Supporting Life in Space at NASA

A Case Study for The Mechanical Design Process

Introduction

A key need in manned space exploration is a reliable Portable Life Support System (PLSS). These systems provide all of the functions necessary to keep the astronaut alive and comfortable during a spacewalk. The first generation PLSSs were used during the Apollo Program and the image of moon walkers with large back packs is memorable. The second generation, the Shuttle Extravehicular Mobility Unit (EMU) PLSS was designed in the 1970s for use on the Space Shuttle; it has also been used to support International Space Station assembly and maintenance. It was designed for the microgravity of low-earth orbit and had to be small to fit through the hatches on the space shuttle.

It has been over thirty years since a new life support system has been developed and many new technologies have evolved during this period. Further, NASA is now planning visits to Mars and asteroids, as well as a return to the moon. Thus, a project was initiated in 2005 to develop the next generation Advanced PLSS using new technologies.

The primary challenges in designing the Advanced PLSS are the co-development of maturing technologies and, even more difficult, the integration of these technologies in a small envelope. This is a complex systems integration problem as well as a packaging exercise, as heat management is very challenging in the vacuum of space and minimizing volume is of vital importance in spaceflight applications.

- **The Problem**: Integrate evolving technologies in a compact envelope
- **The Method**: Engineers are developing a series of prototypes so they can evaluate component and system performance as well as technology readiness in this complex system-of-systems.
• **Advantages/disadvantages**: These methods take time, but the final system needs to be highly reliable as astronauts lives depend on them.

**Background**

Who can forget the images from the moon of Neil Armstrong and Buzz Aldrin exploring the lunar surface with large packs on their backs (Fig. 2)? These “packs” were their Portable Life Support Systems (PLSSs) providing oxygen, regulating pressure, removing carbon dioxide and trace contaminants, controlling humidity and maintaining the temperature of the space suit avionics as well as the astronaut. They also provided radio communications and telemetry to give mission control information on the astronaut’s and PLSS’s health.

These Apollo PLSSs, developed in the 1960s were 26 inches (66 cm) high, 18 inches (46 cm) wide, and 10 inches (25 cm) deep. They weighed approximately 84 pounds (38 kg) on Earth, which, in the Moon’s gravity is 14 lb (6.4 kg). Additionally, on top of the PLSS, behind the astronaut’s head was a separate unit called the Oxygen Purge System (OPS), an emergency backup system to maintain suit pressure and remove carbon dioxide and heat through a continuous, one-way air flow vented to space. The OPS weighed an additional 41 pounds (19 kg) on Earth or 6.8 lb (3.1 kg) on the Moon. The first four missions (Apollo 11 through 14) were limited to 4 hours. Later, the EVA (Extra-Vehicular Activity) duration was doubled to 8 hours by increasing the size of some of the systems.

The PLSS for the Space Shuttle/Space Station was part of the EMU, the name for the entire space suit. These life support systems, developed in the 1970s are commonly referred to as the Shuttle/ISS EMU PLSS. They weighed 141-160lbs (64 - 72 kg) on Earth and are weightless in the microgravity environment of low-earth orbit. While this system is heavier than the Apollo PLSS, it has more capabilities and utilizes different materials to improve robustness and resist corrosion. Improving the resiliency of the system and preventing corrosion contamination is extremely important on the ISS as the PLSSs are used repeatedly, as opposed to the one time use PLSSs that were discarded on the surface of the moon after the completion of each Apollo spacewalk.

In 2005 NASA began a new, Advanced PLSS design program. The goals of the Advanced PLSS are:

• Simpler, more robust and reliable system design
• Optimized for low-earth orbit and Langrangian point EVA operations. Provides flexibility for deep space or lunar missions, and is “Mars forward”.
• Generate more sensor data
• Provide EVA capability in more severe situations (e.g. very hot environments)
• Provide additional emergency capabilities (60 minutes, as opposed to 30 minutes in Apollo and Shuttle/ISS PLSSs)
• Weight ≈ 150 lbs

This will be a low volume product with less than 20 PLSSs to be built over the life of the product.

The Advanced PLSS program is divided into five phases:

• PLSS 1.0 Breadboard tested to refine subsystems and to be sure that all systems work together. Tested in summer 2011.
• PLSS 2.0 Fully integrated system assembled in March 2013. To be tested in late 2013.
• PLSS 2.5 Pre-production prototype to run on Nitrogen
• PLSS 3.0 System to run on O₂ with human subjects in vacuum chamber
• PLSS 3.1 Flight test unit for demonstration on ISS

This case study was written during Phase 2.0 testing. From here on, the Advanced PLSS will be referred to simply as the “PLSS”.

**PLSS – a System of Systems**

The PLSS has Oxygen, Ventilation, and Thermal Subsystems that provide the same life support functions as in the Shuttle/ISS EMU PLSS. The schematic for the PLSS is shown in Fig. 3. The important systems and sub-systems are described in this section.

The right side of the diagram is the Space Suit Assembly (SSA) and is outlined in orange. Inside this suit, the astronaut wears a conformal item of clothing knows as the Liquid Cooling and Ventilation Garment (LCVG). The LCVG is woven with approximately 300 ft of plastic tubing through which chilled water is circulated to keep the crew member cool. The LCVG also incorporates ventilation ducting that draws the space suit gas back into the PLSS for reconditioning (carbon dioxide and water vapor removal, etc.).

The PLSS is on the left broken into its three major sub-systems: Oxygen (purple and orange), Ventilation (green) and Thermal Control (blue).
The Oxygen Subsystem has both primary (purple) and secondary (orange) high pressure storage tanks and regulators. The primary storage tank holds 200 in\(^3\) (3,277 cc) of O\(_2\) at 3000 psi (320.7 MPa). The pressure regulators not only control the supply of oxygen to the astronaut, but maintain a reasonable pressure inside the suit. One goal of this project was to develop a new Primary Oxygen Regulator (POR). Where the Shuttle/ISS EMU PLSS had only two pressure set points, the new regulators will have ~4000 possible set points across the full range of 0-8.4 psid. The additional set points provide significant operational flexibility because the suit can be operated at any pressure or slowly transitioned between operating pressures. With respect to suit pressure, there is a tradeoff between physiological habitability and suit mobility. As the suit pressure is reduced the flexibility of the suit increases, making it easier to work; however, there is a lower limit to the habitable pressure range (approximately 2.8 psia, per the current medical literature). The accuracy of the regulation band of the nested set-points of the primary and secondary regulators along with regulator droop (both performance characteristics dependent on the regulator technology) impact the regulator set-points with respect to the physiological limit. Having the flexibility to change the set-point means that this regulator design can be used regardless of the desired set-pressure in accordance with the mission definition, medical community opinion, or vehicle interfaces. This advanced capability also enables slow transitions between suit pressure set-points that could reduce pre-breathe duration. Prior to an EVA, the astronaut has to complete a “pre-breathe” period during which he or she breathes 100% O\(_2\) to purge dissolved nitrogen from the body’s fluids and tissues so that it does not come out of solution when operating inside the space suit at reduced
pressure. This phenomenon is known as decompression sickness or “the bends” and is the same condition to which underwater divers are susceptible. Symptoms of decompression sickness range from pain to paralysis or even death. If symptoms of decompression sickness are observed, treatment involves placing the affected individual under increased pressure. On Earth, such treatment is conducted in a hyperbaric chamber. If such an event were to occur in space, treatment would involve pressurizing the suit as high as possible (8.4 psid) inside the vehicle or habitat (usually at 10.2-14.7 psia); in this manner, having another feasible regulator set-point achieves the in-suit decompression treatment capability.

The Ventilation Subsystem manages carbon dioxide, water vapor, and trace contaminants. Its main component is the Rapid Cycle Amine (RCA) system. The RCA system is a regenerative assembly capable of simultaneously removing carbon dioxide (CO₂) and humidity from the gas stream. Amines are organic compounds that, when exposed to CO₂ or water vapor absorb them, and when exposed to the vacuum of space release them. The RCA has two amine sorbent beds that are alternated between these two modes. During the uptake mode, the sorbent is exposed to the ventilation loop to adsorb CO₂ and water vapor, while during the regeneration mode, the sorbent rejects the adsorbed CO₂ and water vapor to a vacuum source. While one bed is in the uptake mode, the other is in the regeneration mode, thus continuously providing a sorbent bed to remove CO₂ and humidity from the system. This is referred to as a “swingbed” system as the two sorbent beds “swing” alternately between the two modes. The RCA has the potential of a ~ 65% mass decrease compared to EMU PLSS scrubber which only removed CO₂ necessitating a separate system for humidity control. Additionally, the CO₂ scrubbers on the Apollo and Shuttle/ISS EMU PLSSs utilized chemicals that were consumed as they were used. Thus, CO₂ removal capability could be exhausted during an EVA and was a limiting factor in determining EVA duration. Since the RCA is regenerable real-time during an EVA, CO₂ removal capability will no longer be a consumable or a limiting factor.

One of the most important subsystems is the Thermal Control Subsystem, the PLSS water loop. It must not only maintain the body temperature of the astronaut, but must remove heat generated by fans, pumps, instruments and electronics used throughout the PLSS.

This may seem simple, but there is no possibility of convection with the vacuum of space. Thus, conductive heat transfer between the metal structures within the PLSS and evaporative heat transfer accomplished by the Spacesuit Water Membrane Evaporator (SWME), Fig. 4, are the primary methods of heat rejection. Water circulating through the LCVG and avionics coldplates picks up heat and circulates it through the SWME. The SWME rejects crew and electronics heat by evaporating water through a hydrophobic, porous hollow-fiber membrane. The membrane is formed into channels and the thermal control loop water is passed through them. The pressure difference with the vacuum of space in the vapor channels causes water vapor to pass through the pores in the membrane and then to evaporate. This evaporation cools the remaining water flowing through the channels.

Copyright David G. Ullman 2013
Key requirements on the SWME include removing 810 W of heat from 91 kg/hr water flow. It must have a volume of 2048 cm$^3$ (125 in$^3$) or less, and a mass of 1.59 kg (3.4 lbm) or less while operating in a vacuum of 10-12 torr. The SWME when fully refined is expected to have a 400% improvement of operational life as compared to the Shuttle EMU system. Further, it will dramatically reduce water quality requirements as it is much less sensitive to contamination than the Shuttle/ISS EMU sublimator that provides cooling for the EMU PLSS.

Part of the thermal management challenge for the PLSS is cooling the avionics. In PLSS 2.0 they are all contained within a box slightly smaller than a shoebox, which is mounted on a coldplate that interfaces with the water loop, rejecting the heat via SWME. For PLSS 2.5, the team is considering a distributed avionics architecture that will allow the PLSS structure to act to distribute the heat more evenly. This would allow the avionics coldplate to be eliminated from the design, reducing the volume and weight of the system. It is also anticipated that the modular architecture would more readily facilitate component-level testing and software upgrades.

### Technology Readiness

One challenge in the development of the PLSS, and true of most evolving systems, is that many of the sub systems are not fully mature. NASA uses a Technology Readiness Level (TRL) scale to communicate maturity (see appendix A).

At the beginning of the project the RCA, SWME, and O$_2$ regulators were TRL 1 (basic principles observed) and progressed to TRL 3 (proof of concept) in component-level analyses and functional testing between 2007 and 2010. The components and system progressed to limited TRL 4 (validation in laboratory) in PLSS 1.0.

In PLSS 2.0 these systems will be tested to a higher fidelity TRL 4 because testing will include vacuum, but not all the thermal, vibration, and radiation conditions. PLSS 2.5 will be tested in all relevant environments, but it still will not operate with O$_2$, so it will not yet be TRL 5 (validation in relevant environment). PLSS 3.0 will bring the testing to TRL 7 (demonstration in operational environment) and PLSS 3.1 (the flight certification unit) will attain TRL 8 (mission qualified). A demonstration on the International Space Station (ISS) will mature all the subsystems and the system of systems to TRL 9 (mission proven).

### Thermal packaging
As mentioned in the introduction to the SWME, heat management is a significant PLSS design challenge. Table 1 shows the amount of heat (metabolic rate) generated by the crew in different working conditions. On the first row, 88 watts is human resting heat generated. When running hard a person generates about 1000 watts. For short periods, the crew may generate much more heat than that, so PLSS 2 testing will evaluate more than 2000 watts of heat generation and rejection. Also shown in the Table are the amount of CO₂ and H₂O generated. The word “injection” is used here as the table is taken from the requirements for PLSS 1 where the crew was simulated and the heat, CO₂ and H₂O had to be “injected” into the system.

Additionally, electronics adds 80-120 W depending on the mission and battery selection. Batteries are not 100% efficient and the waste heat due the inefficiencies must be removed from them or they will overheat, shortening their lives.

How the heat is managed in the PLSS is highly dependent on the packaging of the components within the envelope. In terrestrial electronics, heat can be dissipated by convection, moving air over the components. Here heat must either be removed by the circulating water in the Thermal Control Subsystem or conducted through the PLSS structure to a place where it can be removed. Thus, the PLSS must be packaged in a minimal space and, at the same time, help manage the heat flow. These two together are referred to as thermal packaging. NASA doesn’t have a single method for designing thermal packaging, but has an integrated team of designers, test engineers, and analysts who iterated continually for about 9 months to get to a PLSS 2.0 design that hopefully will change little as the system matures.

This team used Microsoft Project for project planning and an integrated suite of CAD and analysis tools including:

- Pro/Engineer (aka Pro/E): a solid modeling CAD package for design work. The solid model was used to generate drawings and code for manufacturing parts, to generate the Thermal Desktop model and as an input to Femap and Nastran for stress analysis.
- MacroFlow: a software tool for rapid and accurate flow and thermal design using for evaluating pressure drop and flow conditions given a particular hardware configuration
- Thermal Desktop: a design environment for generating thermal models of systems. Thermal Desktop develops the capacitance and conductance network for input to SINDA/FLUINT.

<table>
<thead>
<tr>
<th>Metabolic Rate (W)</th>
<th>CO₂ Injection (g/hr)</th>
<th>H₂O Injection (g/hr)</th>
<th>MGC (g/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>300</td>
<td>28</td>
<td>34.7</td>
</tr>
<tr>
<td>117</td>
<td>400</td>
<td>37</td>
<td>44.3</td>
</tr>
<tr>
<td>293</td>
<td>1000</td>
<td>93</td>
<td>82.6</td>
</tr>
<tr>
<td>469</td>
<td>1600</td>
<td>149</td>
<td>88.8</td>
</tr>
</tbody>
</table>

Table 1: Heat generation data
• SINDA/FLUINT: a finite-difference, lumped parameter (circuit or network analogy) tool for heat transfer design and fluid flow modeling. This system allows detailed thermal modeling and computational fluid dynamics (CFD).
• Femap and Nastran: tools for stress analysis

Prototype Design and Testing

In order to test the integrated PLSS design and especially to increase the TRL of the new technologies, a series of prototypes are being used. As noted in the background section, PLSS 1.0 testing is complete.

PLSS 1.0 (Fig. 5), a breadboard was tested from June-September 2011. The testing accumulated 233 hours over 45 days, while executing 119 test points; an additional 164 hours of operational time were accrued during the test series, bringing the total operational time for PLSS 1.0 testing to 397 hours. As can be seen from Figure 5, packaging was not considered. The overall PLSS 1.0 test objective was to demonstrate the capability to provide key life support functions. These functions included suit pressure regulation, carbon dioxide (CO₂) and water (H₂O) removal, and thermal control. Specific goals were to:

• Confirm that the components perform in a system-level test as they have performed during component-level testing. The push toward TRL 4.0.
• Identify unexpected system-level interactions
• Operate the PLSS in nominal and off-nominal, steady-state and transient EVA modes with respect to metabolic rate, suit pressure and flow rate, and environmental conditions

PLSS 2.0 was designed and built in 2012 and 2013 and tested in late 2013. It is a fully integrated PLSS design building on lessons learned from PLSS 1.0. It is a complete system as shown in Fig 6. It is designed to work with Nitrogen. Oxygen will
not be used in the entire system until PLSS 3.0, but substantial analysis and sub-component level testing will be conducted throughout the process to verify oxygen compatibility at both the component and system levels. Thus, by the time the team proceeds to PLSS 3.0, a full oxygen compatibility assessment will have been completed.

PLSS 2.0 will be tested with the Space Suit Assembly Simulator (SSAS), a high-fidelity simulator of the space suit volume (Fig. 7). NASA only has a small number of prototype suits and they are continually being used to support various tests, so it would have been impractical for the PLSS team to monopolize one for a year or more. Also, where real suits are very complex adding concerns not important for PLSS testing, the SSAS simplifies the suit-PLSS interfaces for the purpose of development testing.

To build the SSAS the team laser scanned the prototype space suit to generate point clouds of scanned data. Then cleaned up and meshed the point clouds to generate Pro/E CAD files. They then had molds built and plastic injection molded the space suit shown in Fig. 7.

Inside the SSAS they installed an instrumented mannequin. It is wrapped in aluminum tape and then heater tape that simulates the metabolic heat that the crew would generate. The mannequin is wearing a liquid cooling and ventilation garment (LCVG) so that it has the appropriate interfaces to the PLSS water and ventilation loops.

The SSAS and manikin combination well simulates the correct volume, heat generation, gas mixing and other factors of the real space suit and crew member. It is instrumented with equipment to support PLSS 2.0 testing, including interfaces to a simulated vehicle water loop, simulated metabolic gas consumption and suit leakage, interfaces to inject water vapor and carbon dioxide to simulate metabolic products, a displays and controls module, a sound level meter, gas analyzer, etc.

PLSS 2.0 system testing goals are to examine nominal EVA operations; evaluate control algorithms, limit checking, and fault detection requirements; simulate failure
modes from FMEA and monitor system response and controls; and evaluate methods of control/user interfaces. Also, as mentioned previously, PLSS 2.0 testing with help the critical new sub-systems reach higher fidelity TRL 4.

Conclusions
The PLSS is a work-in process, an effort to develop a system of systems that includes many new technologies. It uses a series of prototypes to refine the system and the sub systems simultaneously. It is a good example of the use of prototypes and of technology readiness.

Links/References
Packaging Factors for Portable Life Support Subsystems Based. On Apollo and Shuttle Systems,

Space Suit Portable Life Support System Test Bed (PLSS 1.0) Development and Testing,


Software:
MacroFlow, Innovative Research Inc.
http://inres.com/products/macroflow/overview.html
FeMap, a finite element code,
NASTRAN

This case study was written by David G. Ullman, Emeritus Professor of Mechanical Design from Oregon State University and author of The Mechanical Engineering Process, 5th edition, McGraw Hill. He has been a designer of transportation and medical systems and holds five patents. More details on Professor Ullman can be found at www.davidullman.com. In writing this case study he was assisted by Carly Watts, Space Suit & Crew Survival Systems, NASA Johnson Space Flight Center.
Appendix A: NASA Technology Readiness Levels

- **TRL 1 Basic principles observed and reported**: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
- **TRL 2 Technology concept and/or application formulated**: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
- **TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept**: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
- **TRL 4 Component/subsystem validation in laboratory environment**: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
- **TRL 5 System/subsystem/component validation in relevant environment**: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
- **TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)**: Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
- **TRL 7 System prototyping demonstration in an operational environment (ground or space)**: System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation is available.
- **TRL 8 Actual system is completed and "mission qualified" through test and demonstration in an operational environment (ground or space)**: End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.
- **TRL 9 Actual system "mission proven" through successful mission operations (ground or space)**: Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.