Development of a Reusable Biological Sounding Rocket Payload (ODU SubSEM II)

by:

Nathanael Miller

Edited by:

David Talaiver
& Ersin Ancel

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Dr. Robert Ash

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About This Document

The objective of this document is to provide an explanation of all the systems on board the ODU SubSEM II sounding rocket payload. Primary emphasis in this document will be given to the mechanical system. For detailed discussion of the electrical system consult this document's electrical engineering counterpart, which can be found in the space systems library.

Acknowledgments

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Faculty Advisor
Dr. Robert Ash
Project Manager
Nathanael Miller
Systems Engineer
Ersin Ancel
Graduate Students
Tara Fuller
Denise Witherspoon
Biology Team
Dr. Eugene Williams
Cloe Manarinjara
Sean Moore
Jeannette
Trac Nguyen
Alex Perros
Adam Lowe
Kate Shelly
Sarah Ullah
Mechanical Team
David Talaiver
Sean Potter
Matt Marchlik
Chris Underwood
Eric Bell
Dawn Huffman
Morgan Smith
Blaine Campbell
Ryan O'Dawe
Han Choi
Baboucar Faal
John Miller
Niki Hence
Tressa Snyder
Zin Low
Mike Lake
Electrical Team
Chrysostomos Michaelides
Raoul Sheridian
Richard Hare
Chris Szymanski
Aaron Anderson
Breon Mitchell
Daniel Sachau
Richard Williams

Introduction

In a joint effort, undergraduate students at Old Dominion University (ODU) have been working with a biology team at Salisbury University (SU) to develop a reusable sounding rocket payload that will test the elasticity of metastatic cancer cells after exposure to microgravity. This second-generation experimental payload, ODU's SubSEM II, is a follow-up to a payload launched in May of 2005. The end goal of this undergraduate research project, made possible by an educational outreach program grant from Innovative Business Solutions Incorporated, is to address a question of scientific validity that possibly has great cultural interest, while at the same time benefiting the students involved with exposure to a non-simulated, legitimate research environment. The project has resulted in a truly cross-disciplinary team of more than 30 students, working together over the course of 22 months, beginning in May 2005. The team has been composed of students majoring in biology at SU, and in mechanical, aerospace, electrical, and computer engineering at ODU.

The resulting payload has been designed to be placed in a Sub-orbital Student Experiment Module (SubSEM) that will be launched by a Terrier/Improved-Orion launch vehicle from NASA's Wallops Flight Facility. The rocket will carry the experiment to an altitude well above 100 km, where, after exposure to the microgravity of free-fall in a vacuum, the cancer cell solutions will be pumped robotically through filters of known porosity in order to measure the effects of microgravity on their elasticity. The experiment module operates by forcing nine independent samples through nine separate filters. The survivability of the cells as they cross the filtration membranes will be established by determining the cell densities after the experiment has been executed. A variation in cell population density between data taken in the SU laboratory and data taken via the microgravity counterpart experiment will indicate whether the absence of gravity has an affect on the metastasis of these cancer cells, with potentially important implications for astronauts who will embark on inter-planetary voyages, as well as patients seeking advanced cancer treatment. The harsh vibrations and accelerations resulting from a solid-booster sounding-rocket launch environment, and involving greater than 20 g's of acceleration, along with the delicate requirements of carrying living cells, had to be accommodated in order to meet the mission objectives. The primary challenges to overcome regarding the science of the mission included: the transportation and introduction of live biological cell specimens into a space launch environment; being able to maintain sample viability up to, and through the launch sequence; and providing for the safe return of the sample upon completion of the flight and payload recovery. The inaccessibility to the launch vehicle prior to launch, the high loads generated by the launch, the launch vehicle's flight characteristics, and the time delay associated with the retrieval of the rocket were some of the most significant challenges imposed by the launch vehicle.

Mission Concept

ODU's SubSEM II is expected to launch from NASA's Wallops Flight Facility onboard a Terrier Orion launch vehicle. The vehicle will carry a modified SubSEM module to an estimated altitude of 200 km and provide approximately 300 seconds of microgravity exposure. The launch sequence for the biological payload begins in a laboratory in Salisbury, Maryland, approximately 10 hours prior to the launch. It is here that the biological specimens will be loaded into a fluid manipulation unit. This preparation process will take place in a controlled laboratory environment. The fluid manipulation unit (FMU) will contain the cells throughout the mission, perform the experiment, and return the sample for analysis after the experiment is executed.

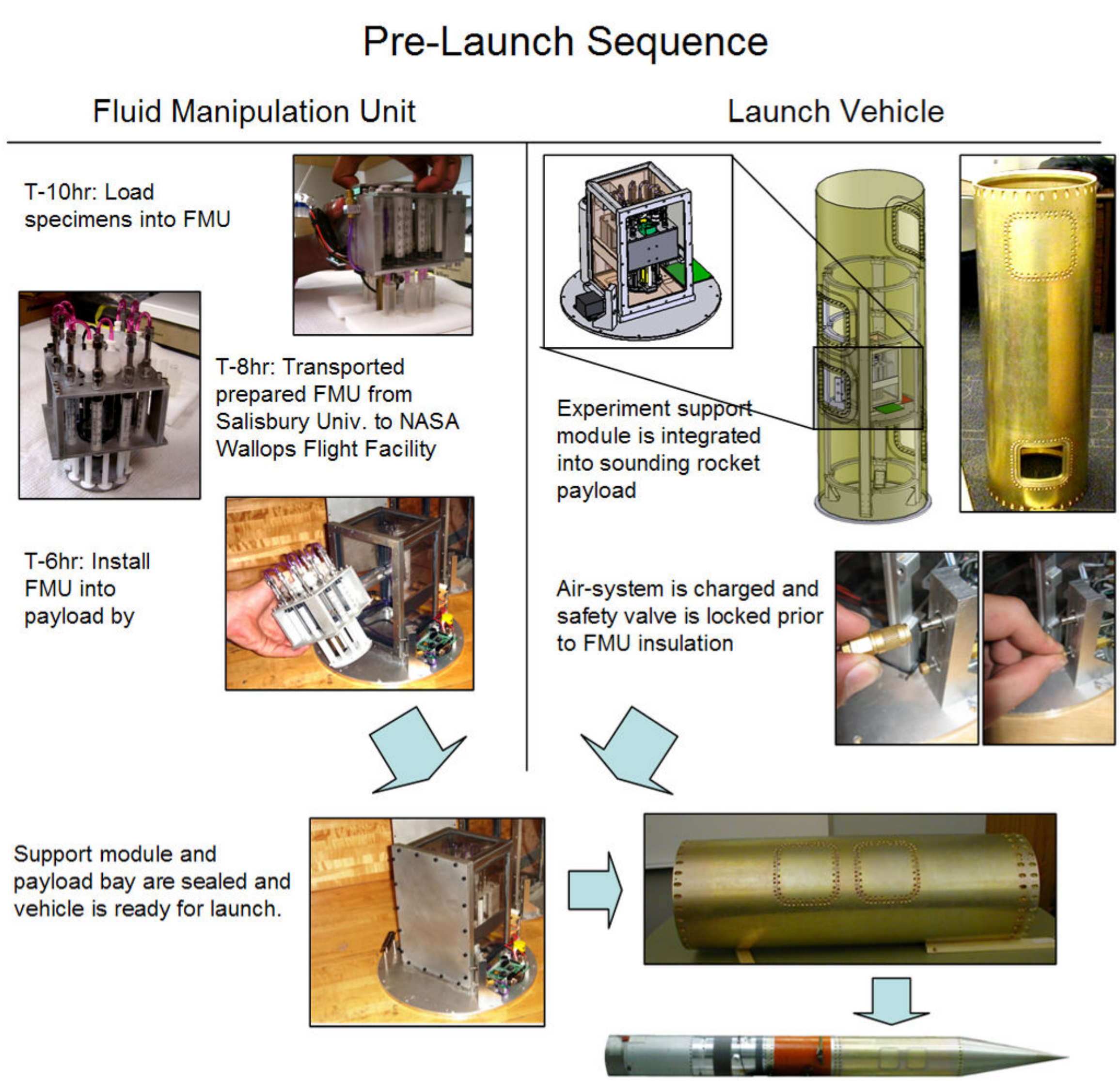

Figure 1. ODU SubSEM II pre launch operation sequence.

Approximately eight hours prior to launch, the test article (fully charged FMU) will be transported by motor vehicle from the Salisbury University laboratory to the NASA

Wallops Island Flight Facility approximately two hours later. At that time, preparations, such as charging the ODU SubSEM II air system, will have already occurred as part of the preparations for loading the unit into the experiment module on board the sounding rocket. The current SubSEM II payload module has been designed for installation through *Hatch Number Three* on the SubSEM payload unit.

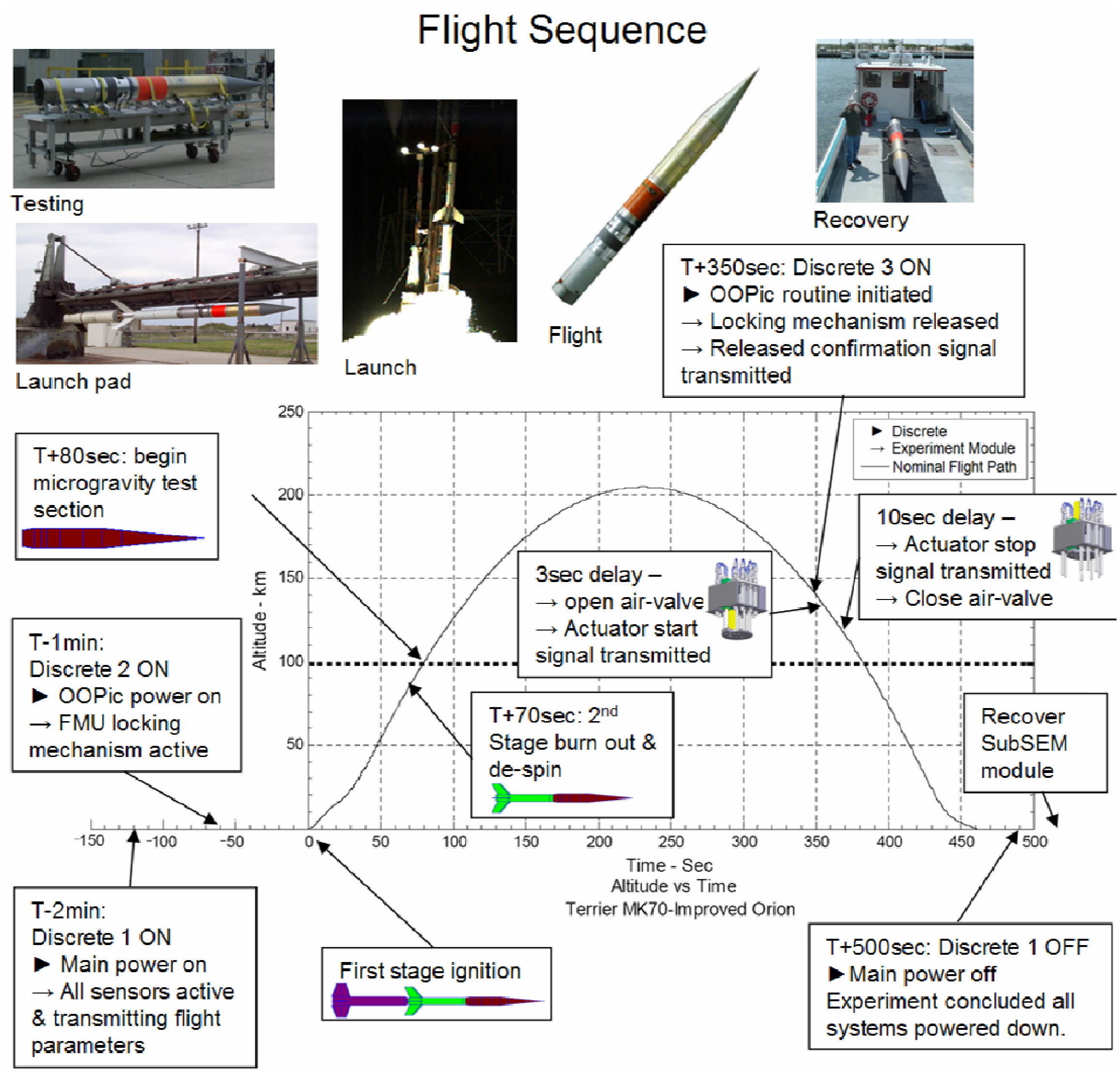

Figure 2. ODU SubSEM II flight operations timeline.

At six hours prior to launch, the charged and transported FMU will be installed on-board the sounding rocket payload. The introduction process consists of installing the FMU and securing it in place, connecting the pneumatic actuator and the electronic connections emanating from the FMU to the payload systems constituting the ODU SubSEM II experiment module. After installation is successfully completed, the biological payload containment vessel hatch will then be sealed, the outer rocket skin hatch (No. 3) will be secured, and the payload will be readied for launch by NASA personnel.

After the SubSEM II payload element has been fully installed as part of the complete NASA SubSEM payload, its operation and control must rely on standard NASA interfaces and command procedures as executed through the NASA Wallops Support Module which is attached directly to the SubSEM payload unit. Immediately prior to launch, the Wallops Support Module initiates a discrete signal command to the SubSEM II experiment, activating its power system and sensor arrays. At that time, all the SubSEM II system and environmental parameters will begin to be transmitted to the ground. This first discrete command will be followed closely by a second discrete command activating the microcontroller onboard the SubSEM II module. As soon as the microcontroller boots up, it commands power to a locking mechanism, causing it to position itself to prevent the FMU actuator from executing the experiment inadvertently during ascent. Within seconds of the “safing operation”, the first stage of the spin-stabilized sounding rocket is ignited. After approximately 70 seconds, the second stage of the launch vehicle will have completed its burn and the spinning payload will be de-spun, producing the reduced gravity portion of the flight trajectory. At 80 seconds, the decelerating vehicle will pass through 100 km altitude where atmosphere drag exerts a negligible force on the payload and the microgravity portion of the trajectory is begun. At approximately 350 seconds, a third discrete signal will be used to command the microcontroller to initiate the FMU filtration process. The microcontroller first releases the locking mechanism, allowing it to move out of the way. When the locking mechanism has been repositioned, a signal will be sent, via telemetry, confirming that the locking device is clear of the actuation path. Subsequently, the microcontroller activates a switch that causes the pneumatic solenoid-valve to open thus actuating the sample transfer phase of the experiment. When the pressurized pneumatic line begins to drive the plunger assembly away from its “stowed position”, a signal will be transmitted back to the ground indicating the filtration phase of the experiment has been initiated. When the FMU plunger mechanism reaches the full extent of its travel, a second signal is transmitted, indicating that the experiment has reached its final position and that the experiment has been completed. Shortly after that, the payload will have fallen low enough to re-enter the atmosphere, experiencing increasing levels of aerodynamic drag and finally splashing down in the Atlantic Ocean. The payload power provided by the initial discrete will be terminated at this time (by reversing the state of the first discrete) and the SubSEM II module will power down. A recovery vessel will retrieve the payload and return it to the NASA Wallops Flight Facility. Once at Wallops, a de-integration process will take place and the FMU will be retrieved. The samples will be removed and transported back to Salisbury University for analysis no later than 14 hours after the launch.

System Design

The fundamental problem ODU's SubSEM II payload had to address was how does one simultaneously conduct multiple experiments at the same time in the same conditions while exposing them to microgravity? Additionally, if the intent is to make a scientifically justifiable claim, an accurate characterization of the details of the actual microgravity flight experiment is critical. Short cell-culture viability time intervals and the need to perform sample preparation and analysis in a laboratory environment drove the design to accommodate a sample introduction near the time of launch.

In developing a system that could ultimately achieve scientifically meaningful results, the first challenge to overcome was gaining an engineering understanding of the science. This task was found to be surprisingly difficult. Identifying the critical information needed to develop requirements was the single most challenging and costly aspect of the entire project. A lack of experience in this area resulted in an eleven-month process, during which an understanding of the science, as it related to an engineering solution, was developed. The resulting biologically acceptable solution consisted of a pre-filtrate syringe (a.k.a. the master syringe), a filter and filter housing, a check-valve, and a post-filtrate syringe (a.k.a. the collection syringe). The experiment would be considered executed when all the fluid had left the master-syringe.

Establishing the biology system made it possible to define the design requirements for a portable fluid manipulation unit. This unit was devised to allow proper and convenient handling of the cell solutions before, during and after the experiment was conducted. To drive the filtration element of the experiment, a pneumatic actuator mechanism was selected and housed in the portable unit. Linked together with nine identical biological fluid containment and transfer units, the actuator mechanism could propel the nine fluid transfer plungers simultaneously by employing pneumatic pressure provided by a self-contained pressure tank source. Based on the selection of the actuator, an entire air-system was developed, along with the necessary redundancies associated with the use of such a stored energy system. In-depth descriptions of these systems follow.

Once a system design was achieved that was capable of executing the basic scientific experiment, it was then possible to develop instrumentation and control elements that could maintain and monitor the conditions experienced by the test specimens. A container was built to house the fluid manipulation unit and to preserve a laboratory-like environment. Once the biological system was contained the task of instrumentation could be completed. Sensors to monitor the vital functions of the apparatus were specified and procured to allow for monitoring the experiment during the course of the flight. Such monitoring is essential in order to yield scientifically acceptable results. Far more critical however, was the monitoring of the experiment environment. To insure that the container environment stayed within the prescribed temperature and pressure intervals, sensors were fitted inside the vessel to monitor conditions during the flight. Additionally, to verify that an acceptable acceleration environment was achieved, a high-fidelity accelerometer was fitted to the payload to measure peak accelerations during the course of the microgravity exposure. The necessary controls, power systems, data and telemetry handling systems, and operational procedures were also developed and implemented.

Biology System

Metastatic cancer is a cancer that is able to spread from a primary tumor to secondary sites throughout the body. Many of the incapacitating effects and deaths caused by cancer are not due to primary tumors, but rather from the metastasis of cells originating from the tumor. A metastasized cell has the capability of breaking away from the primary tumor and passing into the circulatory system. The blood stream then allows cancer to spread to different sites, where it leaves the blood stream and begins to develop into secondary metastatic tumors. It is thought that the ability of a metastatic cell to move in and out of the blood stream is closely related to its ability to deform sufficiently to squeeze through the small openings in the blood vessel wall and basement membrane.

Experiments conducted in the 1980s and 1990s have shown that microgravity has a significant influence on a large number of cell functions. Many of these affected functions and properties are the same functions that are altered when a cell becomes metastasized. For instance, it has been shown that a cell's cytoskeleton is affected by microgravity. The ability of a cell to move in and out of the blood stream requires, among other things, changes in the cytoskeleton. This, and several other similar conditions, led to the hypothesis that if these cells were exposed to microgravity, their dispersion through the host's body would be affected.

In an attempt to examine these effects, an experiment has been developed to measure cell deformability in Earth's gravity (1g) and again in microgravity (μg). This is accomplished by transporting a sample of cells on a flight trajectory that provides approximately 250 seconds of weightlessness exposure to the cancer cell solution. Subsequently identical cell solutions will be forced separately through set of filters of varying porosity. The influence of reduced gravity on metastatic cell deformability will then be measured by determining the number of cells that can survive passage through these decreasing pore size filters. The filters chosen for this experiment have well-defined pore sizes of 5μm and 8μm, with nominal cell diameters of 10μm or larger. Only the cells that can sustain a critical level of deformability will survive this forced filtration process. The remaining cells will either break up, or will simply not pass through the filter. By utilizing identical samples, testing them over the most sensitive portion of the porosity range (Fig. 1), between 5 and 8 μm, and executing identical experiments on the ground and in microgravity simultaneously, the observed differences in cell survivability can be detected.

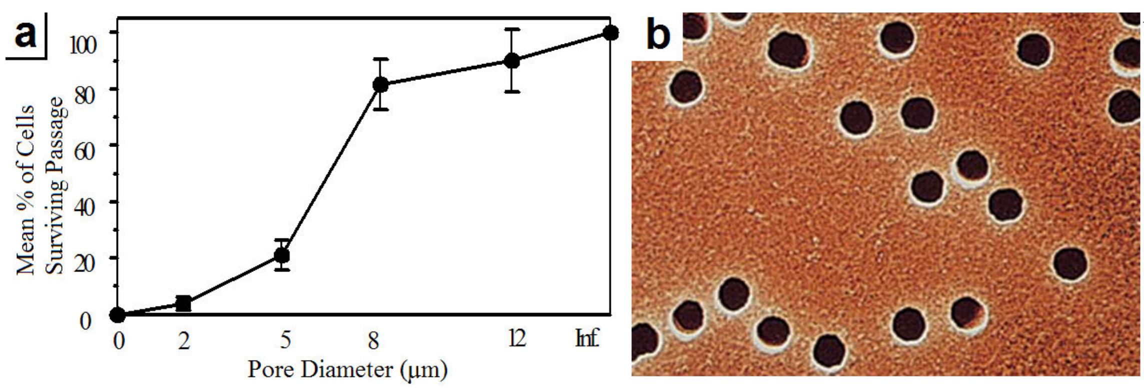

Figure 3. (a) Cell survivability as a function of filter porosity: (Error bars are ± 1 standard error from five independent trials for each filter pore size.) (b) Scanning electron microscope (SEM) image of Millipore filter membrane.

Developing an engineering design that met the science needs, proved more difficult than anticipated. The foremost concern was packaging of the samples in a vessel that could withstand the anticipated launch loads. A rigid requirement mandating complete sterilization of the entire system, combined with other geometric considerations discussed later, led to the selection of commercial off-the-shelf (COTS) medical syringes. This was also motivated by a need to have multiple biologically independent and identical samples.

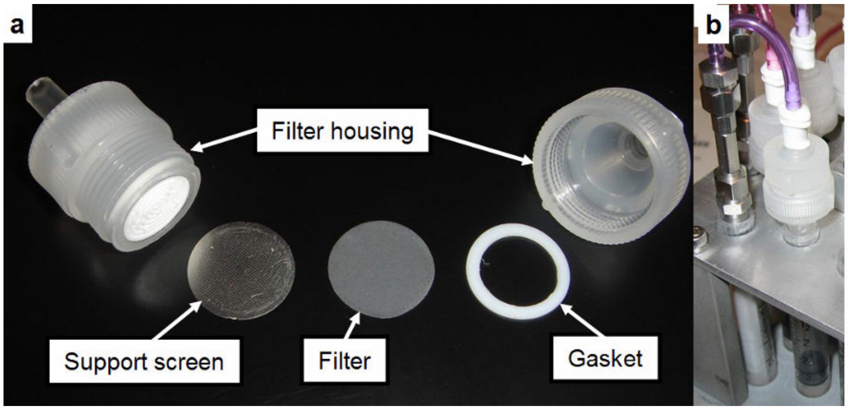

Figure 4. (a) Broken down filter holder assembly. (b) Check-valve and filter holder assembled with syringes in FMU chassis structure.

As shown in Figure 4, the selection of a standardized syringe allowed for the use of commercially available filter holders. The mechanical tolerances required to secure the fragile filter membranes in place prior to filtration was a task deemed best performed by the manufacturer.

The system was capable of containing the samples prior to filtration, i.e. prior to transporting the cell solutions through the filters, and collecting the filtered cell data after the transfer. The system design is acceptable if access to the samples can occur immediately after filtration. Cell density will be measured at the end of the experiment, and cell growth rate is a function of density. This creates a problem, because the different size filters will produce different filtered cell densities, and subsequently, different growth-rates would occur after filtration. Thus, a means of "fixing" the sample growth-rate at the end of the filtration step was required.

To avoid population growth disparities, the biology team developed a fixative solution capable of preserving the live cells, without allowing for change in cell densities, for up to 24 hours, if needed. This biological solution produced an engineering difficulty because any exposure to the fixative prior to filtration would affect the cell growth rates. Since the premature mixing of the samples and the fixative would result in an overall failure of the experiment, it became absolutely essential that the unfixed and fixed fluid solutions not mix in any way prior to the filtration. Given the expected violent nature of the flight environment leading up to the filtration step in the experiment, extra precautions needed to be taken to avoid premature mixing of the fluids. This problem was solved by the addition of an inline check-valve to prevent backward migration of the fluid from the collection syringe to the master syringe. The final system design allowed a plunger-actuated master syringe to transport the samples across each filter membrane, through a check-valve, and into a small quantity of highly active fixative. The suspended cells would then be transported back to the laboratory at Salisbury University after the payload was recovered and the intact FMU was removed from the payload.

Fluid Manipulation Unit

The necessity to introduce samples shortly before the launch proved to be by far the most daunting challenge in the development of ODU's SubSEM II payload. The previous mission used a sample injection approach. In that approach, the biological samples were introduced to the launch vehicle by opening the payload hatch and connecting a tube and valve system to the wall of the ODU experiment. The cell solutions were transferred through the payload's primary containment wall and into a syringe on the inside of the experiment module. This method proved to be limiting, especially when considering the possibility of a launch abort. A launch abort would require that the entire biological system be flushed, sterilized, and prepared for a second launch attempt, 24 hours after the first launch abort. The near-impossibility of sterilizing the entire unit without any residual contamination in order to permit recharging, and a rapid turn around was a major concern. This was the primary consideration that motivated a design shift to a removable Fluid Manipulation Unit concept in SubSEM II.

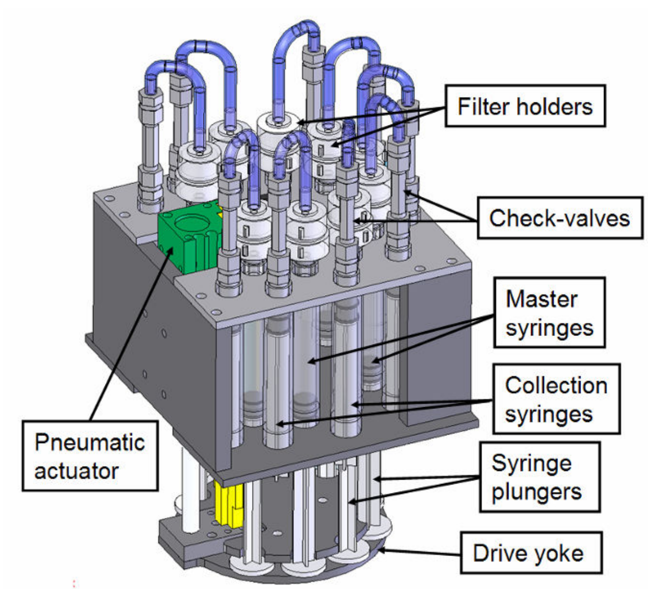

Figure 5. Detail view of FMU assembly.

The fluid manipulation unit (FMU) is designed to be a reusable structure, which houses nine independent biological experiments as shown in Figure 5. The FMU is designed as a removable element in the SubSEM payload unit while it is installed on the launch vehicle. The cell solution samples will be loaded into the unit in the controlled laboratory environment at Salisbury University to ensure that the FMU system meets sterility standards prior to charging and to assure data integrity. This was important because the particular cell culture being used is extremely active and very sensitive to foreign contamination. The FMU portability allows for increased control during sample preparation without compromising the integrity of the mechanical sample restraint mechanism that remains attached to the SubSEM payload experiment deck.

The spin-stabilized nature of the launch-vehicle introduces a highly undesirable characteristic for an experiment based on microgravity exposure. While a complete absence of gravitational acceleration would be ideal, compensation for centripetal acceleration can be made by exposing all the samples to equal loading. For this reason, an axisymmetric sample configuration (about the spin axis of the rocket) was selected, with each sample syringe equally spaced as close to the spin axis of the rocket as possible. The need to maintain the samples aligned on a minimum radius circle around the rocket axis translated to an high aspect-ratio configuration, which conflicted with the overall SubSEM payload bay maximum height specification. The final overall dimensions of the FMU were driven by the size of the hatch through which the device had to pass when it was reinstalled in the SubSEM payload module.

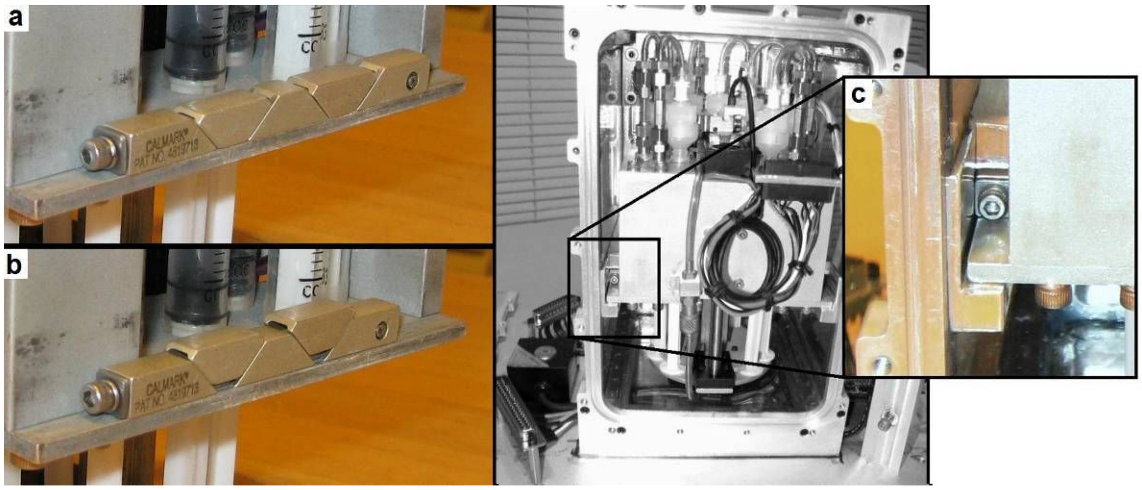

Figure 6. (a) Card-lok in contracted state. (b) Card-lok in expanded state. (c) Card-lok installed in container/FMU assembly.

The precise and reliable placement of the FMU inside the payload is critical for mission success. As shown in Figure 6, the FMU is secured to guide-rails on the inside of the container-walls, using a set of *card-lok retainers*; an off-the-shelf solution provided by Calmark Corporation. These retainers allow the FMU to be precisely positioned while accommodating the high-energy launch loads and affording a safe and reliable method of installation within the six-hour hold prior to launch.

Once the syringe configuration was specified, the actuation method had to be considered. The actuation mechanism could either be integrated into the FMU itself, or an external actuator could act on the unit after installation. In the case of an FMU-mounted actuator, the need to make a pneumatic connection after FMU installation was considered to be the main limitation. The pneumatic issues were outweighed by the reliability considerations associated with positively guaranteeing actuator contact with a passive FMU. As a result of selecting an FMU-integrated actuator the syringes are secured to the mounting fixture in the laboratory, and the actuator connection is guaranteed because the nine syringe plungers are attached to a single drive yoke.

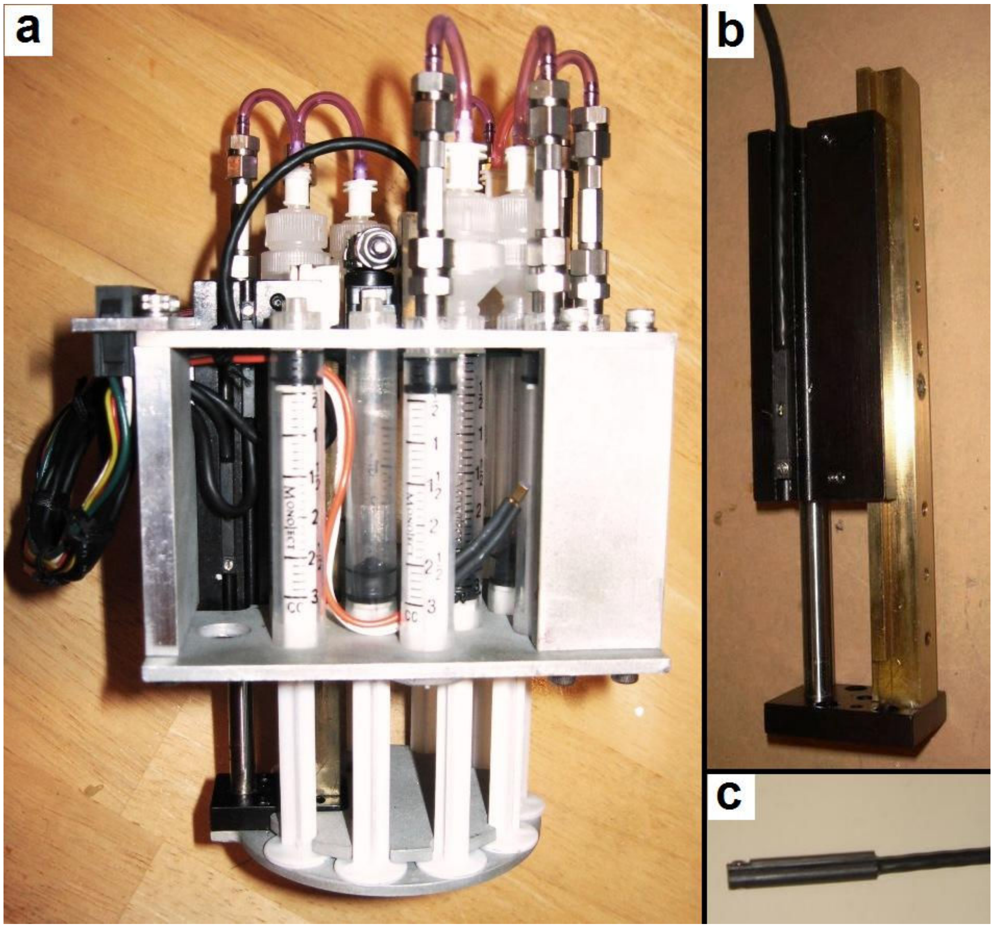

Figure 7. (a) Partially disassembled FMU allowing view of installed actuator, actuator-lock, and installed position sensors. (b) Pneumatic actuator with position sensor installed. (c) Position sensor.

After considering a wide range of devices, from in-house developed lead-screw systems to piezoelectric linear drives, the primary actuation system was selected to be an *AGMS 1-4 Mini Power Slide* as shown in Figure 7. The factory-integrated position sensor, its overall size, and rugged construction meant that the power slide was a near-optimal selection. In the early phases of the FMU development, binding of the syringe plungers was a serious concern. Many of the early prototype designs exhibited problems associated with misalignment and plunger deformation resulting in excessive actuation force requirements. The AGMS 1-4 offered a configuration that could hold the "plunger-yoke" in the proper orientation—even with asymmetric syringe loading. Asymmetric loading might be expected because filter pore sizes vary from filter to filter thereby facilitating asymmetric pressure drops and force loadings.

From the sample flight data available the first-stage burnout is the time when the launch vehicle experiences maximum dynamic pressures. At that point, a near instantaneous load reversal occurs switching the load on the payload from a positive 20 g's to a negative 5 g's. To prevent an inadvertent filtration event from occurring at this point in the flight, an actuator locking-arm mechanism was developed that was capable of preventing pre-actuation of the system during the ascent. Additionally, the locking-arm was intended to safe guard against the likely event of air leakage past the pneumatic valve. Thus, the locking mechanism was designed to function as a secondary actuation system. The locking mechanism was based on a standard *Hobbico CS-12MG* hobbyist servo design with metal gears for durability. Unfortunately, the servo could not sustain significant bending loads along the rotational axis, and our testing reveled appreciable axial load potential. Taking advantage of the characteristics of the servo, a cantilever system was evolved by fitting the actuator with a custom servo-horn. When assembled, the servo-horn transferred the load of the primary actuator as an axial load acting on the active end of the servo. To allow the servo to move when the primary actuator was loaded to capacity, two ball-bearing mini rollers were incorporated, thus reducing bearing friction. Additionally, an inset magnet was housed in the body of the servo-horn to activate a hall-effect sensor as shown in the Figure 7. To assure functionality, the actuator-locking mechanism was tested at 120 percent of estimated maximum operational conditions, which are limited by the capabilities of the air system, with no sign of binding or lack of actuation force on the part of the servo.

Finally, a major component of the FMU design requirement was a robust system monitoring capability. The FMU is the heart of the experiment and is the single most-complicated element in the entire system. Failure of the FMU to function would have catastrophic implications for the entire experiment. To ensure that complete operation of the system is verified, the FMU is fitted with three identical hall-effect sensors in key locations. These industrial-grade sensors were selected for their compact size, reliability, and most importantly, the non-mechanical nature of the operating principle. The first sensor is located to give positive confirmation that the servo locking-arm has moved out of its “safing” position prior to experiment actuation. A second sensor is positioned to indicate that the actuator is in its initial operational position. If the actuator becomes dislodged for some reason prior to the filtration step, the second sensor will report this movement. Finally—and most importantly—it is critical to know that the experiment was completely executed while under the influence of microgravity. For this purpose, a third position sensor was located to indicate that the actuator and the nine individual plungers had reached the "experiment complete" configuration. These signals, along with the signals from a temperature sensor inside the FMU and the wires to the servo, are linked to the rest of the payload by a 20-pin umbilical cord. The cord connects through the wall of the container via an hermetically sealed plug and thus communicates with the outside.

Pneumatic System

Early in the design process, the relatively severe power restrictions motivated a decision to build the fluid transfer system around a stored energy supply other than the launch-vehicle's battery banks. The options considered were lead-screws, linear-spring systems, carbon-dioxide systems (for standard and compact packaging considerations), and pneumatic systems. A pneumatic system was down-selected because it could offer a relatively constant actuation force, unlike a spring system, and it did not exhibit many complicating factors associated with a compressed CO_2 system. In addition, the low cost and accessibility of compressed air made this selection ideal for the repeated exercise of the system that would be an integral part of its development, redesign, and subsequent operation.

The pneumatic actuation system has three major components: a source of pressurized air, a means of controlling the air flow, and the actuation mechanism. On SubSEM II, the source of pressurized air was an onboard storage tank. The storage system was designed to be charged on the ground up to 72 hours prior to launch, and to hold an adequate pressure (85 psig) to facilitate actuation at the desired point in the flight. A service panel for technician access consisted of a snap quick-disconnect (QDC) and a redundant needle-valve that provided a reliable, simple, and secure method for charging the system. A Clippard *EV-2* solenoid valve, shown in Figure 8, is used to control the flow of pressurized air. One option considered in the system design was to maintain the actuator constantly pressurized and mechanically release the actuator to initiate filtration. The use of a solenoid overrode this idea because it drastically reduced the number of constantly pressurized connections, ergo reducing the number of possible points of leakage during assent. The final component of the pneumatic system is a slide actuator that directs the force needed to successfully transport fluid though the biological system.

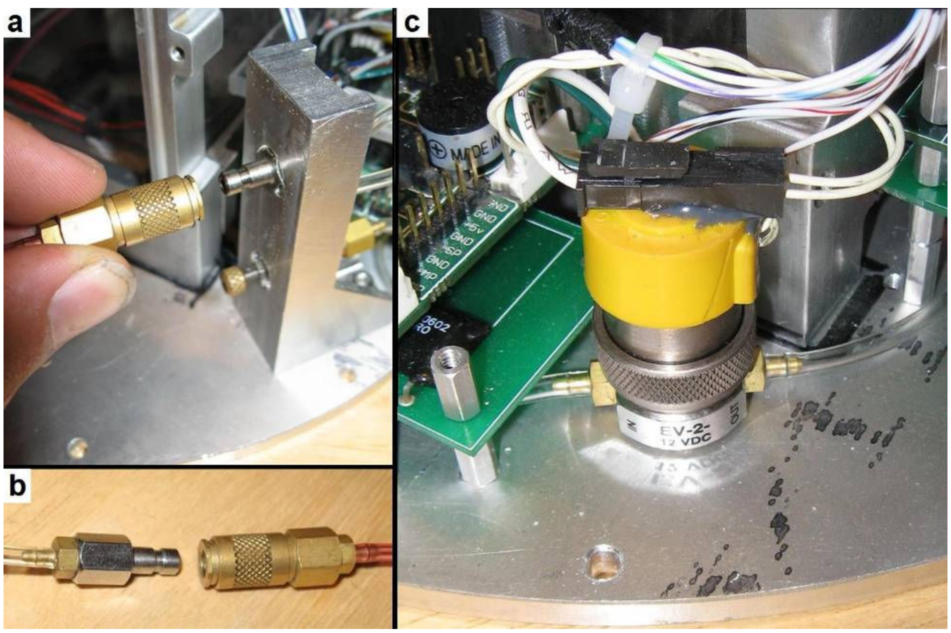

Figure 8. (a) QDC being connected to air-system service panel. (b) Detail view of QDC/Checked-flow mate assembly. (c) Pneumatic solenoid installed on baseplate.

The system was designed to operate in a linear serial fashion as shown in figure 9. While such a sequential system is susceptible to single-point failure the precise control of the airflow was accomplished. In preparation for system pressurization a connection is made with an outside air line via the service panel mounted QDC. After ensuring the redundant needle-valve is open, the system is pressurized to the desired pressure. The needle-valve is then closed and the external charging connection is removed. At this point, the pneumatic system is active and waiting for the command to open the solenoid valve. On the descent and before reentry, near the end of the microgravity exposure, the third discrete command causes solenoid valve to open. This forces pressurized air into the actuator and starts the fluid transfer and filtration operation. After the actuator reaches its final position, the valve is closed and the experiment is completed.

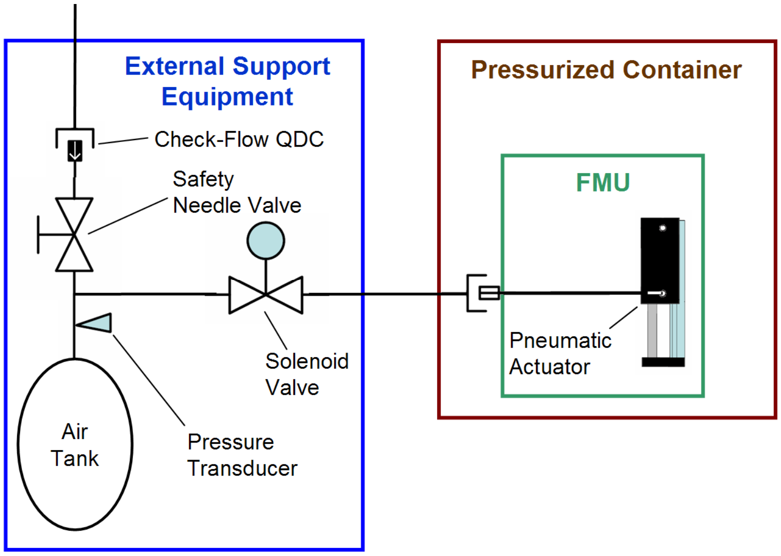

Figure 9. Schematic drawing of pneumatic system with physical component placement noted.

There was initial concern that driving the syringes too rapidly might resulting in erroneous data. To overcome this problem, a flow control valve was initially implemented; however, after testing the system it was determined that there was no need for a flow-control valve because full flow was required to move the fluid at the proper rate. Another issue related to the internal mechanism for the flow control valve was identified. The internal valve/plunger system was driven against a spring diaphragm as the valve was powered opened and this was the downward direction along the line of flight. This was unacceptable due to the peak 25g downward acceleration that occurred during powered ascent. Thus if the valve was to be mounted in its designed orientation the entire system was significantly more susceptible to failure during launch. The use of a solenoid valve solved all of these problems because it has only a fully closed and fully open state and a different internal mechanism. The solenoid valve opens when an internal plunger is forced upwards; this means that the intense launch loads work to keep the valve closed instead of forcing it open. This drastically improved the functional reliability of the valve component of the pneumatic system.

Testing was critical to ensure that the launch and flight environment did not cause a leak, or any other event that could result in system failure. Because the pneumatic system is responsible for providing the means of transporting the fluid in the biological system, a pneumatic failure will result in total experiment failure. The greatest concern was leakage though the many barbed pipe connections located throughout the system. Since the module was designed to be pressurized up to 72 hours before launch, even a small leak could ultimately cause total system failure. Many extended duration pressurization tests were conducted by bringing the system up to operating pressure and monitoring system pressure over time. These long duration tests showed that the tube connections could not rely entirely on the barbs sealing themselves. Small clamps were installed at every connection, after which the system lost only 1 psi during a 72-hour duration test. This satisfied the criteria required for successful experiment completion.

Container

In any bioassay the desire is to perform two identical experiments with only one varying parameter. In the case of ODU's SubSEM II module, the only parameter variation desired is gravity. The objective of the containment vessel is two-fold: First, to maintain a nominal laboratory environment from the time that the charged FMU is installed until the experiment has been executed and the sample is successfully recovered. Second, the vessel is to serve as the primary biological containment vessel. Typically two levels of containment are required for harmful biological materials.

A fairly rigorous development phase led to the design and construction of the containment unit. The primary factors that drove the container to its final form were: the pressure specification developed from launch vehicles nominal and off-nominal pressure conditions; the size of the FMU that was controlled more or less by the external rocket hatch dimensions; a planner-seal container-hatch design for serviceability and reliability concerns, and the need for overall ease of construction. Early in the design process, a clear-walled container was considered to be a major design goal. The rationale being that once the experimental device was sealed in the container, the ability to visually observe the system's state would reduce the dependence on complex sensory equipment during development and testing.

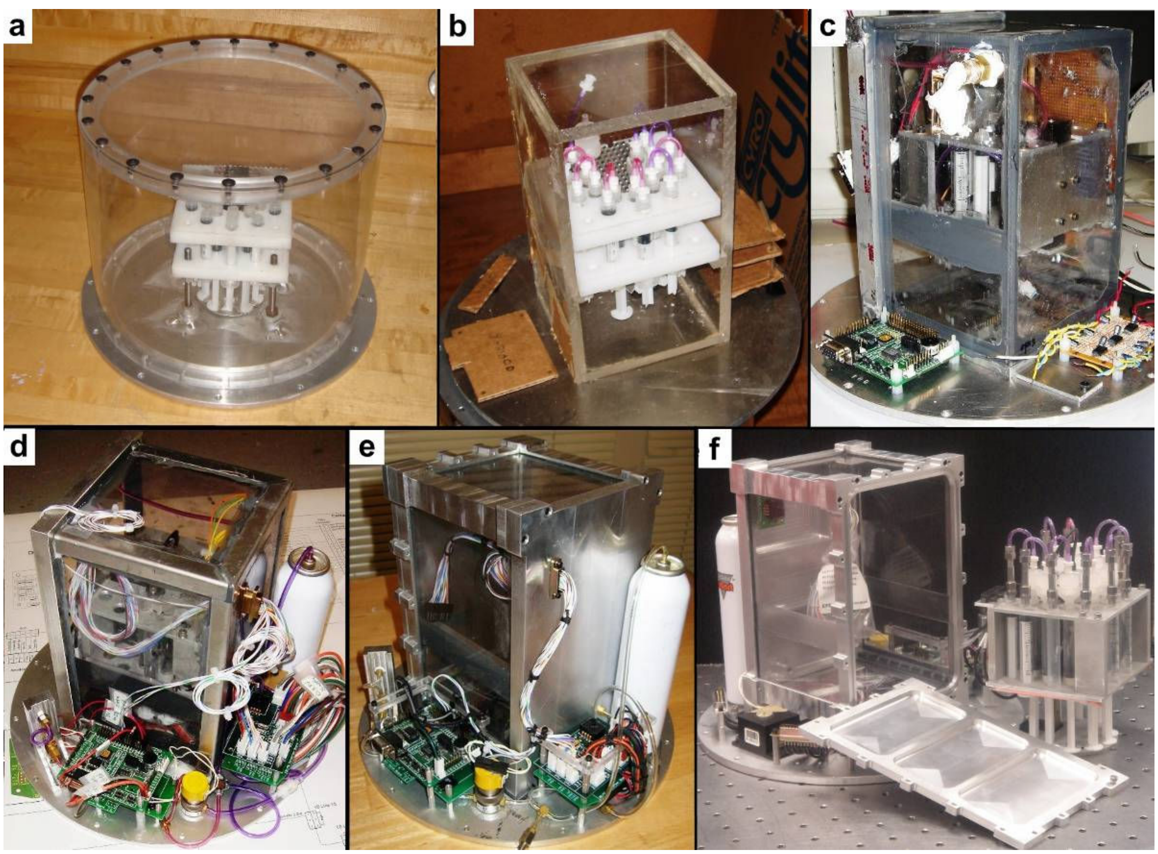

Figure 10. (a) Original cylindrical container design. (b) Proof of concept prototype for box configuration made from acrylic. (c) Polycarbonate container prototype assembled. (d) Polycarbonate container with corner supports after adhesive failure. (e) Back view of final box assembled. (f) Front view of final box assembly.

Other early design considerations were to establish manageable boundaries, indicating what hardware and infrastructure was to be inside the container and what infrastructure needed to be located outside the containment. The internal component and device dimensions were selected to minimize size in order to meet access/serviceability requirements, which would also reduce the size, weight, and effective pressure loads of the vessel. The only other device besides the FMU that is placed inside the container, is the environmental pressure sensor. Wire boundary-crossing analysis constituted a major element of the component-placement study. Reduction of the number of electrical conductors penetrating the container boundary was considered paramount at the time. From this study it was determined that a minimum number of boundary-crossing electrical connections could be made by placing only the FMU inside the container. In the end, the dimension-selection process was restricted to the FMU configuration and sample introduction/mounting requirements.

As with all other systems on the module, an iterative prototype development was undertaken from concept to completion. The first three design iterations were built by the team; the final two designs were specified at a level of precision that was beyond our fabrication capabilities. The components for the last two iterations were prepared by the ODU machine-shop and the units were assembled and tested by the team as shown in the Figure 10.

The final design, seen in Figure 11, utilizes an aluminum frame consisting of a front-bolting flange, a back panel, and four corner braces to support the main structure and to hold the major tolerances.

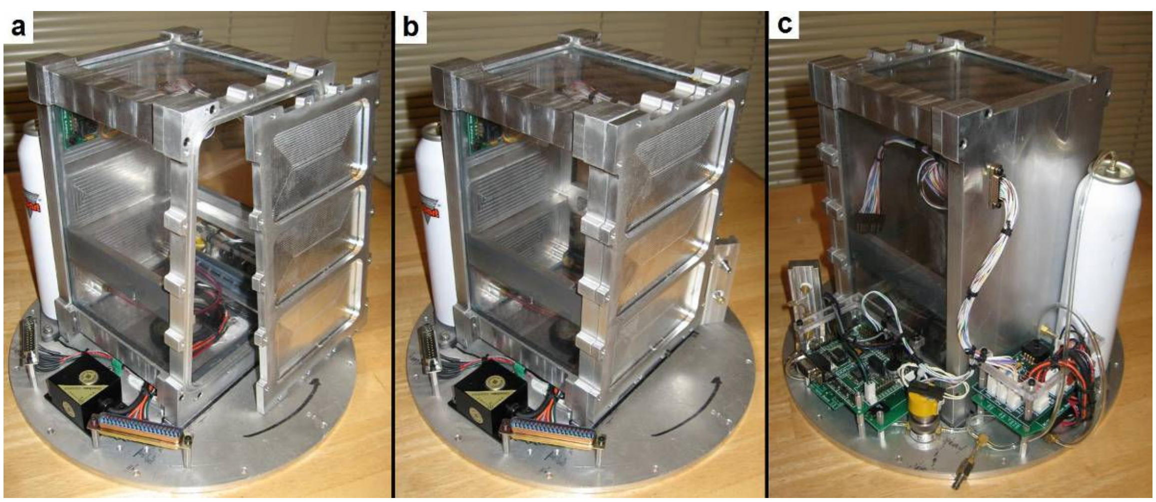

Figure 11. (a) Front of container with hatch removed. (b) Front of container with hatch in place. (c) Back of container showing electrical hermetic connector.

Earlier container prototype iterations relied on glue-joints, which afforded only very crude tolerance control while the glue cured. Inside the aluminum frame, clear polycarbonate walls were secured and sealed in place with *Scotch-Weld*^{TM} *Epoxy Adhesive 2216 B/A*, a high-strength bonding agent produced by *3M*. The selection of polycarbonate was a shift from acrylic, which we found to be unacceptably brittle. Unfortunately the polycarbonate has very poor bonding properties. The selection of the epoxy was a result of a series of more than 20 tests that led to a proven procedure of combined surface-preparation and adhesive-application techniques. The final design is notably different from its predecessors in that the adhesive is not the primary structural element. The final unit was free-standing and structurally-sound prior to the application of the adhesive sealant.

As the final container design evolved, an approximate container mass was estimated. The estimate revealed that the system was precariously close to its ten-pound limit, and as a result, a detailed mass analysis was performed prior to final container construction. The analysis, which took into account every individual available component, including wire length estimates, crimp connector counts, and fasteners, indicated that the module was almost 1.4 pounds over the weight limit. As a result, a numerical stress analysis using ANSIS and Autodesk Inventor was performed on the containment structure to minimize any non-essential structural mass. As shown in Figure 12 below, the mass reduction efforts were successful in that they resulted in total system mass below the allowable limit.

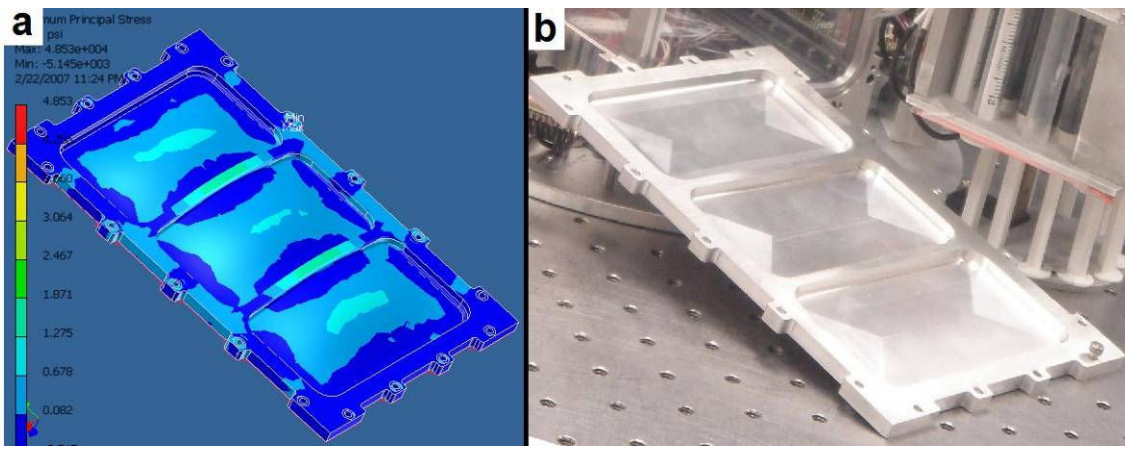

Figure 12. (a) Results from FEA mass reduction effort. (b) Finished hatch plate.

The fourth generation container utilized a flat gasket, tested, and proven under laboratory conditions. Upon being advised by experienced flight-hardware engineers, the design was updated to use an O-ring design. The O-ring hatch seal is the only component of the design "outsourced" to a graduate student with industry experience.

The bulkhead wire feed-through, which allows the FMU to send and receive signals to the rest of the payload, made a lasting impression concerning the value of a good mentor. During the course of the first 19 months of the project, a hermetic wire feed-through was sought. Quotes were obtained from many vendors and various in-houses solutions were attempted. After talking to an experienced instrumentation technician, a solution to the problem was identified and completely specified within a week. The component specification had previously been developed incorrectly, which resulted in extremely high-cost solutions.

The end result was a micro-dsubminiature high-density connector with hermetically sealed electrical connections. A connector was sampled and tested for leak rate compliance. The device passed a longitudinal static test in a small test rig, as shown in Figure 13, and has since been integrated into the container back-panel design.

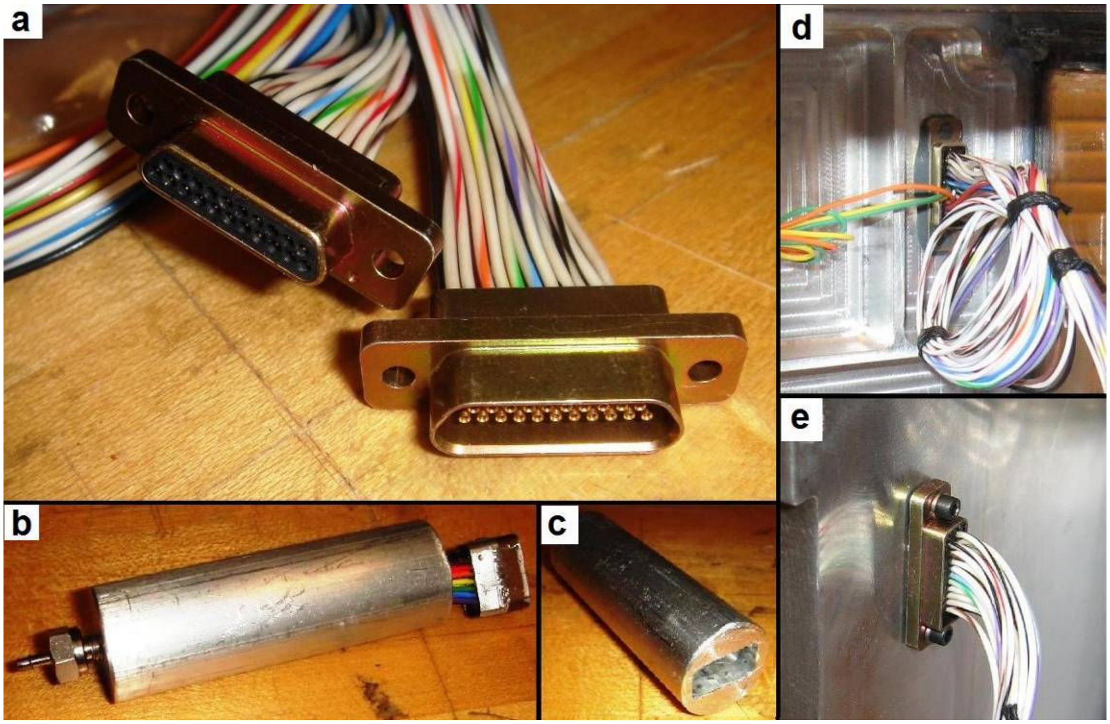

Figure 13. (a) Male and female micro-dsubminiature high-density connectors. (b) Leak test/connector validation assembly. (c) Leak test fixture. (d) Inside view of mounted connector. (e) Outside view of installed connector.

Another container penetration was required to allow for the actuator air supply. In the fourth generation container, this was accomplished using a bulkhead fitting. The pneumatic bulkhead fitting, while small by most standards, was large and cumbersome in comparison to the other pneumatic components in the system. In an effort to save weight and boost reliability, a fully integrated solution was designed which relied on barb fittings from Beswick Engineering. These fittings had already been proven in the extensive testing of the air system and were integrated into the back panel. The result was a significant reduction in complexity, and an increase in the precision of the penetration.

Controls and Instrumentation

The electrical system is potentially the system most prone to failure in the entire payload. With more than 50 pieces and parts assembled and 200 wire terminations, the possibility for a critical electrical failure is great. However, much, if not a majority of the risk can be mitigated by using proper equipment and ruggedization techniques when assembling the system. In an effort to increase the overall system reliability, higher-grade electrical components, wiring, and wire terminations have been used. As shown in Figure 14, custom-printed circuit boards (PCBs) with masked electrical traces are used to decrease the likelihood of circuit failure. All the wires will be sufficiently strain-relieved, and wire bundles will be tie-bound with lacing wire. On the first payload ODU launched, a few of the components failed under testing and launch loads. To avoid such a reoccurrence, all components will be bonded to their boards.

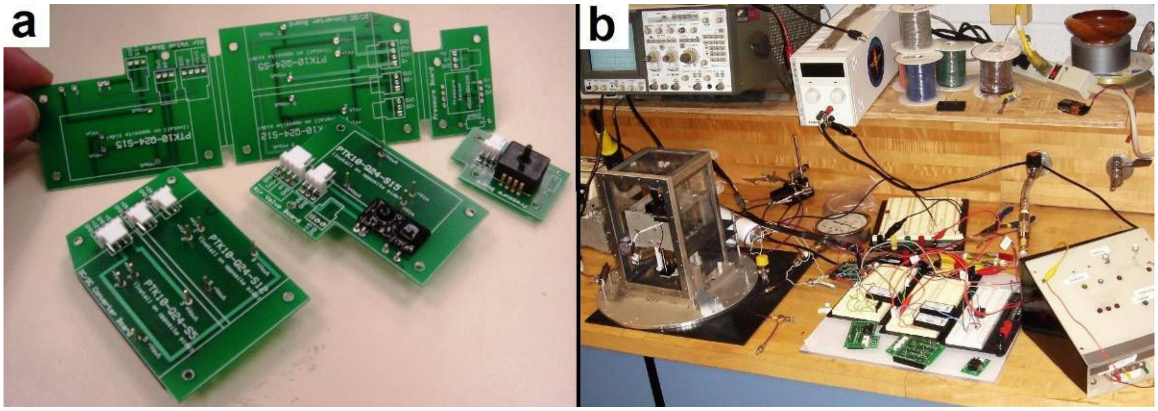

Figure 14. (a) PCBs fully assembled with original circuit board in background. (b) Circuit boards in front of PCB validation setup.

If the FMU is the heart of the system, the electrical system is certainly the brain. All the payload's functions and monitoring systems are processed and controlled by the electrical system which are shown in their assembled configuration in Figure 15. The electrical system can be split into mission-critical components, engineering sensors, and environmental sensors. The critical components of the system are the elements that perform the fundamental operations of the experiment. They include the servo which commands the actuator-stop-arm to a given position, the pneumatic solenoid-valve, the power system, and the microcontroller. The microcontroller relies on the arrival of an external discrete signal from the SubSEM payload unit. Upon receiving that signal, the system will come to life and execute the experiment.

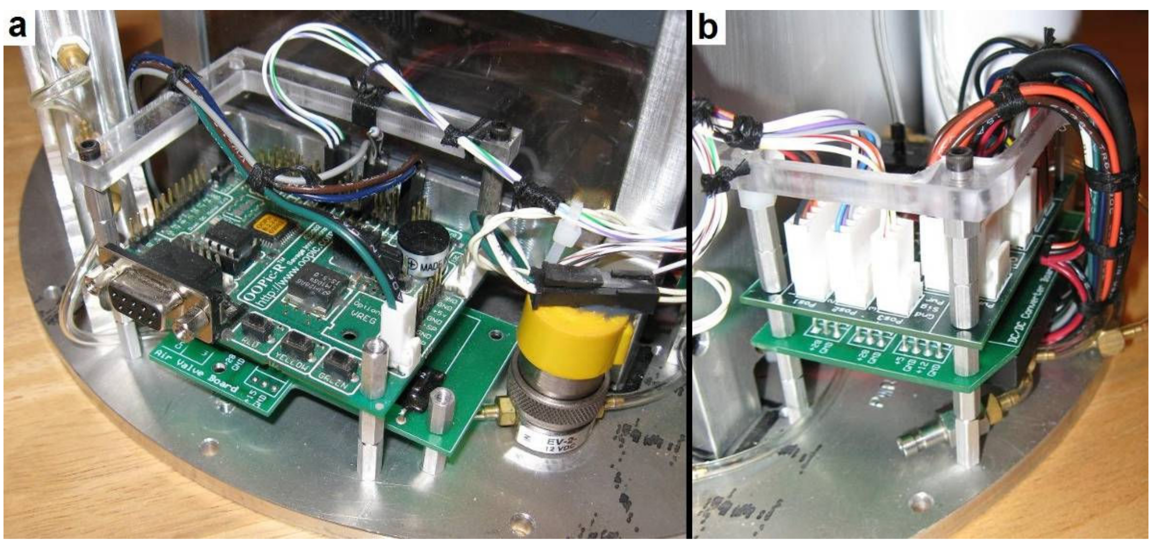

Figure 15. (a) OOPic with air-valve power board below. (b) Signal distribution board below with main power boar.

The engineering sensors monitor the system and report system health and performance. The three position sensors, as mentioned previously, monitor the physical execution of the experiment. The time of execution is essential for verifying the duration of the cell exposure to microgravity. The other engineering sensor is the air-tank pressure sensor, which monitors the health of the air-system. In the event of a failure, this sensor could be a key element in determining the cause.

Finally, the environmental sensors are a suite of instruments that will confirm the continuous maintenance of nominal laboratory ambient pressure and temperature conditions. The important sensor for monitoring cell viability is the temperature sensor. This sensor will be located in the middle of the FMU and will only report the temperature during the flight. A wireless sensor (still in development) may be included that will allow temperature monitoring between the time the samples are introduced into the FMU at Salisbury University and the time just prior to payload launch. This waiting period could be as much as six to eight hours, and a wireless sensor would potentially give our biology team valuable data when interpreting the biological results. To monitor for a containment failure, a pressure sensor is mounted inside the containment vessel. To verify that we have actually experienced microgravity at a level that is biologically meaningful, we need to measure acceleration. An instrument that can read accelerations in the biologically acceptable range has been selected and implemented. The expected primary acceleration that will be experienced by the payload during free-fall will be due to the rotation of the payload. To maximize sensitivity to such motion, the accelerometer is located as far away from the payload rotational axis as possible. If acceptable environmental conditions were not maintained during the flight, this sensor suite will facilitate interpretation of the biological data.

Other Testing

To develop a reliable system that is ready for flight, it is essential that the system be able to be tested in as close to flight conditions as possible. The SubSEM payload unit has a module called the Wallops Support Model (WSM). The WSM handles all the power, data transmission, and timing functions that service the SubSEM bays. A WSM simulator has been developed to allow for simulation of near-flight conditions. The system was developed to be portable, and was built around a NI USB-6210 bus-powered multifunction I/O data acquisition unit made by National Instruments. This unit, in conjunction with LabVIEW, has the bandwidth and sufficient programmable capability to completely simulate the electrical flight environment as generated by the WSM. As seen in the Figure 16, the WSM simulator consists of a PC based software simulator, an I/O card, and a module that allows for computer-driven discrete functionality.

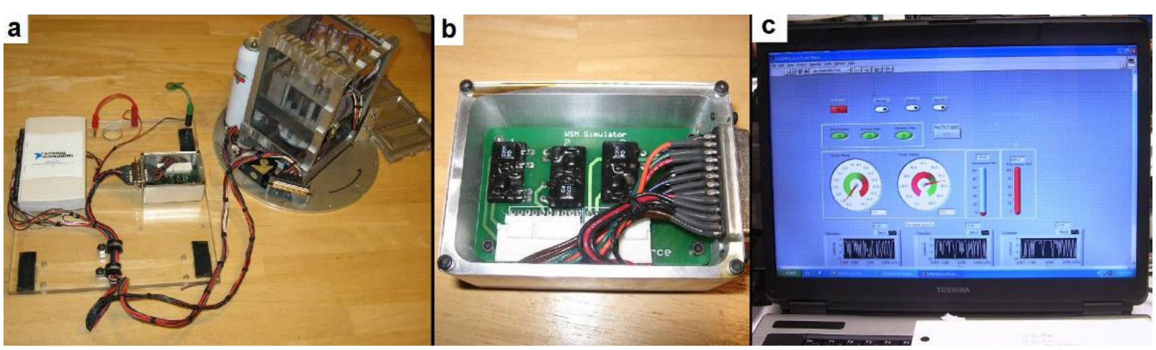

Figure 16. (a) WSM simulator connected to experiment module. (b) WSM simulator power module with solid state relays. (d) Simulator computer interface created in LabVIEW.

This system connects directly to the experiment module and simulates the electrical environment provided by the launch vehicle. When connected, the module is run off the computer's clock to simulate missions in real-time.

This portable simulation system allows for significant flexibility in system development and demonstration. The ability to consistently exercise a system while it is under development allows for a level of knowledge and understanding of system performance that is not otherwise possible. Seeing in-house electrical and mechanical systems consistently work together builds a strong understanding of how the systems interact with each other. Other benefits of having such a flexible testing system include the ability to perform high fidelity testing with minimal setup and test design.

Conclusion

ODU's SubSEM II sounding rocket payload has reached a high level of development. The development of the system has passed demonstration and capability-testing phases, and is currently moving into a flight-testing phase. A testing and flight-simulation schedule has been established and the unit is waiting for a flight opportunity. During the course of this project, considerable milestones have been reached in the development of an undergraduate research program at Old Dominion University. Since May 2005, more than 30 undergraduate students, three graduate advisors, and two faculty advisors at Salisbury and Old Dominion Universities have taken part in this joint effort. A significant component of the effort invested in ODU's SubSEM II is dedicated to the development of an ongoing undergraduate space-systems engineering presence at the school. The opportunity for this team to experience real-world design pressures, and to have a hand in cutting-edge research in the area of space biology, has greatly benefited all who have served on the team.

The ongoing and future work of this team will focus on capturing what has been learned and transmitting it to future teams. In part, the intent is to accomplish this by continuing to build an ongoing and self-perpetuating core of students in the engineering college who are focused on the advancement of space-related activities. This series of efforts is being supported by the development of a strong technical library that documents the knowledge attained and the lessons learned. The space-systems engineering library is expected to continue to grow as the college reaches ever-increasing levels of competence in the development of space systems. The intent is that knowledge and experience gained with this flight will give guidance to future space-systems engineering efforts at Old Dominion University