Advanced Two-System Space Suit

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Abstract

We present the results of our research into the development of an advanced space suit design, based on the concept of separating the head and torso pressurization systems.

Summary

Current Extravehicular Mobility Units (EMU's) must be improved for use in long-duration extravehicular activities (EVA's), as they are at risk of exposing the astronaut to explosive decompression, relatively inefficient in resource consumption, cumbersome, and expensive to maintain due to their complexity. To attack some of these issues, it is the aim of this project to design and develop a two-component space suit—a head bubble and a pressurized body suit—connected to each other through a neck-dam system. The separation of the head from the body will allow the astronaut more time to reach safety in the case of decompression and minimize O_2 loss by allowing for independent pressurization of the body and eliminating loss through the soft joints. Moreover, concurrent research on pressurization methods for the body-- with emphasis on mechanical counter-pressure and the use of dense polyurethane membranes—will pave the way toward a more practical, mobile, and inexpensive unit. For the success of the two-chamber space suit (TCSS) idea, design and functionality of the neck-dam system is vital. As outlined below, the neck-dam system and our ideas for body-suit pressurization show a strong potential for space-flight applicability, thereby, allowing engineers to modify the current EMU to provide maximum resource efficiency, while maximizing safety, reliability, and mobility.

Introduction

Space Suit Background

Technologies for protection from harsh environments, where pressure and temperature extremes are not compatible with human physiology, have had some remarkable milestones over the last sixty years. The beginnings of helmet and pressure suit innovations date from 1934 when Wiley Post with Goodrich Rubber Company developed the first pressurized high-altitude suit, which in its final design, consisted of a can-like aluminum head unit with a front window and rubber waist entry (Mohler 1998). From these early roots, the modern space suits of today evolved.

The current Extravehicular Mobility Unit (EMU) is an improved version of the original developed in 1975 by Hamilton Sundstrand and ILC Dover. The two major subsystems of the EMU are the Portable Life Support Subsystem (PLSS) and the Space Suit Assembly (SSA). The SSA is comprised of a Hard Upper Torso (HUT), Lower Torso Assembly (LTA), boots, gloves, and other integrated components. The EMU provides life support functions, such as oxygen supply, carbon dioxide removal, a pressurized enclosure, temperature control and micrometeoroid protection. The suit and PLSS contain 7 hours of expendables including O_2 for respiration and pressurization, water for cooling via the Liquid Cooling garment (LCG), a battery for electrical systems, and lithium hydroxide for carbon dioxide removal.

The SSA provides full body pressurization and respiration at 4.3 psid using O_2. A Pre-breathe of 40 minutes is required to transition from 10.2 psia habitat or cabin pressure to 4.3 psid (Furr 1987). This period of out-gassing is essential for transitions to a lower pressure environment and is analogues to the precautions taken in deep sea diving. Inadequate pre-breathing will result in nitrogen bubbles forming in the blood stream; a condition known as the bends that can be fatal. Airflow, supplied by the PLSS, enters the suit at the helmet and flows down to the torso and extremities. Used air containing water vapor and CO_2 is removed at the elbows and feet to be transported back to the PLSS where CO_2 is removed and water vapor is condensed using a sublimation system. The water is then recycled back into the cooling system.

The Liquid Cooling Garment in which water is circulated through a network of fine tubing to remove excess body heat performs thermal regulation. The excess heat is subsequently removed at the sublimator and transferred to the outside environment.

Problem Statement

The use of O_2 in current EMU's to pressurize the whole body presents a number of problems. Even under normal operating conditions, current EMU's lose up to 50 liters of O_2 per eight-hour EVA through the many joints and seams of the suit. This great loss of O_2 limits current EMU endurance and makes it inadequate for long duration missions. A single pressurization system also puts the suit at a high-risk of micrometeoroid puncture. With current EMU's, even a small puncture could result in rapid decompression of the entire suit. This catastrophic situation can easily be fatal, as studies have shown an astronaut has from 9-11 seconds of consciousness in which to save his or herself. (Parker and West 1973)

The Sublimation cooling system is designed for use in a hard vacuum and will fail under terrestrial conditions, such as those found on Mars. Even with only1/150th the pressure of Earth, the delicate balance of the sublimation system will be disrupted and the astronaut will overheat.

Current EMU's have rigid torso and arm sections and soft joints for movable parts. When pressurized, these soft joints become very rigid, limiting mobility, especially in key areas like the hands. The complex designs of current space suits incorporate several control systems that contribute to the weight and complexity of the unit. For example, the liquid cooling layer alone adds 6.5 pounds when dry. These systems have a profound impact not only on resource consumption and cost but on safety and mobility, as well. The more complex the design, the more troubleshooting required, and the more components that have the potential to malfunction or break.

Rationale

The goal of the TCSS development team is to develop a variety of new features that address the problematic areas of current space suit designs. These solutions will be compatible with current EMU's and well suited for integration in the next generation of space suit designs. In contrast to current suit designs that utilize oxygen for full body pressurization, we are developing a two-system suit that separates the respiration and pressure system of the helmet from that of the upper and lower torso. This will be done using an advanced neck dam system. One objective of our project is to limit the amount of oxygen lost by eliminating its use from the neck down. With this in mind, we arrived at the conclusion that a neck dam system can serve as a crucial element for continual expansion of manned space endeavors.

In addition, the neck dam provides added safety while in a hazardous space or terrestrial environment. The neck dam technology, when perfected, can easily be extended to create airtight seals throughout the suit, leading to compartmentalization. A Separation of components allows pressure to be maintained in other parts of the suit, particularly, the head region, should one area be compromised. With existing EMU's, a puncture by a micrometeoroid is life threatening. Utilizing a compartmentalized suit, the time of useful consciousness in the event of a puncture is likely to be extended from seconds to minutes or even hours.

Limiting resource consumption is a necessity for long-duration missions. Another key benefit of the neck dam is that, once the head is contained, a variety of options become available for pressurizing the rest of the body. One could use mechanical counter pressure or make use of another readily available gas, such as CO_2, to pressurize the torso and extremities. This would greatly diminish the amount of oxygen consumed and allow a drastic reduction in payload weight, resulting in decrease mission cost. Mechanical pressure affords a wide range of motion. Consisting primarily of a skin-tight layer of material, its simplicity ensures a higher level of reliability and safety. An additional design concept utilizes alternate gases for pressurization of the body. The ability to use alternate gases for pressurization provides the versatility to adapt to many environments.

Breathable polymers are available that can maintain suit pressure while allowing water vapor to exit for recycling or removal. The ability to use evaporative cooling is an option not present in current EMU's and a simplification of the cooling system would significantly reduce weight. Further study is planned to determine whether evaporative cooling will provide adequate thermal regulation. Lower pressures result in increased evaporative water loss and possible dehydration without proper precautions. Further testing is required to adequately understand the requirements of an evaporative cooling system. A method of sweat removal, collection, and recycling is a necessity.

Similar polymers could also be used in a breathing apparatus, which is necessary in a mechanical counter pressure suit due to the high pressure placed on the torso. The breathing apparatus provides direct mechanical counter pressure to the torso and the restraint layer. It also acts as a buffer volume to accommodate the change in chest size during breathing. Integration of the polymer provides a method of removing exhaled water vapor that might accumulate in the apparatus.

The polymer will also serve as an interface within the neck dam, maintaining the gas pressure in the head region, while allowing the moisture expelled while breathing to diffuse to the upper torso where it might then be collected.

Methodology and Results

As mentioned previously, this project focuses on the development of both a neck dam and alternate torso pressurization system. Below are presented the results of research and preliminary testing of these systems, with special emphasis on design concepts and test procedures.

Head Unit

The separation between head and torso is the basis of the new EMU. This separation can be achieved through a neck dam system, which will serve as an interface between the head bubble and the body of the EMU. It will require careful consideration in development and testing to minimize discomfort and risk. A system of sensors will be used keep the neck dam airtight without restricting blood flow or neck-head mobility (see Figure 1). The new head unit will also contain micro sensors to monitor temperature, oxygen, $C0_2$, moisture and pressure. The bubble receives ambient gas and humidity control from a backpack.

The functionality of the TCSS relies heavily on the removal of heat and moisture from the head unit and neck apparatus. The cooling requirements of the head and neck in air at sea level are 15.9 and 32.6 Btu/hour, respectively. Insensible water loss rates range between 7 and 11 g/hour for the head and 4 and 5 g/hour for the neck. It has been demonstrated that for each degree of increase in temperature (°F or °C), sensible energy rejection from the body increases by 20 Btu/hour (Parker and West 1973). These factors are part of the design and prototype development.

The Neck Dam System is designed to maintain a regulated pressure against the neck while allowing for comfort and vapor removal. The outer bladder layer maintains proper pressure and the polymer neck seal applies the pressure to the neck while diffusing water vapor. The requirement for a neck pressure bladder separated from the permeable membrane is dependent on the membrane's elastic properties, which have yet to be determined. With an appropriate membrane, the bladder and membrane could be one unit. In this case, pressure and moisture removal would be one system.

The following test procedures will be necessary to determine the viability of the head unit and torso pressurization interface:

1. Neck bladder pressure tolerance window evaluation for personnel comfort and safety. This test will be done with UC Berkeley IRB approval.
2. Evaluation of the seal performance with attached head bubble at ambient 1 atmosphere with differential pressures of –4 psi, +4 psi, +8 psi, and +10 psi while breathing normal air mixture (i.e. 20% oxygen). This test will be conducted with UC Berkeley IRB approval.
3. Integration testing of the complete head unit with various torso pressurization designs. Establishment of the neck unit pressure and moisture/temperature control pack through either ports to the neck unit directly or through the EMU collar plate.
4. Vacuum test after preliminary tests under low atmospheric pressures.

The elements of the design discussed above represent only one of a number of alternative methods for establishing a safe yet comfortable neck seal between the head bubble and lower torso of the EMU. The isolated head unit can be incorporated into current EMU's for improved safety or used with an alternative pressurization system, an example of which is discussed in detail below.

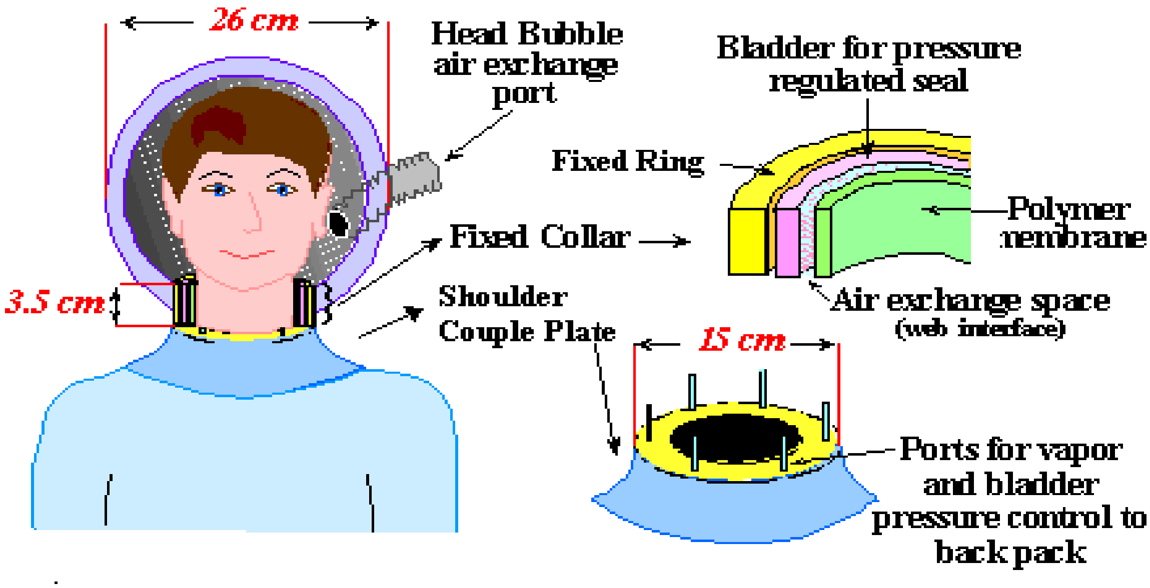

Figure 1. Head Unit Assembly

<u>Mechanical Counter Pressure</u>

During extravehicular activity (EVA), oxygen is normally supplied at 4.3 psi -5.2 psi in a conventional full-pressure suit, with the entire body pressurized with oxygen. An alternate approach is to deliver oxygen to an isolated helmet, while pressure is applied to the torso mechanically. The torso portion is engineered to balance the helmet pressure. A powerful leotard having elastic properties, insignificant gas permeability, and durability can provide many advantages over conventional systems because no hard joints or bearings are needed. Paul Webb (Webb 1968) first published this concept, performed early experiments, and demonstrated a complete elastic mechanical counter pressure (MCP) suit in 1968 as described by Annis and Webb (Annis and Webb 1971).

The original elastic MCP suit developed by Webb (Webb 1968) showed major advantages. It had increased mobility and dexterity, reduced metabolic cost of movement, and had excellent heat dissipation from evaporation of sweat; however, it was never fully developed. The heat dissipation quality of an MCP alone promises significant reductions in the mass and complexity of life support equipment, such as used in the Portable Life Support System designs (PLSS) of current EVA suits that require a cooling garment. An MCP space activity suit can not only save weight by eliminating stored refrigerant and machinery to dissipate heat, but it is inherently safer because punctures and tears will not cause the catastrophic loss of pressure that is a risk with current EMU's. Human tests showed that there was negligible blood pooling (Annis and Webb 1971).

During the last three years, Honeywell, Inc., in collaboration with Dr. Paul Webb and Clemson Apparel Research, has developed a modern prototype of the original mechanical counter pressure suit (Annis and Webb 1971). The emphasis has been a glove that interfaces with the existing Shuttle EMU lower arm assembly at the wrist disconnect. At this point in the development program, human testing of this glove prototype has concentrated on the proof of concept. Experiments have been performed in a glove box at a differential pressure of -222 mmHg, which simulates the pressure difference an astronaut would experience during EVA. The duration of the human glovebox tests has typically been up to 120 minutes.

In addition to the glovebox testing at Honeywell, a proof of concept test at low vacuum conditions was performed in the 11-ft chamber at NASA JSC in September 1999 (see Figure 2). The test was performed at pressures as low as 1 Torr for exposure times of up to 60 minutes. Two different test subjects performed identical tests. The results of these tests showed that the MCP technology is adequate to protect a human hand in low vacuum conditions.

In the recent Cooperative Agreement Notice (CAN) issued by NASA, the TCSS Development Team at UC Berkeley designated Honeywell, Inc. as a subcontractor to develop a mock-up MCP suit. The mock-up will interface with the head unit and breathing apparatus (described below) that will be developed by the TCSS Team. This will serve as a proof of concept for both the neck-dam system and the MCP.

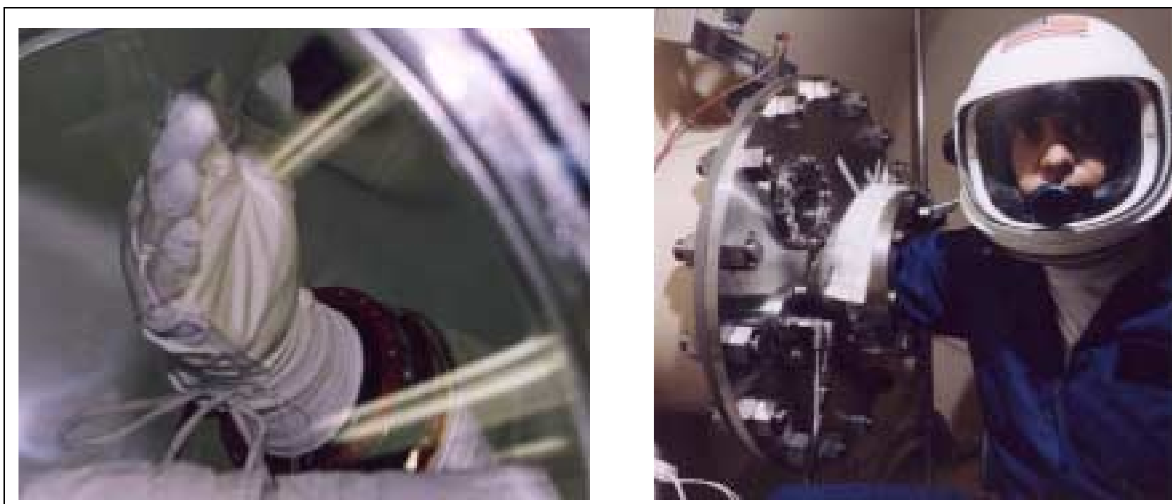

Figure 2. Mechanical Counter Pressure Glove with EMU Lower Arm Assembly in Glovebox at –222 mm Hg Differential Pressure (left) and In Vacuum (right)

<u>Breathing Apparatus</u>

The breathing apparatus is a set of conformal chambers located between the comfort layer and the restraint layer. These chambers are made of rubberized materials that inflate at the pressure of the pneumatic system (about 4 psi). Under these conditions the breathing apparatus provides direct mechanical counter pressure to the torso and the restraint layer. It also acts as a buffer volume to accommodate the change in chest size during breathing. Valves are needed to separate the exhaled air from the fresh air.

The objective of this work is to define the Human-Pneumatic interface for a Mechanical Counter Pressure (MCP) space suit.

The MCP Space Suit breathing interface provides the following functions:

1. Pneumatic enclosure to permit breathing in the space environment. This system consists of a helmet and pneumatic seal. The seal must have a minimum leak rate, permit breathing, and not cause discomfort to the crew.
2. Breathing apparatus that permits effortless breathing while the torso is subject to mechanical counter pressure. The apparatus consists of inflated chambers and valves that compensate for the volume displacement of the lungs. It is capable for various levels of exertion and does not cause discomfort to the crew.
3. Passive management of the exhaled humidity so the visor remains clear. The crew will lose orientation and direction if their visor is fogged and they lose visual contact. Gas tight water permeable membranes permit the control of exhaled humidity without the need for air processing equipment.

Breathable Polymer

As previously mentioned, an alternate design concept utilizes breathable polymers to both serve as a pressure garment bladder and as a means to allow sweat to pass through the suit. Several gases can be used with this system, as long as oxygen is provided for respiration. A comfort layer with a polymer coating rests against the skin, while pressurized air flows between the comfort layer and another polymer layer. To maintain shape and integrity, a Pressure Garment Restraint (PGR) layer is used to prevent the polymer from ballooning. Pressurized gas can be obtained from the environment or stagnant air can be used in a closed-loop system. These options allow this suit design operate in a variety of conditions.

Although a variety of polymers exist, we are focusing on a moisture-permeable dense breathable barrier film whose properties would allow us to regulate temperature, pressure, and humidity and provide a biological barrier. Currently, the polyurethanes under testing are Bionate 55D, BioSpan, CarboSil 20 90A, and PurSil 20 80A, all products developed by The Polymer Technology Group, Inc.

The advantage of dense polymer membranes is that they allow the transmission of sweat, in vapor/gas form, via diffusion. This is enabled by the concentration gradient in the material; the side of highest concentration diffuses across the film to establish equilibrium. Sweat vapor/gas arrives on the polymer surface closest to the body, dissolves into the membrane, travels across and then exits the opposite side of the membrane in the form of vapor/gas. The true benefit of this property is that only vapor/gas can transfer. Liquid is unable to pass through the material, regardless of its pressure, viscosity, or surface tension. The rate of transmission for a specific dense breathable barrier film "is directly proportional to the vapor pressure or concentration difference and the film area, and is inversely proportional to the film thickness." (Ward and White, 1991)

Another benefit of the dense breathable barrier film is its relatively high resistance to puncture and tear, which in turn prevents possible leakage. Polyurethanes have a combination of high elongation and high tensile strength, which significantly decreases the possibility of the material cracking or tearing, even under severe conditions. The material is also quite flexible, providing optimum movement and comfort.

All the materials currently under testing are composed of aromatic urethane hard segments and exhibit remarkable mechanical properties. In addition, BioSpan has excellent flex life, hydrolytic stability and elasticity, and the Bionates have good oxidative stability and abrasion resistance.

Polyurethane Testing

We have currently begun testing of various polymers to determine their feasibility in both the body of the suit and the breathing apparatus that would be necessary in a MCP suit.

The material characteristics to be determined are:

1. Water permeability as a function of temperature.
2. O_2 permeability as a function of temperature and pressure.
3. Young's modulus of elasticity.
4. Photochemical behavior (e.g. resistance to ultraviolet light)
5. Aging characteristics of the above attributes.

Test Protocol

The protocol for our experiment can test water and gas permeability, permeability to mineral components of sweat, the ability of the polymers to maintain constant pressure, and durability. Water is poured into the sealed, pressure-retaining flask developed by UC Berkeley undergraduates and staff (see Figure 3). The material is then stretched minimally and secured over the top of the vessel using a clamp. The internal pressure is raised to 5 psig while a heating element maintains constant internal temperature. After the entire system is weighed, the vapor loss is monitored at regular time intervals. After an eight-hour period, the system is weighed again to determine the mass of water that diffused thorough the membrane. Variations of the experiment described above can determine gas retention and water transmission separately as functions of temperature and pressure.

Preliminary Tests and Results

In our preliminary tests, we have measured a sample polymer's permeability to water vapor. The material was stretched over the container with water heated to approximately 40^{o} C. Weight loss was measured approximately once every hour, over 6.5 hours. For comparison, the same experiment was run without anything covering the container and with a non-permeable material covering it. The non-permeable material test was simply to evaluate the efficiency of our test setup. If there were significant weight loss with the non-permeable material, we would conclude that there is some alternate means of vapor loss in the test chamber. By comparing the results for the open chamber to the results of the chamber covered with the polymer, we were able to gauge the polymer's ability to transfer water vapor. If the weight loss with the covering was close to or equal to the weight loss without the material, we could infer that the polymer is efficient in water vapor removal. The results of this preliminary test are given below.

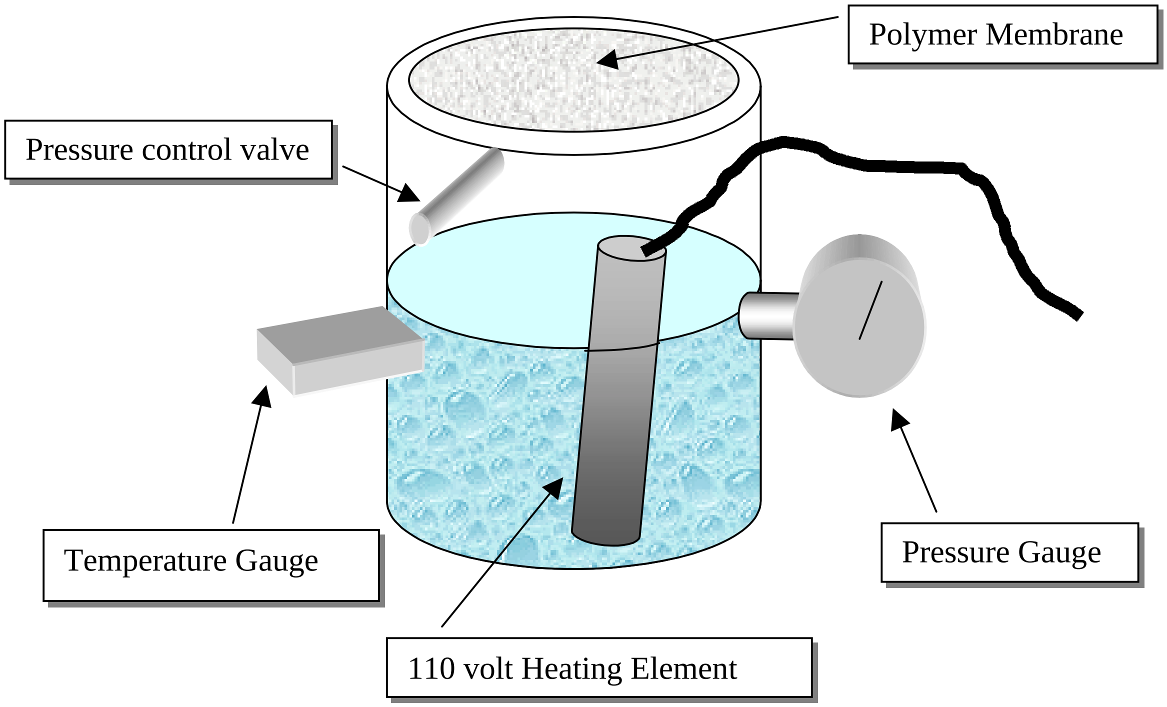

Figure 3. Polymer Test Chamber

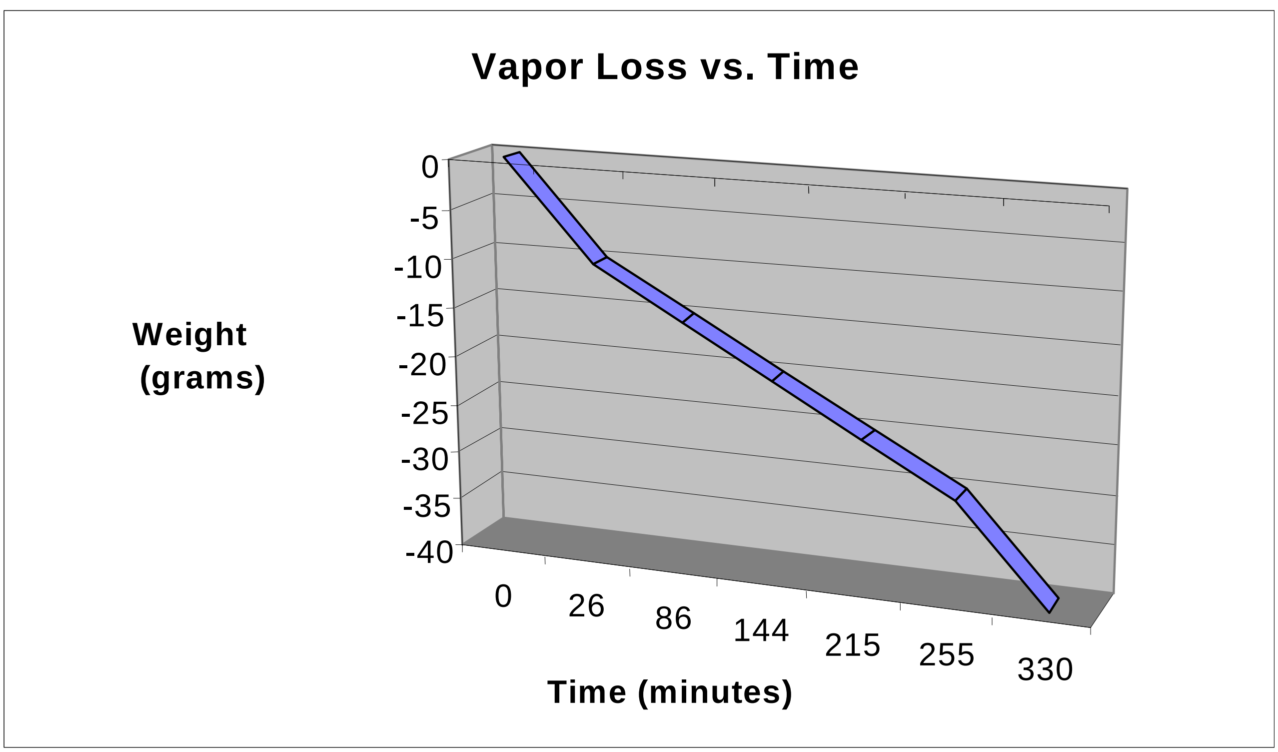

Figure 4. Preliminary Test Results

Results

Figure 4 presents the results of the water permeability test conducted with the polymer membrane covering the test chamber. When a non-permeable material (vinyl) was used to cover the chamber, no significant weight loss was recorded over 11 hours. Our data for the open chamber test were tainted by a heating malfunction. The heater has been replaced, and the test will be conducted again. Additional testing was conducted to determine the pressure retention of a polymer sample. However, the sample failed the test when it developed holes under high pressure. This was probably the result of age and mishandling. A new sample was obtained and will be tested.

Further Polymer Testing

Two alternative approaches to polymer testing are as follows:

1. Using two chamber dialysis / diffusion cells, flat membrane permeability is measured.
2. In a second approach, membrane tubes are hydrated and filled with a radioactive labeled solute. They are then placed into a test tube containing solute free solution. The experiment consists of monitoring the radio concentration of the solution in the test tube as a function of time while controlling the temperature at 37 °C. The permeability coefficient could be determined from regression analysis of the radioactivity in the reservoir tube as a function of time as applied previously by Ward in 1993. This experiment assumes permeability of solute is not significantly different for that of water.

These testing procedures, with the preliminary test procedure already developed will provide sufficient data to determine the characteristics of various polymers under various conditions.

Conclusions

By separating pressurization systems between the head and torso, safety, resource consumption, weight, mobility, and complexity can be improved. Furthermore, the separation allows for the development of innovative torso pressurization systems that show definite advantages over the current EMU. The neck-dam system will be tailored for use in the current EMU's, as well. This provides great versatility for varying environments. Alternate torso pressurization systems include, but are not limited to, the mechanical counter pressure suit and the polymer membrane pressurization system described above. Although further testing must be done, the design concepts presented in this paper show promise for space suit applicability.

Future Studies

The TCSS Development Team will continue its research and testing of the above mentioned design concepts, with emphasis on testing. Furthermore, the team has developed collaborations with Stanford University and the Art Center College of Design, in Pasadena, CA. In addition, relationships are being developed with California Institute of Technology and University of California, San Diego. These schools will take on various aspects of an overall suit design in an effort to produce a complete proof of concept suit.

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