Development of Feedwater Supply Assembly for Spacesuit Cooling

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2.0 Abstract

Engineers at the NASA Johnson Space Center are currently working to redesign a part of the spacesuit called the Advanced Portable Life Support System (PLSS). The PLSS is worn as a backpack and contains a thermal loop system that regulates the temperature of the spacesuit by absorbing heat generated by the crew member (CM) and evaporating water from the Feedwater Supply Assembly (FSA). The FSA is a compressible bladder that contains water to be used for cooling in the thermal loop. This year, the Washington University in St. Louis Reduced Gravity Team had the opportunity to design, build, and test an original FSA prototype in microgravity as a part of NASA’s Systems Engineering Educational Discovery Program.

The FSA consists of a bladder compression system with an electrical sensor that triggers a low water level alert. Testing in microgravity investigated the accuracy of the low level alert and how the bladders behaved in a zero gravity environment. These trials provided invaluable data to the engineers at NASA designing the PLSS, as they are unable to test their own prototypes in microgravity.
3.0 Introduction

For the fourth year in a row, Washington University in St. Louis’s Reduced Gravity Team, comprised of engineering undergraduates, were selected to conduct research through NASA’s Systems Engineering Educational Discovery program. This year, the team comprised of six students from a variety of engineering disciplines designed, built, and tested a feedwater supply system with low water level alert in a microgravity environment. After several months of planning and ground testing, the team performed their experiment in April aboard the ZERO-G Corporation’s modified Boeing 727 aircraft that creates a microgravity environment.

NASA’s Microgravity University Systems Engineering Educational Discovery program (SEED) allows teams of university students to fly research aboard the Weightless Wonder, an aircraft flown for reduced gravity research. Each team, with the assistance of a NASA mentor and a faculty mentor, develops an experiment to test onboard the aircraft, writes all necessary documentation, builds the experiment test bed, flies the experiment on the Weightless Wonder, and conducts all data analysis to answer their research questions.

The team submitted a proposal in October 2011 to continue research with the SEED program. This year, the team was assigned a new research project: Development of Feedwater Supply Assembly for Spacesuit Cooling. With the knowledge and guidance of their NASA mentor Ian Anchondo, the team developed a water bladder system that can be compressed in zero gravity and alert the crew member when dangerously low levels of water remain.

Participants in the SEED program participate in the same application and approval process that NASA employees and researchers go through to complete similar experiments. After selection in December, the team worked with their mentor to design the experiment. In mid-February, the team submitted a twenty-nine page Technical Experiment Data Package that covered all safety information and equipment specifications. During the Flight Week in April, the team underwent physiological training, presented their experiment to the Test Readiness Review board, and performed their experiment aboard the Weightless Wonder. Upon returning to the Washington University campus, the team will analyze all collected data and provide recommendations to their NASA mentor. Presented in this report are the preliminary findings from this data and a discussion on challenges the team faced when engineering the bladder system. The team’s final report with all results, conclusions, and suggestions for further testing will be completed and submitted to the SEED program in mid-June.

The primary research objectives aboard two microgravity test flights were to test the ability of the FSA to trigger a low water level alert and to observe how the bladders expanded in zero gravity. Half of the trials consisted of filling the bladders slightly above the low level and documenting if the infrared sensors triggered an alert. In the second half of the trials the team completely filled the bladders and observed how zero gravity affected how they inflated and the maximum fill height.
The secondary objective of the microgravity test flights was to conduct outreach experiments for elementary and high schools demonstrating the characteristics of gravity, using toys such as spinning tops and Slinkys. An outreach presentation will be given at a local elementary school this spring. In addition, photos, videos, answers to questions submitted by students, and other educational resources will be available on the team’s website.
4.0 Research Problem

An astronaut depends on the spacesuit for protection from the extreme temperatures and lack of oxygen in outer space. The spacesuit keeps a crew member (CM) alive during extravehicular activity (EVA). Spacesuits must provide life support, but also allow the CM to move with minimal restrictions. Because the spacesuit is integral to the CM’s performance during EVA, engineers are continuously improving space suit design.

Engineers at the NASA Johnson Space Center are currently working to redesign a part of the space suit called the Advanced Portable Life Support System (PLSS) that will be completely packaged September 2012. The PLSS is worn as a backpack and consists of three main subsystems: the oxygen system, the ventilation system, and the thermal system. The oxygen system provides the CM pressure regulated oxygen. The ventilation system circulates air in the suit while removing potential contaminants and carbon dioxide (Barnes, Chullen, Conger, Leavitt 2010). The thermal loop system regulates the temperature of the suit by absorbing heat generated by the CM and evaporating water from the Feedwater Supply Assembly (FSA). The FSA is a bladder that contains water to be used for cooling in the thermal loop. This reduced gravity project addresses the design of the FSA.

In the Extravehicular Mobility Unity (EMU), the spacesuit currently in operation, the water used in the thermal loop is contained in a hard tank internal to the backpack. This hard tank takes up a large volume in the backpack, leaving less space for other vital systems. In the backpack, the current FSA is pressurized using oxygen. If the oxygen fails, the astronaut loses breathing air and suit cooling. The FSA designed by this team will be internal to the suit, and therefore will not rely on oxygen pressure, eliminating this single point failure scenario. By eliminating this scenario, the risk of suit cooling failure if the oxygen system malfunctions is also eliminated. However, moving the FSA internal to the suit means the new design must fit within very small volume constraints.

The goal of this project was to design, build, and test a water bladder with a low level alert internal to the suit. The water bladder must be clear to allow the CM to visually inspect the bladder for contaminants prior to EVA. Essential to the FSA is a low level alert that sends a signal to the CM when dangerously low levels of water remain. This low level alert must perform in microgravity and thus cannot rely on gravity to collapse the bladder.

In the microgravity trials, the team tested their FSA’s ability to

- expand to a maximum volume in zero gravity
- signal a low level alert when the bladder reached a specified low volume
- recharge, allowing the bladder to function for multiple EVAs
5.0 Feedwater Supply Assembly Design

The team spent four months designing and building their FSA. After initial team brainstorm sessions, the team narrowed down their designs to three options. Through feasibility studies on available time and budget remaining, the team chose the design that would best meet the test requirements specified by their NASA mentor. The entire FSA had to fit inside the dimensions 16in x 14in x 2in.

5.1 Feedwater Supply Assembly

The Feedwater Supply Assembly consists of several water bladders, a mechanical compression mechanism to maintain outward flow from the bladders, and an infrared sensor system to monitor the amount of water left in the bladders. The FSA will interface with the test bed fluid loop.

5.2 Mechanical Compression FSA

The Mechanical Compression FSA uses elastic bungee cords to compress the water bladders, discharging water from the system. A model of the Mechanical Compression FSA is shown in Figure 1. A close-up of the model is shown in Figure 2.

Figure 1. Mechanical Compression FSA.
5.3 Mechanical Compression FSA Components

The Mechanical Compression FSA components are labeled in Figure 2 by the letters given below.

a. **Top Plate (aluminum)** - The top plate distributes compression across all bladders. It is attached to tops of all bladders and is guided down between the corner braces.

b. **Corner Braces (aluminum)** - The corner braces are attached to bottom plate and guide the top plate to ensure compression of the water bladders is vertical.

c. **Bottom Plate (aluminum)** - The bottom plate places pressure on the bottom of the bladders and acts as the main chassis for the entire water feed assembly.

d. **Bladders (7) (polyurethane)** - The bladders hold the water. Each has a hole in the bottom that feeds into the water manifold. When compressed, water is forced out of the hole into the manifold. The bladders are attached to the bottom plate on one end and the top plate on the other end.

e. **Bungee cords (4) (rubber)** - The bungee cords provide compression to the system. The bungees are attached to top plate and bottom plate at corners such that two cords cross on each side of the system (see diagram).

f. **Bladder Restraints (non-stretch fabric or aluminum)** - The bladder restraints ensure that the bladders only collapse vertically and do not bow outwards when compressed. The restraints are attached at each end to opposite corner braces on one side. Each side has several bladder restraints. In the final design, durable string was
attached to the top and bottom plates to surround each bladder. The string guided the bladders as they filled, limiting the horizontal bowing in 1-g testing.

g. Water Manifold (plastic composite tubing) - The water manifold allows water from all bladders to come together into one outlet/inlet feed. This is attached to the outlet of each bladder under the bottom plate.

h. Infrared Distance Sensors - The infrared distance sensors measure distance between top and bottom plates to give constant water level readings including low level alert.

5.4 Mechanical Compression FSA Operation

The mechanisms of operation for the Mechanical Compression FSA are given below.

Emptying Bladders: Bungee cords are attached to each corner of the top plate of the mechanical system and to the opposite corner of the bottom plate. The bungee cords pull down on the top plate, which in turn presses down on the tops of all water bladders. The bladders collapse vertically, which pushes water through the water outlet at the bottom of each bladder. The water outlets of all bladders flow into the water manifold, which has a singular water outlet which attaches to the rest of system.

Filling Bladders: To fill the mechanical compression system with water, water is pumped into the system through the water manifold at the bottom of the system. As water is pumped in, the bladders are filled with water and expand in the vertical direction, which pushes up on the top plate of the system. As the top plate is pushed up the bungee cords are stretched which provides the potential energy to empty the system when filling is completed.

5.5 Mechanical Compression Low Level Alert Mechanism

Four Sharp analog infrared distance sensors are located on the bottom plate, one near each corner. As the top plate descends each sensor takes a distance reading and the four distances are averaged to find the average distance of the top plate from the bottom plate (avoiding the issue of uneven bladder compression). When the average height reaches a predetermined mark, at which the bladders reach the low water level, the sensor system will signal an alert.

5.6 Fluid Loop

In order to test the FSA’s ability to meet the design requirements, the team built a fluid loop that allowed the bladders to be filled and drained, proving the FSA can be used for multiple extravehicular activities. Using a series of valves, a pump, and tubing, water is first pumped from the reservoir/waste container into the bladders. The bladder fill schematic in Figure 3 shows water flowing from the reservoir to the bladders with the blue valves open and black closed.
To drain, water was pumped from the bladders back to the reservoir/waste container by switching the blue valves closed and the black valves open (Figure 4). The team also used pressure sensors in the fluid loop to measure the pressure of the system before and after water flowed through the pump.

5.7 Containment Glove Box

The containment box is a walled, sealed glove box that houses all subsystems besides the data collection equipment and allows for four attachment points to the aircraft. The box is made of ¼” thick Polycarbonate, and all edges are lined with 1/8” thick angle aluminum. The seal ensures that no water escapes the box and enters the main cabin of the aircraft. A putty sealant was used to seal the box. The box houses the FSA and fluid test loop. The water in the test loop was double contained within the tubing and containment box.
5.8 Preflight Design Changes

5.8.1 Bladder Quantity

Due to the narrow dimensions of the FSA, small dimension bladders were needed to achieve the desired water volume. Internet searches and phone calls to manufacturers did not yield any already manufactured bladders of the proper dimensions. The team found a bladder manufacturer to produce the bladders quickly, but the team’s budget did was not enough to cover the cost of all seven bladders. The team and their mentor decided that microgravity test data with a smaller FSA would still be valuable. If the FSA worked with three bladders, then theoretically the larger system should behave the same with seven bladders. The FSA design used in flight has only three bladders (different from Figure 1).

5.8.2 Removal of Compression Bungee Cords

In the 1-g ground testing, the fully assembled FSA (as in Figure 1) did not function as necessary to meet design requirements. The stiff bungees made it very difficult for the bladders to expand vertically. The bungees created additional force the bladders had to overcome to fill vertically. This additional force caused the bladders to bow, filling the empty horizontal space in the FSA instead of expanding vertically. Since the infrared sensor measured the distance from the top plate to the bottom of the frame, it was imperative that the bladders moved only vertically to get accurate low level alert readings. The team tested the FSA without the compression bungees and found the FSA performed as desired. Without the force of the bungees, the bladders could fully fill without bowing. Therefore, the team decided to test the FSA in flight without the use of the bungees and observe how the bladders behaved in microgravity.
6.0 Methods

The team’s goals were to test the feasibility of their FSA design and the accuracy of the low level alert system in microgravity conditions. This was the first reduced gravity flight of this experiment.

6.1 Trial Description

The primary test objectives were to determine the FSA’s ability to signal a low water level alert, release water at a nominal flow, and recharge water back into the bladder for repeated use.

The trials were divided into two different tests in order to record data to analyze the three test objectives. The first half of the trials tested the FSA low level alert. The bladders were filled during one parabola until their height was just above the low water level. In the following parabola, the bladders were completely emptied. These two steps were repeated five times.

The second half of the trials tested recharge by refilling the bladders to maximum height using a pump system and then tested nominal flow by allowing the bladder to fully deplete. The bladders were filled to their maximum height during two parabolas. In the following three parabolas, the bladders were completely depleted. These two steps were repeated twice, for data on two full-fill full-depletion cycles.

6.2 Test Variables

**Bladder height:** During each trial, the sensors continuously recorded the bladder height. These height values were used to calculate the volume of the bladder during the experiment. When the low level alert signaled, the volume of water in the bladder was recorded, and compared to the desired predetermined low volume. The computer program calculated the rate of change of the volume to determine flow rate. The calculated flow rate was compared to the desired nominal flow rate. The maximum height the bladders reached in microgravity was recorded and compared to the maximum height in 1-g conditions.

**Pressure:** The pressure of the water leaving the bladder was monitored throughout the trials to ensure the FSA operated safely.

6.3 Hypothesis

The team hypothesized that the FSA system would function to meet the requirements of the low level alert, nominal flow, and recharge scenarios. They hypothesized the FSA system tests would collect valuable data on how bladders behave in microgravity for NASA engineers in the design of their own FSAs.

6.4 Quantitative Data

During each trial, the height of the bladders was recorded continuously. The computer continuously calculated the flow rate and recorded the output from the pressure sensors.
The quantitative data gathered will be used to assess the FSA’s ability to signal a low level alert at the desired water level, discharge at a nominal flow, and recharge the bladder.

6.5 Qualitative Data

A webcam was placed inside the box and connected to the laptop in order to film all of the trials with minimal view obstruction. This allowed the team to re-examine the flow of water through the bladder system and provide reference for possible problems with any outlier data. In addition, the flight team noted any observations related to the bladder system, any test anomalies, or any other data which was not recorded by the sensors and laptop. The flight team paid close attention to how a weightless environment affected how the bladders inflated and the maximum fill height.
7.0 Results

The data analyzed in this project was collected during the team microgravity flight days on Thursday, April 26, 2012 and Friday, April 27, 2012. Because there was little time between data collection and the senior design project deadline, this results section is only a preliminary data analysis. The team will conduct a more thorough analysis before the Reduced Gravity SEED Final Report Deadline in June 2012. This section discusses the results of the low level alert tests and full fill tests. Data from the pressure sensors has yet to be analyzed.

7.1 Low Level Alert Analysis

The data from three low level tests were analyzed to determine if the infrared sensor accurately signaled the low level alert. The graphs of these trials are in Appendix A. With more time, graphs of all low level alert tests (on both flight days) will be produced and analyzed.

To produce these graphs, data was spliced together from multiple zero-gravity time periods. The team spent one zero-gravity period filling the bladders past the low level alert. At the end of the zero-gravity period all valves were closed and the motor was turned off for the duration of the 2-g period. Once the plane reached zero-gravity once more, the team then turned on the pump, opened the valves, and fully drained the bladders. The zero-gravity data was spliced together to show how the bladder volume changed while the pump flowed water in and out of the bladders. The splicing caused some large discontinuities in the peaks of the graphs.

The discontinuities could be a result of human test error during the trials. The valves may not have been fully closed during the 2-g portion, causing the bladder volume to decrease without the pump on. Another reason for these discontinuities is under 2-g, the high G force pulls the bladders down, causing the infrared sensors to read that the volume has decreased, when in fact the volume has remained constant and the bladders have bowed (Figure 9). Once the zero-gravity period restarts, the bladders naturally float up to their height when the previous zero-gravity period ended, causing a discontinuity in the peak of the graph.

In the first three graphs, the alert signaled within 7.82% of the 100mL low level, with an average error of 3.94%. The instances of higher error may be attributed to the discontinuities in the data. As the bladders inflated, they often did not move at a constant speed. Sometimes the top aluminum plate would get caught on a corner of the L bracket, which stopped the bladders from filling. As the pump pushed more water into the bladders, the plate would then continue to slide, but would ‘jump’ up to a higher value to make up for the time it spent idle. The ‘jumping’ was less evident in zero-gravity than 1-g testing, as the bladders did not have to overcome the weight of the water and plate to inflate vertically. However, the graphs clearly denote ‘jumping’ (a series of continuous data, then a jump to one data point, then another jump to a series of continuous data), shown in Figure 6.
The team discussed the possibility that the jumps were caused by the infrared sensor. However, the symmetry of the jumps (the heights at which the jumps occurred were the same as the bladders filled and drained and were the same across parabolas on different flight days), show that the jumps were not random errors by the sensors. Instead, the bladders and aluminum top plate got caught on the corner of an L bracket, at the same heights each trial, which stopped the bladders from filling.

One reason for the jumping is the design of the FSA manifold. Water enters through one tube and then must split into three separate tubes to fill each bladder separately. As water is pumped through the manifold, the water may want to continue traveling straight to the farthest bladder tube instead of turning a corner to fill a closer bladder tube. This would cause the farthest bladder from the manifold entrance to fill at a slightly higher rate, causing the top plate to become crooked and get caught in the L bracket. Upon viewing video recordings of the microgravity trials, the plate indeed became crooked because the farthest bladder filled at a faster rate. In Figure 7, the top plate is not straight and the far left bladder is noticeably taller than the other two bladders.
In the graph of low level alert test from Flight 2, the volume starts at a negative value. This is because the calibrated zero water level contained a small volume of water. The pump could theoretically completely drain the bladders, which would record a negative volume level.

From the preliminary data analysis, the infrared sensor is an effective low level alert mechanism for the FSA. With some improvements in the FSA design to reduce the plate ‘jumping’, the team expects the signal error to decrease.

### 7.2 Full Fill Test Analysis

The useful quantitative data from the full fill tests was the maximum fill height of the bladders. From the preliminary data analysis, the bladders reached a height of 9 inches in microgravity. This is three inches taller than the maximum fill height in 1-g. Qualitative results notes how the bladders filled differently in zero-gravity. In microgravity the bladders do not have to overcome the weight of the water and aluminum plate in order to expand vertically. In 1-g the bladders bow because the flexible polyurethane material cannot maintain its shape under the weight of the water and top plate. It is easier for the bladders to fill the empty area adjacent, rather than expand straight up. Figure 8 shows the bladders expanding vertically in zero-gravity with no bowing. In Figure 9, the bladders bow in 2-g due to the weight of water it must contain. Similar bowing occurs in 1-g.

When the bladders bow, it gives an inaccurate infrared sensor reading. The trials proved the bladders do not bow in zero-gravity, which supports the conclusion that the infrared sensor is an effective low level alert for the FSA.
Figure 8. Bladders expanding vertically in zero-gravity.

Figure 9. Bladders bowing in 2-g.
8.0 Discussion

8.1 Results Discussion

These preliminary results support the team hypothesis that the infrared sensor would be an effective low level alert. Even with the imperfections in the FSA prototype, the sensor error was never above 8% in the trials analyzed. The results also showed that the current FSA design is imperfect and cannot be recommended for use as is. However, with some small design changes, this FSA could be a viable option for use in the new PLSS.

Current suggestions for design changes include redesigning the manifold and aluminum top plate. Creating a manifold that more evenly distributes water in the FSA would allow the top plate to be straight while the bladders move, hopefully causing the plate to become stuck less often. Another design change is to round the corners of the aluminum plate. The rounded edges of the top plate would allow it to slide in the FSA with more ease, causing fewer jumps in the data.

8.2 Design Tradeoffs

During the process of narrowing down design options, the team learned valuable lessons in analyzing different engineering designs. When the team came down to two final design choices, they had to make tradeoffs because neither design would perfectly meet the design criteria. The first option had the ability to fit inside the specified volume, but would cost too much money to entirely produce. The second option had dimensions larger than the specified volume, but could be built given the available budget. The first option required expensive custom manufactured bladders, while the second option used already manufactured bladders. The team had to decide if it was better to make a smaller part of a design, or create a prototype that would have to be scaled down.

During lengthy teleconferences, the team mentor stressed the importance of the design dimensions and stated there was little flexibility in the layout of the PLSS to accommodate a larger FSA. Although custom manufactured bladders were the riskier and more expensive option, the team agreed that this design would make the best FSA. The team learned that often the final product does not match the original design, but making a small scale prototype can still gather valuable data.

Above gathering valuable data for the team’s NASA mentor, this project was an opportunity for the team to experience how real-world engineers approach design problems. This project was open ended and only had to satisfy a few requirements, which actually made the design process more difficult. The team of undergraduates from different engineering backgrounds had to combine their strengths to build the best prototype. Through the SEED Program, the team was able to work on the exact same project NASA engineers were working on, and become real NASA engineers.
8.3 Prototyping Stage

Although the team carefully planned out their FSA, when it came to construction the team quickly learned that the prototyping stage can result in many design changes. The electrical system of the FSA (infrared sensors) did work as expected. There were some spikes in the data readings, but that was easily fixed with a moving average filter. On the other hand, the mechanical components of the system did not function as expected. The bungee compression system did not move the top plate down evenly. The bungees also provided a very large force for the bladders to overcome to move vertically. The bungees caused the bladders to bow at a height of only a few inches. The team added string guides around the bladders that contained them if they bowed. This did improve the system, but the team ended up taking off the bungees completely for microgravity testing. They decided it was more important to observe the bladders in microgravity and test the low level alert without the mechanical compression, rather than risk the FSA not functioning at all during the flight. Engineers can plan out their designs in great detail, but when building the system, the team found there were many unforeseen problems that required creative troubleshooting.
9.0 Conclusions

The preliminary data results show the team’s FSA was able to

- expand to a maximum volume in zero gravity
- send a low level alert to the CM when the bladder reaches a specified low volume
- recharge, allowing the bladder to function for multiple EVAs

The team was able to collect valuable data for their NASA mentor and other engineers designing the FSA because NASA engineers do not get the opportunity to test their designs in microgravity. The video recordings and graphs will show the NASA engineers how bladders behave in microgravity, and therefore how the system will behave when it is in use by a crew member in the PLSS.

Although the team cannot recommend the use of the FSA used in testing, with design changes to ensure the bladders fill evenly and the top plate remains level, this FSA can be a viable addition to the PLSS. The NASA engineers building the new FSA can benefit from inspecting the individual parts of the team’s FSA. NASA engineers may decide to incorporate components of the team’s FSA, such as the custom manufactured bladders or infrared sensor. The team looks forward to keeping in contact with their NASA mentor on the progress of the FSA and complete PLSS design in the future.
10.0 References


Appendix A: Low Level Alert Tests

The following graphs show water bladder volumes and low level alert signals during three low level alert trials over 2 flight days.
Appendix B: Full Bladder Fill Test

The following graph shows water bladder volume and low level alert signal during a full fill test on the first flight day.
The same test matrix was used for both flights.

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