a,line,,86
lsel,a,line,,87
lsel,a,line,,88
nsll,s,1
esln,s
type,3
esurf
allsel

!_____
!End of Contact Wizard Input

!Solution
/solu

! Constraint in all direction
!at location of USB
lsel,s,line,,78
nsll,s,1
d,all,all,0
allsel

! constraint in Y direction on area
!were bolts are
lsel,s,line,,44
lsel,a,line,,54
lsel,a,line,,80
nsll,s,1
d,all,uy,0
allsel

! Pressure applied modeling the
!tightening of the hold down bolts
lsel,s,line,,30
lsel,a,line,,33
lsel,a,line,,35
lsel,a,line,,38
```

```
nsll,s,1
sfl,all,pres,792000
allsel

! Pressure force applied to
!interior of assembly
lsel,s,line,,4
lsel,a,line,,21
lsel,a,line,,47
lsel,a,line,,48
lsel,a,line,,49
lsel,a,line,,50
lsel,a,line,,51
lsel,a,line,,66
lsel,a,line,,67
lsel,a,line,,68
nsll,s,1
sfl,all,pres,105000
allsel

! Pressure force applied to
!exterior of assembly
lsel,s,line,,27
lsel,a,line,,28
lsel,a,line,,29
lsel,a,line,,30
lsel,a,line,,31
lsel,a,line,,32
lsel,a,line,,33
lsel,a,line,,34
lsel,a,line,,35
lsel,a,line,,36
lsel,a,line,,37
lsel,a,line,,38
lsel,a,line,,39
lsel,a,line,,40
lsel,a,line,,41
lsel,a,line,,42
lsel,a,line,,56
lsel,a,line,,61
lsel,a,line,,62
lsel,a,line,,72
lsel,a,line,,73
lsel,a,line,,74
lsel,a,line,,75
```

```
lsel,a,line,,76
lsel,a,line,,77
lsel,a,line,,78
lsel,a,line,,79
lsel,a,line,,80
lsel,a,line,,82
lsel,a,line,,83
lsel,a,line,,84
lsel,a,line,,89
lsel,a,line,,90
nsll,s,1
sfl,all,pres,27500
allsel

!Calculate Solution
solve

!Minimize scaling
!/dscale,1,1
```

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