Development of a Reusable Biological Sounding Rocket Payload

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[Abstract] The absence of significant gravitational forces during space travel has been observed to produce a variety of biological effects on living cells. One effect seems to be the increased motility related to diminished cell separation barriers. It has been proposed that exposure to microgravity can cause cancer cells to become more deformable, thereby enhancing their ability to spread (i.e., facilitating metastasis). Since early 2005, engineering students from Old Dominion University have been working in conjunction with biological sciences faculty and students from Salisbury University to develop a reusable payload system to study that effect. This payload is designed to investigate how exposure to approximately 300 seconds of microgravity affects a specific leukemia strain's ability to permeate through a simulated membrane. The design and development of a reusable payload capable of transporting up to nine experiment units onboard a sounding rocket, safely carry them through launch, and executing the experiment in microgravity are presented in this paper. The methods developed to accommodate the delicate biological requirements in the harsh sounding rocket launch environment are presented along with the measures taken to assure specimen viability before and during the launch of the experiment.

Introduction

Undergraduate students at Old Dominion University (ODU) have been working in a joint effort with a biology team at Salisbury University (SU) to develop a reusable sounding rocket payload that will test the elasticity of metastatic cancer cells in microgravity. This experimental payload, ODU's SubSEM II, is the second generation of a payload that was launched in May of 2005. This undergraduate research project was made possible by Innovative Business Solutions Incorporated, by means of an educational outreach program. The end goal of this project is to answer a question of scientific validity, and possibly great cultural interest, while benefiting the students involved with the exposure to a non-simulated and legitimate research environment. The result has been a truly cross-disciplinary team of over 30 students throughout the course of the last 22 months. The team has been composed of students who's majors span from biology at SU, to mechanical, aerospace, electrical and commuter engineering at ODU.

The resulting payload has been designed to be placed in Sub-orbital Student Experiment Module[1] (SUB-SEM) that will be launched by a Terrier/Improved-Orion launch vehicle, from NASA's Wallops Flight Facility. The rocket will carry the experiment high above the atmosphere where, after exposure to the microgravity of free-fall in a vacuum, the experiment will be robotically executed. The experiment will be conducted by forcing nine independent samples across a set of filters. The survivability of the cells as they cross the filtration membranes will be determined by examining the cell densities after the experiment has been executed. A variation in density between data taken in the laboratory and its microgravity counterpart could indicate if the absence of gravity has an effect on the metastasis of cancer. This could potentially hold implications for astronauts on inter-planetary voyages, as well as patients seeking advanced cancer treatment in the future.

The harsh environment of a solid booster sounding rocket launch environment involving greater than 20 g's of acceleration and fierce vibration loads, along with the delicate requirements of carrying living cells, had to be accommodated if the mission objectives were to be reached. The primary challenges to overcome regarding the science of the mission were, the transportation of live specimens to a space-based testing regime, maintaining sample viability up to, and through the launch sequence, and providing for the safe return of the sample upon completion of the test. The inaccessibility to the launch vehicle prior to launch, the high loads generated by the launch and the launch vehicle's flight characteristics, time delay associated with the retrieval of the rocket, were some of the most significant limitations imposed by the launch vehicle.

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Mission Concept

ODU's SubSEM II is expected[1] 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 200 km and provide approximately 300 seconds of microgravity. The launch sequence for the biological payload begins 10 hours prior to the launch in a lab in Salisbury, Maryland, where 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.

At eight hours prior to launch, the test article will leave Salisbury and arrive at Wallops Island approximately two hours later. At that point, preparations, such as charging the air system, will have already been made for loading the unit into the experiment module in bay three of the payload bay. At six hours prior to launch, the FMU will be introduced to the rocket. The introduction process consists of installing the FMU and securing it in place, and connecting the pneumatic actuator and the electronics housed in the FMU to the payload systems. After this is successfully completed, the hatch will then be sealed on the biology payload containment vessel, the rocket skin hatch will be secured, and the vehicle will be readied for launch by NASA personnel.

Immediately prior to launch, a discrete signal will be sent to the experiment module and its power system and sensor arrays will come online. At this point, all the system and environmental parameters will begin transition to the ground. This first discrete will be closely followed by a second discrete, which will power on the microcontroller onboard the module. As soon as the microcontroller is online, it will command a locking mechanism to a position that will prevent the actuator from executing the experiment during assent. Moments later the rocket will roar to life. At approximately 70 seconds, the vehicle will be de-spun and the reduced gravity portion of the flight will begin. At 80 seconds, the vehicle will clear the 100 km mark where effects of the atmosphere are not expected to be appreciable. At approximately 350 seconds, discrete three will signal the microcontroller while the vehicle is still in free fall in a vacuum. The microcontroller will command the locking mechanism to move out of the way, and the signal will be sent via telemetry, confirming the lock is in fact clear of the actuation motion. The microcontroller will the send a signal to the pneumatic solenoid-valve, which will actuate the experiment. A signal will be sent indicating the experiment has left its initial position, followed by a second signal indicating the experiment has reached its final position and that the experiment has been completed. Shortly after that, the vehicle will re-enter the atmosphere and splash down in the Atlantic Ocean. The initial discrete will be turned off at this time and the module will power down. A recovery vessel will retrieve the vehicle and return it to Wallops. Once at Wallops, a de-integration process will take place and the FMU will be retrieved. The samples will arrive back at Salisbury University for analysis no later than 14 hours after the launch. The sequence is shown in the figure below.

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 understanding of the details surrounding the experiment would be vital. Short cell life spans and the need to perform sample preparation and analysis in a laboratory environment forced issues involving a sample introduction near the time of launch.

In developing a system that could ultimately arrive at 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,[3] during which an understanding of the science as, it relates 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 a portable fluid manipulation unit, i.e., a unit devised to allow for proper and convenient handling of the cells before and after the experiment was conducted. To drive the experiment, a pneumatic actuator was housed in the portable unit. Linked together with nine iterations of the biology subsystem, the actuator could conduct the experiment upon delivery of pneumatic pressure to the portable unit from an external 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 are given below.

Once a functional science system was defined, it was possible to develop systems that would maintain and monitor the conditions experienced by the specimens. A container was built to house the fluid manipulation unit and to preserve a laboratory-like environment. Once the science instrument was contained, the task of instrumentation could be completed. Sensors to monitor the vital functions of the apparatus were implemented to allow for monitoring the experiment during the course of the flight. Such monitoring is essential if a scientific claim were to be made. Far more critical however, was the monitoring of the experiment environment. To insure the container maintains standard temperature and pressure, sensors were fitted inside the vessel to monitor conditions during the flight. Additionally, to verify a proper acceleration environment was attained, 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.

A. Biology System

Metastatic cancer is a cancer that is able to spread from the site of a primary tumor to secondary sites in 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.[4,5] 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.[6,7] 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.[8]

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[9]. 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 spread 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 the cell solutions will be pumped through different filters of varying porosity. The influence of reduced gravity on metastatic cell deformability is measured by determining the number of cells that can pass through filters with decreasing pore sizes. 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 pumping 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.

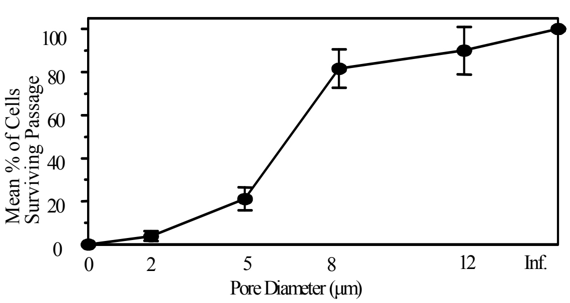

Figure 1. Cell survivability as a function of filter porosity: (Error bars are ± 1 standard error from five independent trials for each filter pore size.)

Developing an engineering solution 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. However, a strong requirement mandating the ability to completely sterilize the entire system, combined with other geometric considerations discussed later, led to the selection of a commercial off-the-shelf (COTS) syringe. This was also motivated by a need to have multiple biologically independent and identical samples. The selection of a standardized syringe allowed for the use of a commercially available filter holder. Holding the tolerances required to secure the fragile membranes in place prior to the experiment was a task deemed best performed by the manufacturer.

The system in place at this point was capable of holding the samples until the experiment—transporting the solutions across the filters, and collecting the fluid data after the experiment—was complete. Such a system would work if access to the samples was available immediately after the experiment was conducted. Cell density will be measured at the end of the experiment, and cell growth rate is a function of density. This causes a problem, because different size filters will be used resulting in different cell densities, and subsequently, different growth-rates after the experiment is conducted. Thus, a means of "fixing" the sample growth-rate was required.

To accommodate this need, 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. While a biological solution was reached, an engineering difficulty was developed. Since mixing of the samples and the fixative prematurely would result in failure of the experiment, it became absolutely essential that the two fluids did not mix prior to the experiment. Premature mixing of the solutions had to be guarded against, given the expected violent nature of the environment leading up to the experiment. This problem was put to rest by the addition of an inline check-valve, which would prevent backward migration of the fluid from the collection syringe to the master syringe. The final system will allow a plunger-actuated master syringe to transport the sample across a 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 science lab after the experiment section of the rocket has been recovered.

B. 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 this approach, the biological samples were introduced to the launch vehicle by opening the hatch on the missile and connecting a tube and valve system to the wall of the payload. The cells were passed through the payload's primary containment wall and into a syringe on the inside of the vehicle. This method proved to be limited, especially when considering the case of a launch abort. A launch abort would require that the entire biological system be flushed, sterilized, and prepared for a second launch attempt. This was the primary consideration that motivated a design shift to a Fluid Manipulation Unit in SubSEM II.

The fluid manipulation unit is designed to be a reusable structure, which houses nine independent biological experiments. The FMU is designed to be introduced into the launch vehicle just prior to launch. The samples will be loaded into the unit in a controlled lab environment to ensure sterility and data integrity. This was important because the particular cell culture being used is extremely active and very sensitive to foreign contamination. The FMU allows for well-controlled sample preparation without compromising the integrity of the sample restraint system under launch conditions.

The spin-stabilized nature of the launch-vehicle introduces a highly undesirable characteristic for an experiment based on microgravity exposure. While no 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 the radii of the sample syringe as close to the spin axis of the rocket as possible. The need to keep the samples to a minimum radius drove for a high aspect-ratio configuration, which conflicted with the overall height requirement given by the SUB-SEM standard. The final overall dimensions of the FMU were driven by the size of the hatch the device must pass through when it is introduced to the launch vehicle.

The precise and reliable placement of the FMU inside the payload is critical for mission success. The FMU is secured to guide-rails on the inside of the container-walls with 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 six hours of launch.

Once the syringe configuration was determined, the actuation method had to be considered. The first concern was whether the actuation would be integrated into the FMU itself, or otherwise. The need to make a pneumatic connection upon FMU introduction was the main objection to having an FMU-integrated actuation device. This was outweighed by the reliability considerations of being able to positively secure—in the lab—the nine plungers of the syringes to a single yoke, guaranteeing a connection to the actuation source.

From the sample flight data available, [x] the first-stage burnout constitutes the point of the launch where maximum dynamic pressure occurs. At this point, a near instantaneous load reversal occurs from a positive 20 g's to a negative 5 g's. This event led to the development of an actuator-locking-arm mechanism that would prevent pre-actuation of the system during ascent. This locking mechanism was designed to act as a secondary actuation system in the event of leakage past the pneumatic valve. The mechanism was based off a standard *Hobbico CS-12MG* hobbyist servo with metal gears. A custom servo horn fitted with two ball-bearing rollers to reduce friction, and an inset magnet to activate a sensor. A double-bearing cantilever system was used to reduce the bending loads experienced on the servo shaft. The system was tested at 120 percent of expected operational conditions with no sign of binding or lack of actuation force.

After considering a wide range of devices, from in-house developed lead-screw systems to piezo-electric linear drives, the primary actuation system, an *AGMS 1-4 Mini Power Slide*, was selected. Its factory-optional integrated position sensor, the size of device, and the rugged construction made it an optimal selection. In the early phases of the FMU development, binding of the syringe plungers was a serious concern. Many of the early prototypes exhibited considerably larger actuation forces than expected because of misalignment and plunger deformation. The AGMS 1-4 offered a configuration that could hold the "plunger-yoke" in the proper orientation—even with asymmetric syringe loading. Such a loading might be expected because multiple filtration pore sizes will be used, causing varying flow restrictions.

Finally, a major component of the FMU design was 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 mission. 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, their independence from a mechanical mechanism. The first sensor is in a location to give positive confirmation the servo-locking arm has moved out of position prior to the driving the actuator. A second sensor is in a location to give a positive indication the actuator is in the initial position. If the actuator becomes dislodged for some reason prior to experiment execution, the sensor will indicate this by loss of signal. Finally—and most importantly—it is critical to know the experiment has completely executed in microgravity. For this purpose a third position sensor is located to give a positive reading when the actuator and the nine individual experiments reach the "experiment complete" state. These signals, along with the signals from the temperature sensor inside the FMU, and the power and signal sent to the servo, are linked to the rest of the payload by a 20-pin umbilical cord. The cord connects to the wall of the container and communicates with the outside via a hermetic connection.

C. Pneumatic System

Early in the design process, relatively severe power restrictions drove a decision to build the 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 won in the down-selection because it could offer a relatively constant actuation force, unlike a spring, and did not exhibit many complicating factors associated with a compressed CO_2 system. In addition, the low cost and accessibility of compressed air makes this selection ideal for the repeated depletion and recharging the system would be subjected to throughout its development, design, and operation.

The pneumatic actuation system has three major components: a source of pressurized air, a means of controlling the flow of pressurized air, and the actuator mechanism. On Sub-SEM II, the source of pressurized air will be from an onboard storage tank. The storage system is designed to be charged on the ground up to 72 hours prior to launch, and to hold an adequate pressure (85 psi) to facilitate actuation at the desired point in the flight profile. A service panel for technician access consists of a snap quick-disconnect (QDC) and a redundant needle-valve that provides a reliable, simple, and secure method for charging the system. A Clippard *EV-2* solenoid valve is used to control the flow of charged air. One option considered was to constantly keep the actuator under pressure and mechanically release the actuator to start the experiment. The use of a solenoid overrode this idea because it drastically reduced the number of constantly pressurized connections, ergo reducing the number of possible sources of leakage. The final component of the pneumatic system is a slide actuator that provides the force needed to successfully transport fluid though the biological system.

The system was designed to operate in a linear fashion with each of its components in series. Though this does allow for the possibility of single-point failure, it also facilitates precise control of system airflow. In preparation for system pressurization, a technician makes a connection into the system via the service panel's QDC. After ensuring the redundant needle-valve is open, the system is brought up to operating pressure. The needle-valve is then closed and the technicians charging connection is removed. At this point, the pneumatic system is active and waiting for the command to open the solenoid valve. On descent and before reentry, a discrete is triggered, which signals the solenoid valve to open. This forces pressurized air into the actuator and starts the experiment. After the actuator reaches its final position, the valve is closed and the experiment is completed.

There was initial concern of actuating the syringes too quickly, resulting in erroneous data. To overcome this problem, a flow control valve was initially implemented, however after testing the system, it was discovered there was no need for a flow-control valve because full flow was required to move the fluid at the proper rate. Another issue that arose with the flow control valve was that it opens when a plunger inside itself moves downward. Therefore, when the rocket launches and exerts an acceleration of up to 25 G's downward, the valve is forced open. 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 a plunger inside itself 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 the harsh launch and flight environment did not cause a leak, or any other event, promoting system failure. Because the pneumatic system is responsible for providing the means of transporting the fluid in the biological system, a pneumatic failure results 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 leakage could ultimately cause total system failure. Many duration tests were conducted by bringing the system up to operating pressure and monitoring its loss over time. These longitudinal tests proved the connection could not rely entirely on the barbs sealing themselves. Small clamps were installed at every connection, after which the system lost only 1 psi in a 72-hour duration test. This satisfied the criteria for successful experiment completion.

D. Container

In any bioassay, the desire is to perform two identical experiments while only varying one 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 preserve a lab environment until the experiment has been executed and the sample is successfully recovered. Second, the vessel is to serve as the primary level of containment. Typically two levels of containment are required for harmful biological materials.

A fairly rigorous development phase led up 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 came from an external rocket hatch dimension, 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 set as 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.

Other early design considerations: where to draw the container boundary, what to house inside the container and what to house outside. The dimensions were selected to minimize internal components for access/serviceability considerations, which would also reduce the size and weight of the vessel. The only other device besides the FMU that will be placed inside the bounds of the container, is the environmental pressure sensor. Wire boundary-crossing analysis constituted a major component of the component-placement study. Minimization of the number of wires was considered paramount at the time. From this it was determined that a minimum number of boundary crossing electrical connections could be made by placing only the FMU in the system. In the end, the dimension-selection process was restricted to FMU configuration and sample introduction/mounting considerations.

As with all other systems on the module, a prototype-oriented course of development was taken from concept to completion. The first three design iterations were built by the team; the final two were specified to a level 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.

The final design relies on 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. Previous iterations depended solely on a glue-joints, which afforded only very crude tolerance control while the glue cured. Inside the aluminum frame, clear polycarbonate walls are secured and sealed in place with *Scotch-Weld™ 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 glue 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 a free-standing and structurally-sound prior to the application of the adhesive sealant.

As the design of the final container was coming to a close, a rough mass estimate was calculated. The estimate revealed the system was precariously close to the ten-pound limit, and as a result, a detailed mass analysis was performed prior to 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 weight. In response, numerical stress analysis was performed to minimize the non-essential structure of the container using ANSIS and Autodesk Inventor. The mass reduction efforts were successful in that they resulted in total system mass below the allowable limit.

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

The bulkhead wire feed-through, which allows the FMU to send and receive signals to the rest of the payload, should make 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, and has since been integrated into the container back-panel design. (picture: close up of panel along with test rig)

Another container penetration was required to allow for the actuator air supply. In the fourth generation container, this was accomplished by a bulkhead fitting. The pneumatic bulkhead fitting, while small by most standards, was large and cumbersome in comparison to 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.

Control 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. Custom-printed circuit boards 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.

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. 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 launch vehicle. Upon receiving that signal, the system will come to life and execute the experiment.

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 cells' 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 of the incident.

Finally, the environmental sensors are a suite of instruments that will confirm a lab environment has been reproduced. 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 rocket and the time the vehicle is powered on. This wait period could be as much as six to eight hours, and such 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 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 vehicle. To maximize sensitivity to such motion, the accelerometer is located as far out towards the perimeter as possible. If environmentally acceptable boundaries have been exceeded, this sensor suite will provide meaning to the interpretation of the biological data.

Other Testing

To develop a reliable system that is ready for flight, it is essential the system be able to be tested in as close to close to flight conditions as possible. The SUB-SEM configuration 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. Currently, a mechanical switch simulates the WSM discretes. (Picture: test rig) Future developments on the simulator will include a computer-driven discrete function, which will be able to use 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 intuition about 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.

I. 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 slated for a flight-ready delivery early in May of this year. 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 bears account of 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.

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