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Final Report

Advanced Worker Protection System

Work Performed Under Contract:
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Abstract

From 1993 to 2000, OSS worked under a cost share contract from the Department of Energy (DOE), contract #DE-AC21-C30178, to develop an Advanced Worker Protection System (AWPS). The AWPS is a protective ensemble that provides the user with both breathing air and cooling for a NIOSH-rated duration of two hours. The ensemble consists of a liquid air based backpack, a Liquid Cooling Garment (LCG), and an outer protective garment.

The AWPS project was divided into two phases. During Phase I, OSS developed and tested a full-scale prototype AWPS. The testing showed that workers using the AWPS could work twice as long as workers using a standard SCBA. The testing also provided performance data on the AWPS in different environments that was used during Phase II to optimize the design. During Phase I, OSS also performed a life-cycle cost analysis on a representative clean up effort. The analysis indicated that the AWPS could save the DOE millions of dollars on D& D activities and improve the health and safety of their workers.

During Phase II, OSS worked to optimize the AWPS design to increase system reliability, to improve system performance and comfort, and to reduce the backpack weight and manufacturing costs. To support this design effort, OSS developed and tested several different generations of prototype units. Two separate successful evaluations of the ensemble were performed by the International Union of Operation Engineers (IUOE). The results of these evaluations were used to drive the design.

During Phase II, OSS also pursued certifying the AWPS with the applicable government agencies. The initial intent during Phase II was to finalize the design and then to certify the system. OSS and Scott Health and Safety Products teamed to optimize the AWPS design and then certify the system with the National Institute of Occupational Health and Safety (NIOSH). Unfortunately, technical and programmatic difficulties prevented us from obtaining NIOSH certification.

Despite the inability to NIOSH certify the design, OSS was able to develop and successfully test, in both the lab and in the field, a prototype AWPS. We clearly demonstrated that a system which provides cooling can significantly increase worker productivity by extending the time they can function in a protective garment. We were also able to develop mature outer garment and LCG designs that provide considerable benefits over current protective equipment, such as self donning and doffing, better visibility, and machine washable.

A thorough discussion of the activities performed during Phase I and Phase II is presented in the AWPS Final Report. The report also describes the current system design, outlines the steps needed to certify the AWPS, discusses the technical and programmatic issues that prevented the system form being certified, and presents conclusions and recommendations based upon the seven year effort.

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Executive Summary

From 1993 to 2000, OSS worked under a cost share contract from the Department of Energy (DOE), contract #DE-AC21-C30178, to develop an Advanced Worker Protection System (AWPS). The AWPS is a protective ensemble that provides the user with both breathing air and cooling for a NIOSH-rated duration of two hours. The ensemble consists of a liquid air based backpack, a Liquid Cooling Garment (LCG), and an outer protective garment. A picture of a prototype AWPS is shown in Figure 1.

Figure 1: Prototype Advanced Worker Protection System

The AWPS uses liquid air to provide cooling and breathing air. The liquid air is stored in the backpack. As the user breathes, air flows from the pack through a heat exchanger where it is vaporized, to the user's mask, which maintains a positive pressure around the user's face. Water is circulated through the heat exchanger to vaporizer and warm the liquid air to a breathable temperature. The water is cooled in the process and is then circulated through the user's LCG, thereby cooling the user. The system is self-regulating. As the user works harder, they breathe harder and require additional cooling. Their increase in breathing rate increases the flow of liquid air, and subsequently provides the additional cooling needed.

The impetus behind the project is the need to extend the useful work that can be performed by hazardous material (haz-mat) workers. One of the key limitations haz-mat workers face is overheating. Most current personnel protection equipment (PPE) does not provide any means of cooling. As a result, the user quickly overheats and must stop working. In relatively warm environments, the amount of useful work that can be performed can be as little as 20 minutes. The AWPS can extend this time to two hours by providing the necessary cooling and breathing air. This increase in useful work can greatly increase the efficiency of clean up operations. As a result, the AWPS can significantly reduce the life-cycle costs associated with site Decommission and Decontamination (D&D).

The AWPS project was divided into two phases. Phase I lasted from October 1993 to July 1995. During this phase, OSS developed a full-scale prototype AWPS. The prototype was then tested at Kansas State University. During this testing, four different human subjects donned the system, exercised on a treadmill inside an environment chamber until they either overheated, became tired or uncomfortable, or the pack was emptied. A total of 28 tests were conducted. Each subject's heart rate, core temperature, and skin temperature at various locations were recorded throughout the test. The same tests were repeated using a standard Self-Contained Breathing Apparatus (SCBA), which provides no cooling.

These tests proved the usefulness of the AWPS. The testing showed that workers using the AWPS could work twice as long as workers using a standard SCBA and that the system drastically reduces increases in the user's core temperature. The testing also provided performance data on the AWPS in different environments that was used during Phase II to optimize the design. Tests revealed specific information on the design of the two prototype chemical protective suits, from which OSS identified several design improvements. For the Level A suit, these design improvements included a provision for expelling breathing air to outside the suit, using a single layer glove to increase dexterity, and flowing air across the visor to prevent fogging of the facepiece. For the Level B suit, proposed design changes included modified glove and boot interfaces together with the incorporation of suit sizing.

During Phase I, OSS also performed a life-cycle cost analysis on a representative clean up effort to quantify the benefits provided by the AWPS. We collected information from several DOE sites as inputs to the analysis. The analysis indicated that the AWPS could save the DOE millions of dollars on D& D activities as well as improve the health and safety of their workers.

Phase II of the project lasted from August 1995 to May 2000. During this phase, OSS worked to optimize the AWPS design to increase system reliability, to improve system performance and comfort, and to reduce the backpack weight and manufacturing costs. To support this design effort, OSS developed and tested several different generations of prototype units. Two separate evaluations of the ensemble were performed by the International Union of Operation Engineers (IUOE), one in September 1995 and one in October 1997. The results of these evaluations were used to drive the design.

During Phase II, OSS also pursued certifying the AWPS with the applicable government agencies. The initial intent during Phase II was to finalize the design and then to certify the system. We successfully completed the backpack's plastic, liquid air storage vessel design, conducted extensive pressure and creep/rupture tests of numerous vessels, and obtained a Department of Transportation (DoT) exemption certifying the pressure vessel design. Unfortunately, we were not able to obtain AWPS certification from the National Institute of Occupational Health and Safety (NIOSH) due to technical and programmatic difficulties.

During Phase II, the NIOSH certification was assigned to Scott Health and Safety Products, the largest supplier of breathing apparatus in the United States. OSS and Scott entered into a cooperative business agreement in February 1997 to develop, certify, and market liquid air backpacks. Scott was to optimize the designs of the systems exterior to the AWPS dewar, such as valves, pump, electronics, battery pack, pack harness, etc., while OSS worked to optimize the dewar design. Scott was then to head up NIOSH certification of the system and market the backpacks. The key drivers during this optimization process included weight, reliability, cost, and performance enhancements to ensure the system met all applicable certification requirements.

Several obstacles were encountered during this design optimization which led to significant redesigns of the dewar. The first problem encountered was the burst pressure of the inner vessel. The inner vessel shape developed during Phase I did not provide the expected burst pressure, which was needed for DoT certification. Extensive testing indicated that the vessels were failing due to buckling of the dished heads, a nonlinear failure not predicted in our original finite element analyses of the inner vessel. This led to a redesign of the vessel shape and associated pickup mechanism and capacitance gauge. This new design was thoroughly tested and approved by the DoT.

The next obstacle was encountered when the first set of six dewars built to completed drawings and procedures were assembled; these dewars were to be used for NIOSH certification. The pickup mechanism did not work reliably in these dewars due to small variations in the assembly procedures and manufacturing tolerance stack up. This led to a minor redesign of the pickup mechanism. The new pickup mechanism worked well initially but began to experience problems after repeated uses. The capacitance gauge began to drift and intermittently drop out while the pickup mechanism began to stick. Several new designs for these components were developed and thoroughly tested. Based upon these results a new dewar design was developed that OSS felt confident would work.

Unfortunately, the redesign efforts slipped the AWPS schedule and increased the development costs. Scott became increasingly concerned about the pack production costs, its weight, and the slippage in schedule as a result of the design modifications. As a result, the agreement between OSS and Scott was terminated. This left OSS financially responsible for not only completing and testing upgrades of the dewar, but also of completing the development of the remaining backpack components that were Scott's responsibility and of NIOSH certifying the system. The cost for this work would have far exceeded the value of the AWPS contract. As a result, OSS aggressively pursued other partners to fill the void left by Scott. However, OSS was not successful in locating a company willing to invest the money required to complete and certify the design.

Despite the inability to NIOSH certify the design, OSS was able to develop and successfully test, in both the lab and in the field, a prototype Advanced Worker Protection System that provides breathing air and body cooling to the user. We clearly demonstrated, through repeated testing, that a system which provides cooling can significantly increase worker productivity by extending the time they can function in a protective garment. Tests demonstrated that subjects using the AWPS can operate up to 2 1/2 times longer than when using a gas-based SCBA that does not provide cooling. Testing also showed that workers could more clearly focus on the task at hand when they received cooling.

We were also able to develop mature outer garment and LCG designs that provide considerable benefits over current protective equipment, such as self donning and doffing, better visibility, and machine washable.

Additional conclusions and recommendations developed from this effort are discussed in the AWPS Final Report. The report also describes the current system design, outlines the steps needed to certify the AWPS, and further describes the technical and programmatic issues that prevented the system form being NIOSH certified.

1.0 Introduction

Throughout the United States, the Department of Energy (DOE) is working to clean up various sites utilized in the production of nuclear weapons over the last 50 years. It is estimated that approximately 7,000 buildings are contaminated with a combination of radioactive and hazardous materials.[1] These buildings must be characterized, decontaminated, dismantled, and decommissioned.

The clean up process is labor intensive and costly. It is estimated that DOE site clean up will cost $300 billion and span the next 30 years.[2] The DOE is currently funding research to develop techniques and systems that will reduce this projected cost.

A key in minimizing clean up costs is maximizing worker productivity. The protective equipment needed to operate in the hazardous environments often limits worker productivity. The protective equipment can reduce mobility, increase muscle fatigue, and limit operating time due to limited consumables, such as air, or to overheating of the user. In a Decommission and Decontamination workshop held in 1996, the need for improved personal protection equipment that reduces heat stress and improves worker efficiency was specifically identified by an Industry Needs Panel.

One DOE funded project that has the potential to fulfill these needs is the Advanced Worker Protection System. The AWPS is a protective ensemble, being developed by Oceaneering Space Systems (OSS), that provides the user with breathing air, cooling for a NIOSH rated duration of 2 hours, and environmental protection. The AWPS consists of a liquid air based backpack, a Liquid Cooling Garment (LCG), and an outer protective garment. The backpack uses liquid air to provide the breathing air and cooling; a more detailed description of the current system is presented in Section 2.

Oceaneering Space Systems has been working on the AWPS for the past seven years under a cost share contract with the Department of Energy, Contract #DE-AC21-C30178, and has made significant progress. During the first phase of the project, which lasted from October 1993 to July 1995, OSS developed and successfully tested a full-scale prototype system. A Topical Report that described the prototype system and the test results was published at the end of Phase I.

The second phase of the project spanned from August 1995 to May 2000. During this phase, OSS worked to optimize the design to increase system reliability, to improve system performance and comfort, and to reduce the backpack weight and manufacturing costs. To support this design effort, OSS developed and tested several different generations of prototype units. Two separate evaluations of the ensemble were performed by the International Union of Operation Engineers (IUOE), one in September 1995 and one in October 1997. The results of these evaluations were used to drive the design.

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1 DOE Decontamination and Decommissioning Focus Area 1996, DOE/EM-0300.

2 Proceedings of the Environmental Technology Through Industry Partnership Conference Vol. 1, DOE/METC-96/1021 Vol. 1, October 1995.

During Phase II, OSS also pursued certifying the AWPS with the applicable government agencies. The initial intent during Phase II was to finalize the design and then to certify the system. However, technical and programmatic difficulties prevented OSS from accomplishing this objective.

This document is the final report for the AWPS contract and describes the activities performed during Phase I and Phase II. The report also describes the current system design, outlines the steps needed to certify the AWPS, discusses the technical and programmatic issues that prevented the system form being certified, and presents conclusions and recommendations based upon the six year effort.

2.0 Overview of AWPS Ensemble

2.1 System Overview

The AWPS consists of three primary components: the backpack, the liquid cooling garment, and the outer protective garment. A simplified schematic of the system is presented in Figure 2.1-1; more detailed schematics of the systems developed during Phase I and Phase II are presented in Sections 4 and 5. Brief descriptions of the components are provided in the following paragraphs and a picture of the AWPS is presented in Figure 2.1-2.

The backpack is a self-contained breathing apparatus that is worn on the back. It consists of a dewar and a bottom box. The dewar is made up of an inner pressure vessel housed inside an outer vessel. The dewar stores breathing air as a cryogenic liquid inside the inner vessel. The space between the two vessels is evacuated to reduce heat transfer from the environment to the inner vessel. This space is also filled with multi-layer insulation to further reduce the heat transfer. Reducing the heat transfer in the dewar extends the backpack's standby time, the time the backpack can rest on the shelf once it has been filled and still provide the rated duration.

A vaporizer is also housed in the dewar vacuum space. The vaporizer exchanges the cooling capacity of the cryogen with water that is circulated through the vaporizer. A pump in the bottom box circulates the water through this heat exchanger and then through the liquid cooling garment, thereby cooling the user.

The cooling provided by the system is self regulating. As the user increases their metabolic rate, their breathing rate and need for cooling also increases. The increase in breathing rate will result in an increased flow of liquid air and therefore an increased amount of cooling.

The dewar is equipped with a patented pivoting pick-up mechanism that can draw out the liquid regardless of the worker's orientation be it standing, crawling, lying on his back or side, or even inverted. The pivoting pick-up mechanism also accommodates a capacitance gauge that measures the amount of liquid air in the dewar. An LED readout of the capacitance gauge signal is visible on the side of the user's facemask.

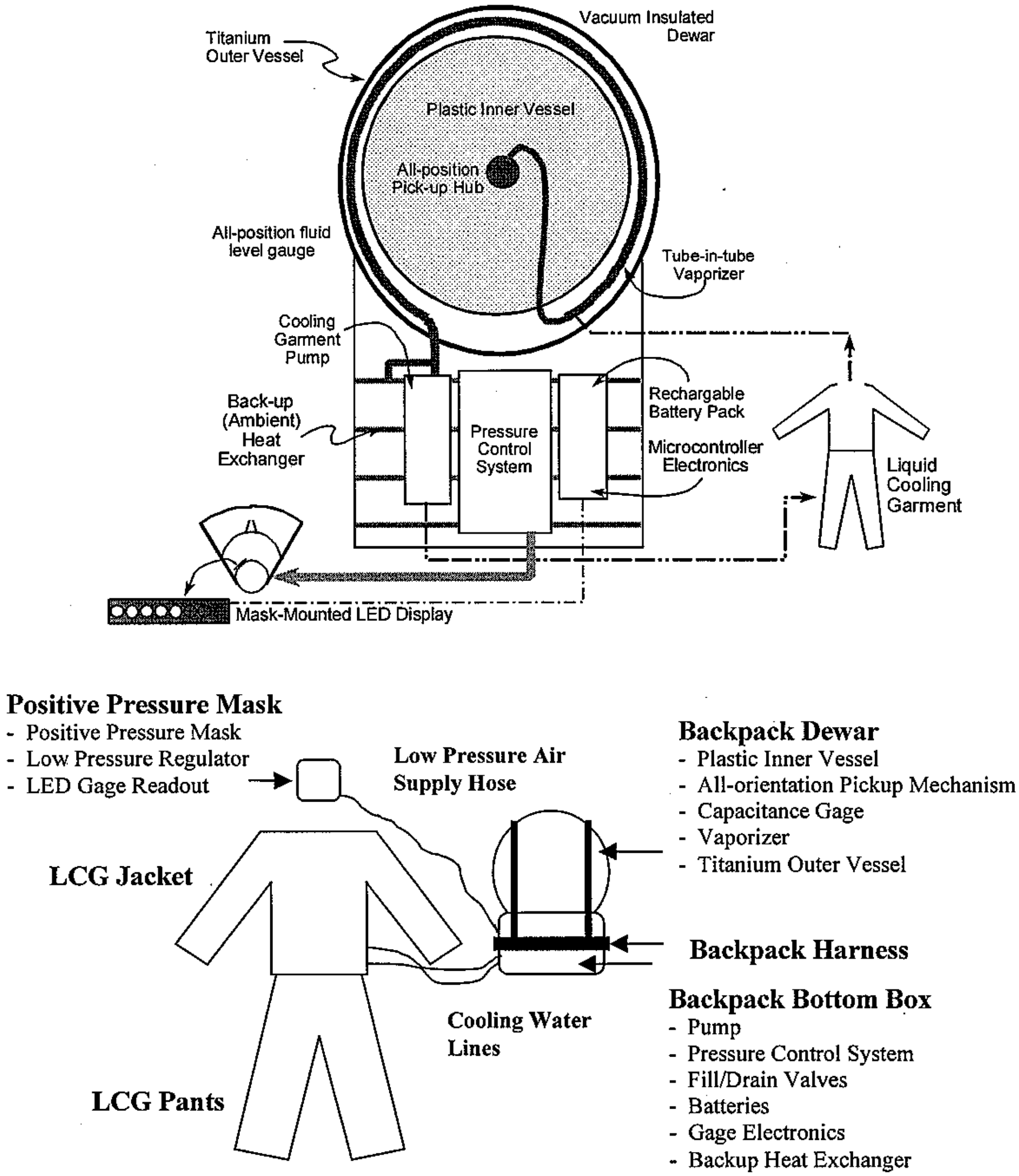


Figure 2.1-1: Simplified AWPS Schematics

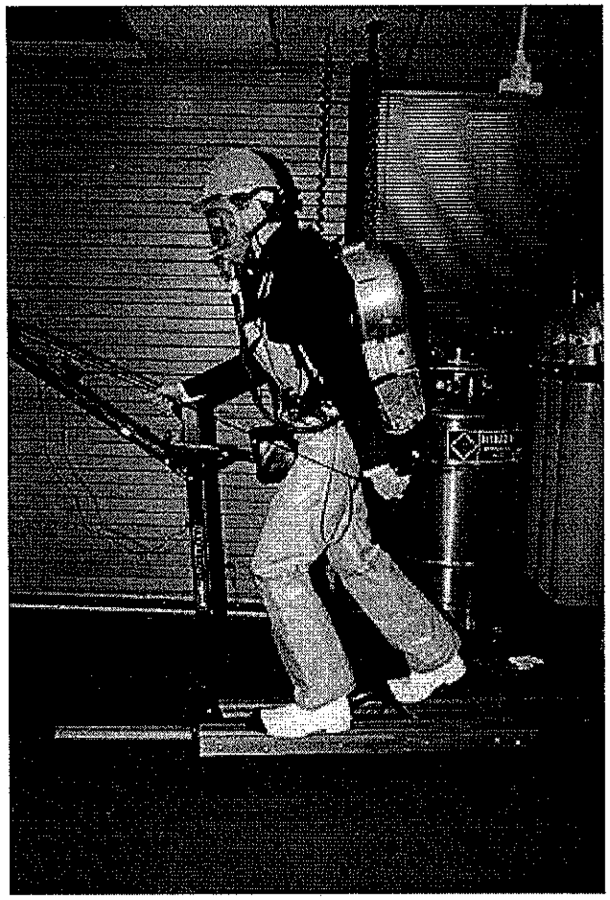


Figure 2.1-2: Prototype AWPS

The bottom box contains shut-off and relief valves to fill, drain, and operate the backpack, and to maintain the internal dewar pressure during operation and storage. The bottom box also houses a secondary heat exchanger to ensure the cryogenic air is warmed to a breathable temperature, a pump to circulate water in the liquid cooling garment, and batteries and electronics to run the pump and the capacitance gauge.

Breathing air is provided to the user, as needed, by a positive pressure facemask developed by Scott Health and Safety Products. The low pressure regulator for the facemask is mounted on the lower front area of the mask and does not interfere with the user's field of view or with the outer protective garment. The air is supplied to the facemask regulator from the dewar bottom box via a flexible line that runs under the user's arm.

The AWPS liquid cooling garment is a two piece garment consisting of a jacket and pair of pants. The garment is made of a stretchy cotton-lycra fabric. The two garment halves each have internal pockets that hold flexible plastic patches. The patches are connected by short pieces of plastic tubing and interface with the backpack via a pair of self-sealing quick disconnects. Cool water flowing from the backpack through the patches keeps the user cool.

The AWPS cooling garment has made major strides in wearability, washability, comfort, and cost by conducting cooling water over the user's muscles through a combination of plastic patches rather than exclusively through tubes. The patches are positioned over the large muscle groups in the body and provide greater surface area for heat transfer than equivalently priced cooling garments that exclusively use tubes. Because the patches are flexible and the interconnecting tubes are located in the proper areas, the LCG allows freedom of movement during vigorous activity. The garment can also be washed because the patches and tubes are protected inside the garment pockets and will not be pulled out in the washing machine.

The outer protective garment is a custom designed, two piece splash suit that provides the requisite splash protection and affords the user with good mobility and visibility. The outer garment fits over and encloses the bottom of the backpack. This design protects the backpack and eliminates the needs for a pass-through for the air hose running from the bottom box to the facemask. The garment conforms to the shape of the pack and thus minimizes folds and bunched material that may trap hazardous materials or snag against structure. The garment also utilizes a glove ring that securely holds the gloves in place but allows them to be easily replaced when needed. An optional caribiner pass-through for use with a lifting or safety harness has also been incorporated into the suit design.

2.2 Evolution of OSS Liquid Air Technology

The key technology for the AWPS, the liquid air backpack, is an evolution of technology developed by OSS for NASA's use in neutral buoyancy simulations of Extra-Vehicular Activities (EVAs). In 1988, NASA identified the need to increase the fidelity of neutral buoyancy simulations by eliminating the umbilical used to provide the astronaut with breathing air and cooling. A backpack with high-pressure oxygen and an additional cooling source was too bulky to fit within the required envelope. OSS, however, designed a semi-closed loop, liquid air system that met the requirements.

OSS' Neutral Buoyancy Portable Life Support System (NBPLSS) pre-prototype was constructed from off-the-shelf parts as a technology demonstrator and was extensively tested in both unmanned and manned configurations in the lab and under water, see Figure 2.2-1. This design was only the third portable life support system to receive a man-rating from NASA, and it accumulated 37 hours of operating time without any life-support system anomalies or failures.

Following the NBPLSS, OSS further developed the technology in 1991 by producing and testing an open-circuit, liquid air backpack. The pack was developed using internal funds and was intended for Self Contained Breathing Apparatus (SCBA) applications where cooling would be of benefit, see Figure 2.2-2. This initial unit was built primarily with off-the-shelf components and instrumentation to gather data needed for future development. In 1992, OSS developed a second-generation liquid air backpack, again using internal funds. The second generation was sized to provide a duration of 2 hours and incorporated a breakthrough dewar design that operated in any orientation and provided gauging of the liquid air remaining in the backpack.

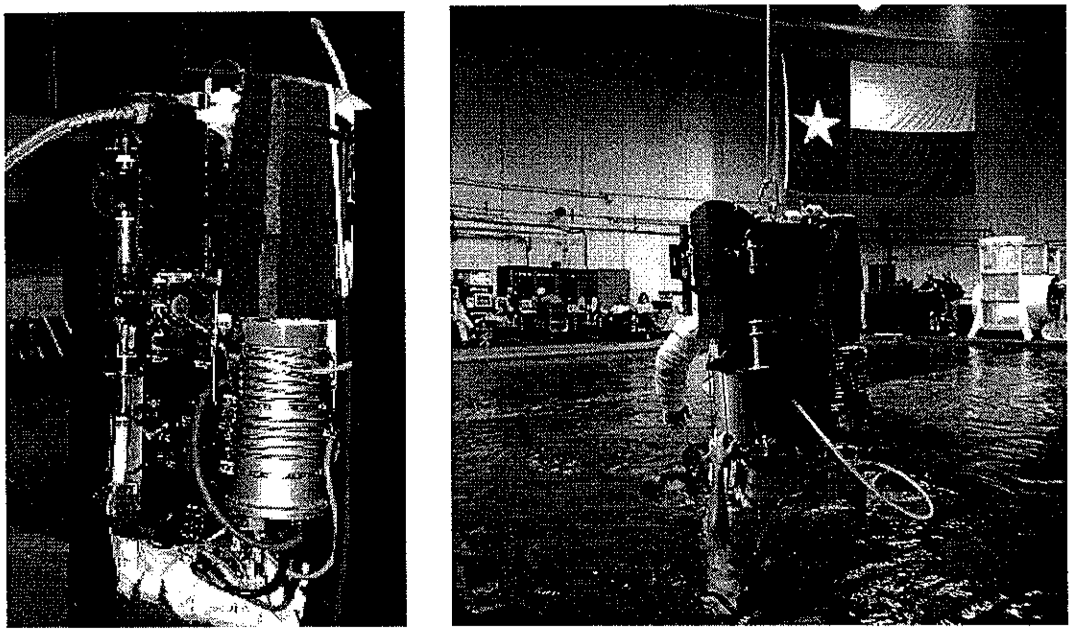


Figure 2.2-1: Neutral Buoyancy Portable Life Support System Developed by OSS

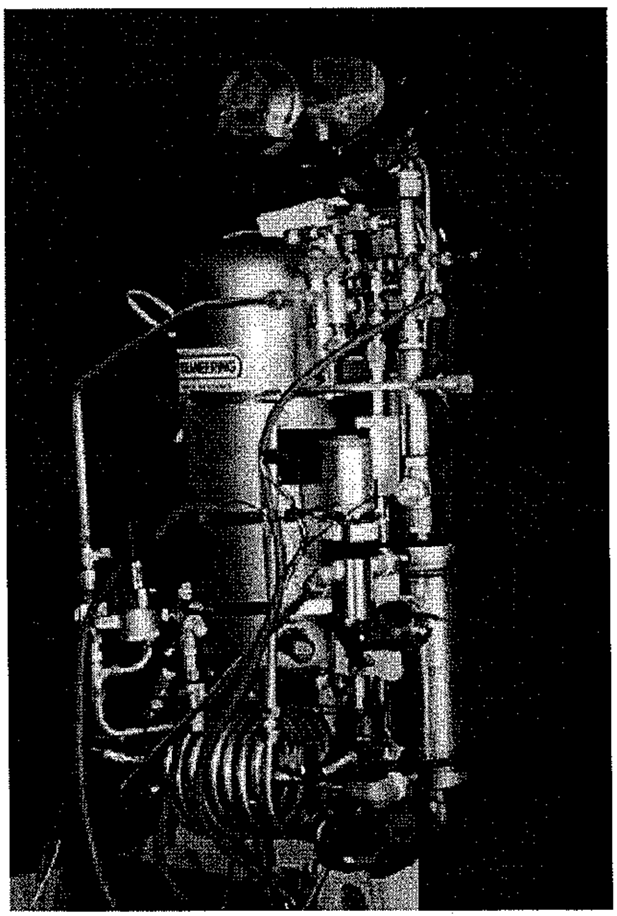


Figure 2.2-2: Prototype Liquid Air Backpack

During this time, OSS supported an Air Force Phase I SBIR awarded to Space Industries Inc. (SII) to study the feasibility of and define requirements for a two-hour duration breathing and cooling system for firefighters. The Air Force wanted to continue with a Phase II award based on the results of the Phase I contract. Unfortunately, Space Industries Inc. was acquired by Calspan and no longer qualified as a small business.

In 1995, OSS was awarded a contract to develop a compact, one-hour duration, liquid air backpack for the Kennedy Space Center (KSC) Fire Department. This unit was to provide only breathing air, with the option of adding cooling later if desired. A prototype unit developed for this contract is presented in Figure 2.2-3. This development effort lasted until September 1999 and paralleled the AWPS effort. Many of the lessons learned from the development of the one-hour unit were applied to the AWPS 2-hour unit and visa versa.

Figure 2.2-3: Prototype 1-Hour LAP

2.3 OSS Patents

Oceaneering Space Systems has applied for and received several patents which cover the systems and technology used in the AWPS. Patent #5,361,591 covers a cryogen breathing apparatus of a subcritical (liquid) nature with an orientation independent dewar (that is, a dewar that operates in any orientation with respect to gravity) combined with a cooling garment. The patent covers use in all applications except under water. Patent rights for an underwater system are shared with NASA and are covered under Patent #5,365,745. A portable life support system for use in space is explicitly included under this patent. The cryogen can be anything related to life support, either air or oxygen. At the time of this writing, OSS is seeking a reissue of this same patent to cover the unit without the cooling garment.

OSS holds additional patents for the dewar technology and design. Patent # 5,438,837 covers an orientation independent dewar with a capacitance gauge. A Continuation in Part covers the dewar without the capacitance gauge as part of the invention, but the gauge, as well as other key innovations, are included as a dependent claims. The cryogen again can be either air or oxygen.

The final patent covers the design of the liquid cooling garment. This patent has been allowed but no patent number assigned as of yet.

3.0 AWPS Goals and Requirements

One of the initial tasks undertaken in the project was to establish requirements and goals for the AWPS. These were established by reviewing regulatory requirements, collecting information from the DOE, and reviewing the limitations of current PPE. This section provides an overview of these goals and requirements that drove the AWPS design.

3.1 Potential Decontamination and Decommissioning Hazards

DOE D&D workers face a multitude of hazards at each of the sites. These hazards include radiological and/or chemical contamination; physical damage such as punctures, cuts, tears, and abrasions; and thermal stress, either heat or cold-related exposures.

Contamination hazards exist at different levels of severity. Based on information gathered during three visits to DOE sites, the principal contamination hazard to DOE workers is contact with radionuclides or other radioactive contaminants, principally particles. In addition, several sites also involve mixed wastes primarily metals, anions, chlorinated hydrocarbons, fuel hydrocarbons, ketones, phthlates, PCB's, explosives, pesticides, alkyl phosphates, complexing agents, and organic acids. While most of the time these contaminants are encountered at relatively low concentrations, some substances have extreme toxic effects at these levels. Much of this contamination is found in specific areas at each site, particularly storage tanks, and former processing facilities.

The nature of D&D work produces severe physical hazards to DOE workers. Much of the dismantling of structures and removal of waste involves different forms of heavy machinery. Therefore, worker PPE and other equipment must protect workers from the excessive vibration, sharp edges, and rough surfaces found in these environments.

DOE D&D will be undertaken in a variety of environmental conditions with a wide range of temperature and relative humidity. The high work loads required for many operations will produce large metabolic energy consumption causing workers to overheat even in low temperature, low humidity conditions. Most protective clothing and equipment by its very nature contributes to worker heat stress. Thus, it is important that clothing ensembles used at

DOE sites be designed to minimize the impact of heat stress. In addition, worker mobility must not be impaired as this also increases heat stress and overall energy expenditures.

3.2 Deficiencies/Inadequacies of Existing Systems

Systems now used in hazardous materials applications have many deficiencies. A Self Contained Breathing Apparatus (SCBA) does not provide sufficient duration for efficient and cost effective hazardous materials operations and does not supply cooling to the subject. Supplied Air Respirators (SAR) have an indefinite duration, but do not supply cooling. They also limit wearer mobility due to the tethered breathing line required for these systems.

When in a fully encapsulating or splash suit, without cooling the wearer is not capable of working safely or comfortably for more than 45 minutes even in a relatively cold environment. The worker typically requires a minimum of an hour rest to cool down after each 45 minute work period. In many environments this work period is reduced to twenty minutes.

Some users are employing either air supplied cooling vest or ice based cooling systems to prevent over heating and extend the work duration. Unfortunately, an air cooling system has draw backs in that it consumes large quantities of compressed air thereby requiring an umbilical, and tends to be uncomfortable because of the tremendous air flow into the suit. The ice based cooling systems also have drawbacks. For example, ice vests, one of the most common ice based systems, provide no means for controlling the amount of cooling provided and typically provide too much cooling initially. The Personnel Ice Cooling Systems (PICS), currently being evaluated by the DOE, eliminates this drawback by providing a means for controlling the amount of cooling provided to the user. However, the PICS is a separate system that must be carried by the worker, in addition their SCBA, thereby increasing the total weight burdening the worker.

Many outer protective garments worn today also have limitations. They are either uncomfortable and bulky, or they are too expensive for large scale operations. Fully encapsulating suits rarely fit the wearer correctly, creating a more stressful and inefficient work environment. A more form fitting suit that is also less expensive would be more efficient to use in operations the size of DOE D&D work.

In addition, very little of the protective clothing in use today provides effective interfaces with other clothing or equipment. End users must use duct tape to seal gloves and boots to garments and to ensure that hoods stay over respirators. This practice defeats the purpose of wearing protective clothing constructed of barrier materials since particulates, liquid, and other contamination can easily penetrate these poorly constructed interfaces. Duct taping is also a time consuming, often two person, operation.

3.3 AWPS Goals

Based upon a review of the DOE needs and limitations of current PPE, the following four goals for the AWPS were established early during Phase I:

1. Provide a high level of respiratory protection consistent with DOE site hazards combined with a cooling garment (to eliminate heat stress and provide for increased worker comfort, productivity, and safety) and protective clothing against both physical and contamination hazards;

2. Integrate all clothing and equipment items such that they fit together, provide complete protection to the wearer, and allow ease of donning/doffing, decontamination, and maintenance;

3. Replace several existing protective clothing and equipment systems with two different systems which can be configured in several fashions to accommodate a wide range of operations while minimizing procurement needs, system maintenance, and training; and

4. Improve cost efficiency of D&D operations.

3.4 AWPS Requirements

The design, certification, fabrication and use of PPE is governed by a variety of government requirements and regulations. One of the key agencies that establish these requirements is the U.S. Occupational Safety and Health Administration (OSHA). OSHA has outlined the responsibilities of employers engaged in hazardous waste operations or emergency response in 29 CFR 1910.120. These regulations include clean-up operations involving hazardous substances that are conducted at hazardous waste sites as required by a Federal government body. Requirements relating to selection of personal protective equipment are covered in paragraph (g) (3) of this document. These rather general requirements specify that:

- Selected PPE must adequately protect employees from actual and potential hazards as identified in site characterization and analysis.

- PPE selection must be based on performance factors characteristic of the site, task specific conditions, task length, and actual/potential hazards.

- Positive pressure SCBA or air-line respirators equipped with escape SCBA must be used when chemical exposure levels create a substantial possibility of immediate death or serious injury.

- Totally encapsulating protective suits must be used when death or serious injury from skin absorption is a potential hazard.

- The level of protection provided by the PPE must be increased when additional information is gained to show additional hazards to employees. Appendix B of 29 CFR 1910.120 describes the EPA's Levels of Protection. Levels A through D are appropriate for hazardous waste site clean-up. The level of protection chosen must reflect both the actual and potential hazards of the site.

- PPE must meet the requirements of 29 CFR Part 1910, Subpart I. This requirement essentially indicates that the protection offered by the clothing and equipment must be commensurate with the actual or potential hazards that may be encountered.

- Totally encapsulating protective suits must pass a pressure test or prevent inward leakage using the procedures specified in Appendix A of the regulation. The pressure test is equivalent to ASTM F 1052, Standard Practices for Pressure Testing of Totally Encapsulating Chemical Protective Suits.

In addition to these general requirements governing the use of PPE, the equipment must meet other specific federal regulatory requirements. Individual requirements have been established for the respirator, storage vessel, protective suits, helmet, and support equipment. These requirements specify not only the performance requirements for the equipment, but also the requirements for the certification testing.

Regulatory requirements for the AWPS include specific requirements for the liquid air backpack, pressure vessel, the cooling and protective suits, and the recharge station. EPA regulations will also govern the amount of secondary waste, and the impact of the system as a whole on the environment. These requirements and regulations are reviewed in the following sections.

3.4.1 Liquid Air Backpack Requirements

The AWPS liquid air backpack is a Self-Contained Breathing Apparatus, a respirator, to be used in Immediately Dangerous to Life and Health (IDLH) atmospheres. These units must be designed to meet criteria established by the National Institute for Occupational Safety and Health (NIOSH) of OSHA. The requirements are specified in 42 CFR Part 84.

An initial review of these requirements was conducted during Phase I of the contract and was used to establish the AWPS performance objectives outlined in the first Phase I Topical Report. Another review of these requirements was conducted during Phase II of the contract to incorporate changes that were made in the requirements during this time.

The primary NIOSH requirements that drive the design of the liquid air backpack are summarized below. Satisfying these requirements posed much larger challenges than meeting those for the protective garments and other support equipment, and so was the primary focus of the development effort.

- The respirator must maintain a positive pressure within the facemask during operation. This prevents any contaminated gases from entering the mask and being inhaled by the user.

- The respirator must supply breathing gas in any orientation including, prone, supine, and inverted. This is not a concern with compressed air systems. However, the APWS liquid air backpack functions properly only when the intake is submerged in the liquid air. Consequently this requirement was a major design consideration in the development of the backpack.

- High air flow rates, at least 200 liters/minute, must be delivered to the user in emergency situations, such as when their mask becomes partially dislodged. This purge flow ensures any potential hazardous gases are flushed out of the mask and not breathed by the user. Typically, an SCBA is equipped with a by-pass switch mounted on the regulator to provide this free flow rate.

- The respirator must weigh no more than 35 pounds, including consumables, unless at least 25% of its weight is consumed in operation, or if it provides cooling as part of its function. In either of the later cases, the weight limitation is 40 pounds. Since the AWPS backpack will use 35% of its weight in operation and provide cooling, the 40 pound standard applies. This requirement turned out be a much bigger design driver than initially thought.

- The respirator must be rated to a standard duration. The NIOSH standard breathing rate of 40 standard liters per minute is used to establish the rated duration of the unit. The AWPS backpack will be rated for a 2 hour duration.

- The respirator must provide adequate breathing gas as a test subject performs a series of physical tasks that increase the demand above the standard breathing rate.

- The air provided by the respirator must have an oxygen content between 19.5% and 23.5%. This is not a critical issue with compressed air systems. However, in a liquid air system, the oxygen percentage of the liquid phase will increase during storage as the liquid nitrogen boils at a slightly faster rate than the liquid oxygen. This requirement impacts the design of the backpack insulation and the recharge station.

- The respirator must be equipped with a gauge showing the amount of air in the tank, and must also sound an audible alarm when the quantity of breathing gas remaining is between 20 and 25%. This requirement holds true for any orientation.

If the SCBA uses a vessel that holds a pressure above 24.8 psia, NIOSH requires that a certification for the pressure vessel be obtained from the Department of Transportation (DOT). If the proposed pressure vessel does not fit into any of the DOT standard classes, an exemption can be requested. In the exemption, the company must present a plan to ensure the exempt vessel provides the equivalent level of safety as similarly related DOT standard vessels.

A third, commercial agency, the National Firefighters Protective Association (NFPA) also levies requirements on gear to be used by emergency workers. Although NFPA approval is not statutory and is not required by the Department of Energy, it is accepted by the SCBA community as a standard for use in extreme conditions. NFPA approval attests that equipment will function normally despite the following conditions:

- A maximum demand for air of 103 liter per minute.

- Severe vibration.
- Exposure to a –25 °F environment for 12 hours.
- Exposure to a 160 °F environment for 12 hours.
- Exposure to a 203 °F environment for 15 minutes, followed by a direct exposure to flame for 10 seconds. It is understood that the unit may be irreparably damaged as a result of this exposure, however it must continue to function during and immediately following the test.
- Use in a corrosive, salt-spray environment.
- Exposure to sand and dust.

Besides these requirements imposed by regulatory agencies, OSS levied additional requirements of the backpack to meet the needs of the commercial SCBA market. These additional requirements constrained the design of the backpack so that it will:

- Have a low profile and fit comfortably on the users back.
- Evenly distribute weight to the wearer's back and hips and not ride up on the wearer's back while bending.
- Function with an OSS-designed liquid cooling garment.
- Provide breathing gas at a comfortable temperature without the cooling function.
- Require minimum maintenance and be logistically supportable from existing commercial resources.
- Be easily donned, used, decontaminated, refilled, and maintained.
- Boil off not more than a pound of cryogen over a sixteen-hour period, and have a full rated duration at normal work rates after 8 hours of boil-off.
- Be competitively priced for a commercial market that includes fire fighters, hazardous material workers, and industrial workers.

The complete set of requirements was compiled into a requirement matrix that specifies each requirement, its source, the test method to verify the requirement, and any comments on the requirement. A copy of the matrix is presented in Appendix A.

3.4.2 Protective Garment Requirements

Protective clothing used for worker protection during hazardous waste management and handling activities (such as site characterization, removal actions, redemption, decontamination, and decommissioning) should effectively isolate the worker from substances harmful by skin contact. Specific design requirements include:

- Selection of materials which adequately prevent the penetration or permeation, as appropriate, of hazardous substances at DOE sites (primarily metals, anions, radionuclides, chlorinated hydrocarbons, fuel hydrocarbons, ketones, pthtlates, PCB's, explosives, pesticides, alkyl phosphates, complexing agents, and organic acids);

- Selection of materials which combine durability and physical hazard resistance with light weight, flexibility, breathability, and related comfort properties;

- Use of seaming technologies and clothing interfaces (such as closures, sleeve to glove attachments, pant cuff to boot attachments, and hood to respirator attachments) which offer garment integrity consistent with either liquid or vapor hazards, as needed;

- Design of garments which accommodate other clothing items or equipment to be worn for additional protection;

- Design of garments which provide a minimum impact on worker comfort, mobility, and functionality to complete assigned tasks;

- Sizing of garments to provide a good fit for the majority of the worker population;

- Design of garments to affect ease of donning, doffing, and decontamination; and

- Garment labeling to clearly identify the use and warnings appropriate to the protective clothing item.

In addition to these requirements, the Respiratory Advisory Committee (RAC) and the Department of Energy require that all Level A and B suits used in Hazardous Materials operations at DOE facilities are to be evaluated for construction and performance in several areas. Testing is conducted by the Industrial Hygiene Group, Research and Development Section of the Health and Safety Division at Los Alamos National Laboratory. The evaluation is completed according to the Los Alamos document LA-10156-MS Acceptance-Testing Procedures for Air-Line Supplied-Air Suits. Testing areas include:

1. Fit Factor Testing. This testing involves the measurement of inward leakage of contaminants during both standards exercises and simulated work tasks.

2. Inducement of Heat Stress. This test examines physiological changes in the user while wearing the protective suit.

3. Temperature. The effects of temperature variations on the performance of the suit and the level of protection provided are assessed.

4. Aging. Suit deterioration is investigated as related to storage and reuse.

5. Communications and Manipulation Tests. These tests include reading, writing, dexterity, and performance of a cylinder repair operation to evaluate how the suit impacts basic worker functions.

6. Noise Generation. The level of noise generated inside the suit is measured.

7. Air-Supplied Hose Performance. Air-supplied hoses, provided with some protective suits, are evaluated for: (a) the strength of the connection to the suit covering, (b) crush resistance, (c) non-kinkability, and (d) strength of hose and couplings by means of rapid pulling test.

Los Alamos National Laboratory also evaluates any other areas of the protective clothing found to be deficient during the above testing. Results from this testing are forwarded to the DOE RAC for review. This group also sets a schedule for future periodic testing of the suit.

Requests for this testing are made using special request form (EH-412) to be forwarded to the DOE Industrial Hygiene Programs Division. The form must be accompanied by a statement regarding the need for the suit, Standard Operating Procedures entailing donning, doffing, decontamination, storage, and reuse protocols, and a statement describing the conditions under which the suit is to be used.

Coveralls and similar garments used in PPE should also be designed to meet ANSI/ISEA 101-1993, Size and Labeling Requirements for Limited-Use and Disposable Coveralls. This standard sets minimum dimensions for key size-related areas of coverall and coverall-like garments. It also addressed coverall labeling and packaging.

While not mandatory, Appendix B of 29 CFR 1910.120 recommends that protective suits meet one of the following standards depending on the suit application. These standards were referenced during the design of the AWPS protective garments.

- NFPA 1991, Standard on Vapor-Protective Suits for Hazardous Chemical Emergencies;

- NFPA 1992, Standard on Liquid Splash-Protective Suits for Hazardous Chemical Emergencies; and

- NFPA 1993, Standard on Support Function Protective Garments for Hazardous Chemical Operations.

At the time 29 CFR 1910.120 was promulgated, these standards were still being developed. Each of these standards have since then been adopted in 1990. Revisions to the standards were made in 1994. Table 3-1 provides the equivalent EPA levels of protection for these standards.

Table 3-1: Protective Suit Types and Characteristics

Suit Design Type	EPA Level	Suit Integrity	Material Performance
Encapsulating suit with AWPS backpack worn internally, attached or detachable gloves and boots (NFPA 1991 compliant)	A	Gas-tight	Resists permeation to chemicals with hazardous vapors
One or two piece 'splash' suit with PLSS worn either internally or externally, integrated with separate gloves and boots (NFPA 1992 or 1993 compliant)	B or C	Liquid-tight	Resists penetration to chemicals which are hazardous as liquids

4.0 Phase I

4.1 Overview

During Phase I, OSS developed and tested a full-scale prototype advanced worker protection ensemble. The prototype ensemble included a liquid air backpack, a cooling garment, and a protective garment. Sub-scale support equipment for the AWPS, such as a recharge station, was also developed during Phase I.

Initially during Phase I, OSS reviewed the requirements and established objectives for the AWPS. The objectives were developed in part from feedback gathered during visits to three DOE remediation sites. Based upon these objectives and requirements, OSS developed general test protocols to be used during the full-scale development during Phase II.

The input gathered during the DOE visits was also used to perform a life cycle cost/benefit analysis. This analysis indicated that the AWPS will provide significant cost benefits to the HazMat industry. The sensitivity analysis performed on the life cycle cost analysis showed cost benefits even with the least favorable assumptions.

Both the requirements/objectives and the life cycle cost analysis were documented in a topical report. The report entitled " Performance/Design Criteria Review Topical Report" was released in March of 1994.

Following the review of the requirements, OSS began developing the prototype ensemble. To support the ensemble design and later testing of the system, OSS performed a Failure Modes and Effects Analysis (FMEA) to identify potential problems with the design and to ensure the system would be safe for manned testing. In-house testing was also performed on various components and subsystems. This testing was intended to evaluate component and subsystem performance, and to test the functionality of various design concepts. The data collected during this engineering evaluation phase was used to update the design.

Once the prototype ensemble was completed, it was tested at OSS in a series of manned tests. This testing was intended to verify the system operation and functionality of user interfaces, and to work out logistics and procedures for filling and operating the system.

Following the in-house manned testing at OSS, the system was successfully tested and evaluated at Kansas State University (KSU). This independent evaluation verified the AWPS' positive effect on user safety, health, and productivity. The test subjects were able to work for twice as long using the prototype AWPS compared to a standard SCBA. The testing also provided important design information on system operation in a variety of environments that was used to drive the design during Phase II.

4.2 Phase I Ensemble Development

The functional schematic for the liquid air backpack developed in Phase I is shown in Figure 4.2-1. The key to this system is a dewar that can operate in all positions. OSS began Phase I working on the design of an all position dewar that utilized a plastic, Liquid Crystal Polymer (LCP), inner vessel housed inside a metal outer vessel.

4.2.1 Liquid Air Backpack

An LCP vessel offers several advantages over a metal vessel. The primary advantage is that an LCP vessel can be easily injection molded to form the complex shape needed for the dewar's pickup mechanism. Such a manufacturing process would also be inexpensive when producing a large quantity of vessels. It was also believed that a low thermally conductive plastic vessel would reduce heat leak in the dewar.

OSS conducted an extensive study to identify the best plastic candidates. LCP was selected over other plastic because of its low permeability, its high strength to weight ratio, good cryogenic properties, low coefficient of thermal expansion, and because it is not toxic.

However, there are a host of design issues associated with a plastic, cryogenic pressure vessel. These included 1) long term vacuum performance of the vessel, 2) tube connections, 3) sealing the vessel once it has been assembled, 4) burst pressure, 5) vessel weight, and 6) long term structural performance of the vessel. During Phase I, OSS attempted to resolve as many of these issues as possible.

OSS first tested LCP samples and various epoxies to ensure a glued LCP vessel can maintain the dewar vacuum. LCP has a very low permeability rate when compared to other plastics but not when compared to metals. Consequently, we were concerned the LCP would allow gases to diffuse into the annulus space between the inner and outer vessels and degrade the vacuum. Degradation of the vacuum can significantly increase heat transfer to the inner vessel. An increase in this heat leak will reduce the backpack's storage time, an important parameter for a commercial liquid air backpack.

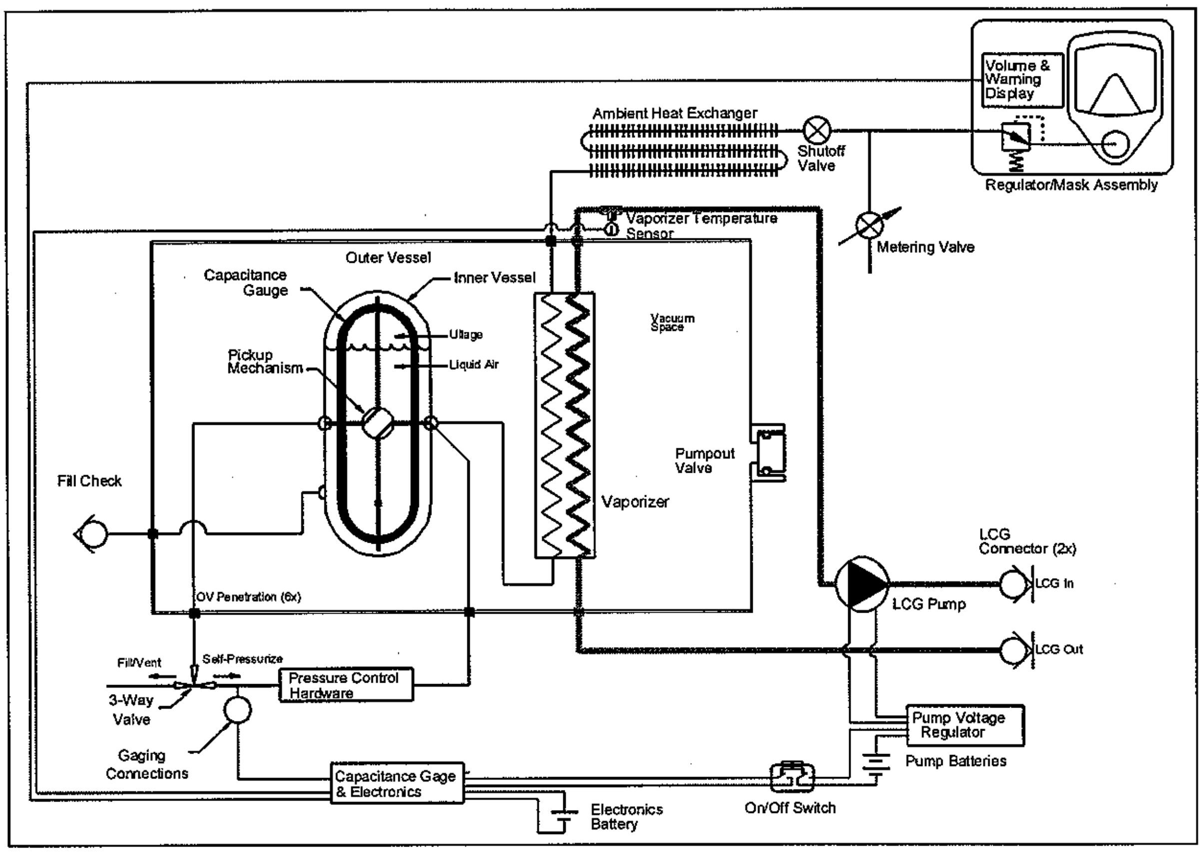


Figure 4.2-1: Phase I Backpack Schematic

OSS measured the helium leak rates of a variety of LCP samples. These samples included plain LCP disks, LCP disks with sealed aluminum tubes glued into them, and LCP disks with glue joints in them. The leak rates measured were very low, 1×10^{-9} cc/sec range. We estimated that a two-hour inner vessel with this leak rate could hold an acceptable vacuum for well over a year.

Following the material testing, we began to develop finite element models of the inner vessel. Finite Element Analysis (FEA) was used to develop a ribbed vessel design that provided the needed factors of safety. Once the design was completed, OSS subcontracted the fabrication of a mold for the inner vessel halves; the inner vessel halves are to be glued together at their perimeter during assembly. A picture of the vessel design is presented in Figure 4.2-2.

Once the molds were completed, twenty LCP vessels were molded. Several vessels were glued together and pressurized to failure in a series of hydrostatic and cryogenic burst tests. The vessels were bursting at less than 130 psig, only slightly more than twice the expected operating pressure of 60 psig. The vessels were designed to burst at 300 psig.

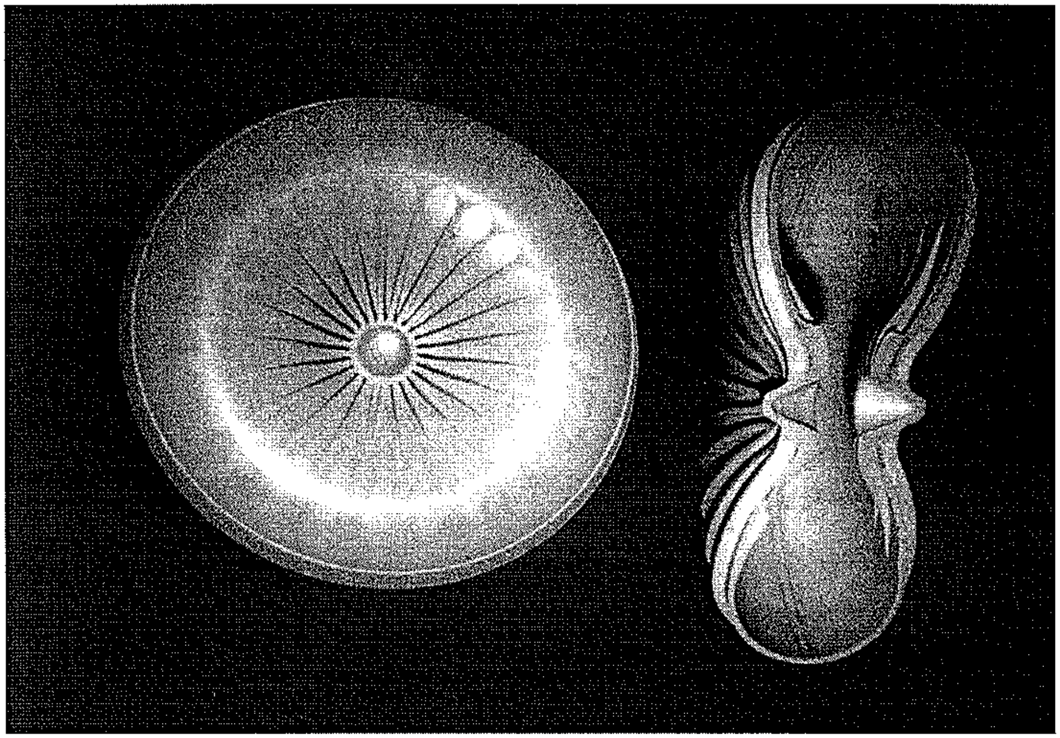


Figure 4.2-2: Initial Inner Vessel Design

It was thought that the low burst pressure was due in part to warping of the vessel edges. This warping may have significantly reduced the strength of the perimeter glue joint and caused the vessel to burst at a much lower pressure than expected. The molder felt confident the warping could be eliminated with minor modifications to the mold. However, the modifications could not be completed and new vessels molded by the end of Phase I.

Since the plastic inner vessel would not be ready to support the independent evaluation at KSU, OSS decided to develop a metal inner vessel. The metal inner vessel was first analyzed using a finite element model. The exterior of the vessel was to be smooth, have no ribs. As a result, the vessel was axi-symmetric, which greatly simplified the finite element analysis.

The inner vessel design was completed and two vessel halves were machined from 6061 aluminum. When welded together, the vessel had the same interior shape as the LCP vessel. It was sized to hold approximately 14 pounds of liquid air, the amount needed to provide a NIOSH duration of 2 hours.

In a parallel effort with the analysis, design, and molding of the inner vessel prototypes, OSS worked on the design of the pickup mechanism, the capacitance gauge, the suspension system, and the outer vessel. Pictures of these initial designs are presented in Figures 4.2-3a and 4.2-3b.

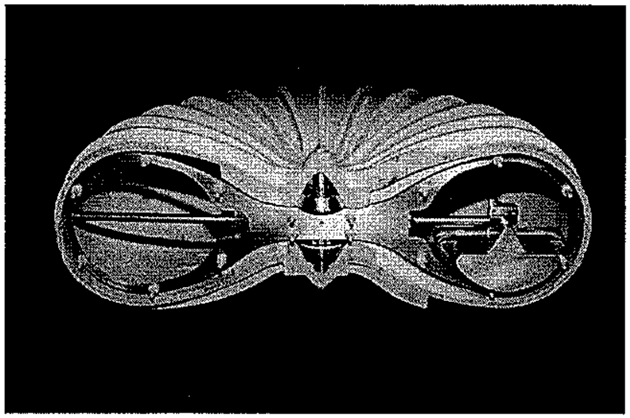


Figure 4.2-3a: Phase I Prototype Inner Vessel Design

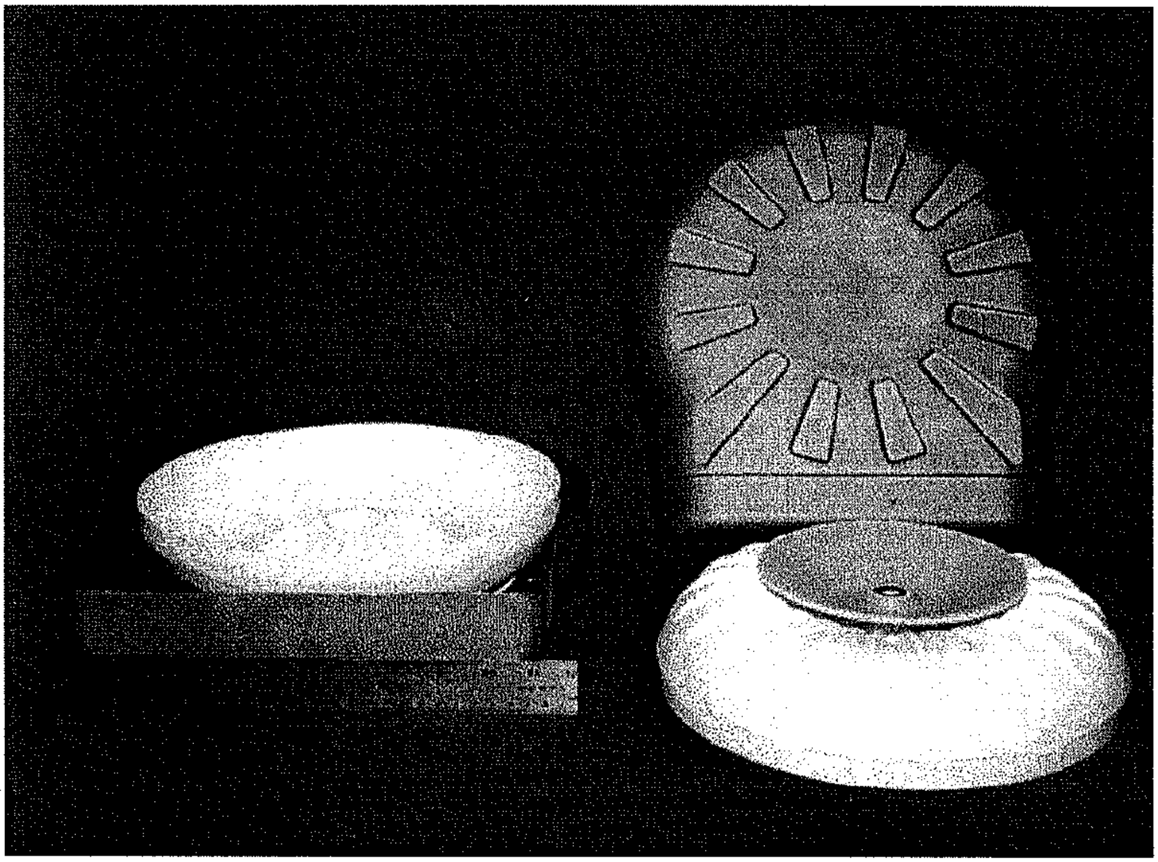


Figure 4.2-3b: Initial Vessel and Suspension System Designs

In this design, the inner vessel pickup mechanism maintains the vent line in the ullage space above the liquid and a liquid inlet at the lowest point of the inner vessel in all orientations. Liquid that is withdrawn from the pickup mechanism goes through the Liquid Hub and Liquid Line into the Vaporizer, a tube-in-tube heat exchanger.

The pickup mechanism design used three dynamic seals. Two of the seals allowed the mechanism to rotate about the vessel's axis of symmetry, and the third seal allowed the "taco-shaped" piece on the end of the liquid inlet to rotate and access all of the liquid in the inner vessel, regardless of orientation. During the development of the design shown in Figure 4.2-3b, OSS tested the reliability and friction of different seal designs and materials. These seals must have extremely low friction. If not, the pickup mechanism may stick and allow the liquid inlet tube to be exposed to the ullage gas. If this happens during operation, the dewar pressure would drop quickly and the system may no longer maintain a positive pressure in the facemask or not provide sufficient air to the user.

After testing several seals, a final design was detailed and a pickup mechanism developed for the metal inner vessel.

The capacitance gauge was developed to interface with the pickup mechanism. The gauge consists of two parallel, metal plates separated by thin nylon washers and bolted together with nylon bolts and nuts. The plates rotate with the pickup mechanism and provide a fairly constant capacitance reading for a given fill level regardless of orientation. The shape of the gauge plates was developed using extensive CAD modeling and analysis.

The gauge plates were fabricated, assembled, and successfully tested in a breadboard fixture. The plates were finally integrated into the metal inner vessel during assembly. Once the dewar was completely assembled, the system was tested in various orientations. The capacitance gauge provided accurate readings in all orientations.

The suspension system developed during Phase I consisted of two cones, as indicated in Figure 4.2-3c. The bases of the cones fit inside dimples in the outer vessel and the tops of the cones fit around the center of the inner vessel hubs.

The cones fabricated for the prototype backpack to be used in the KSU evaluation were made from fiberglass and epoxy. A mold was made and the cones were hand laid on the mold.

During the design of the suspension system, OSS performed load testing of prototype cones to ensure they could withstand the loads generated by the inner vessel internal pressure and the outer vessel vacuum loads. OSS also performed vacuum compatibility tests to ensure the fiberglass and epoxy would not off gas enough to significantly degrade the dewar's vacuum. These tests indicated the materials were acceptable.

The remaining primary dewar component worked on during Phase I is the outer vessel. OSS initially wanted to use titanium for the metal outer vessel. The vessel must carry vacuum loads without buckling and so must be extremely stiff. As a result, titanium is an ideal material.

Unfortunately OSS could not find a cost effective methods for fabrication a titanium outer vessel or a reliable method for sealing the tubes running from the inner vessel out of the outer vessel. Initially we tried to use o-rings that sealed on the tube's outer surface. These seal however leaked when the tubes were cooled to cryogenic temperatures.

As a result, OSS decided to develop an aluminum outer vessel. The outer vessel was added to the finite element models built for the inner vessel and the suspensions. This combined model was used to analyze stresses and deflection in the outer vessel. A detailed outer vessel was developed using the FEA results. Two outer vessel halves were then machined out of 5054 aluminum. Flanges were added to vessel halves to allow them to be easily assembled and disassembled.

Aluminum brackets were welded to the outer vessel to interface with a harness and the bottom box. A commercially available pump out port was also welded to the side of one of the vessel halves. This port was used to evacuate the dewar. A valve operator allows the plug inside the port to be removed and the dewar evacuated. When the dewar is evacuated the plug is replaced to seal the outer vessel. The plug relies on two circumferential o-ring seals to prevent gas from leaking in through the pump out port. The port can also act like a relief device the outer vessel from over pressurizing in the event the inner vessel leaks into the vacuum space. Any pressure in the vacuum space substantially higher than ambient will blow the plug out of the port and vent the high pressure.

The tubes running from the inner vessel to the outer vessel, including the vaporizer, were made from aluminum and were welded to both the inner and outer vessels. The vaporizer was also made from aluminum. The vaporizer is a tube-in-tube heat exchanger that warms the liquid air to a breathable temperature and in the process chills the LCG water. The vaporizer is located in the dewar's vacuum space to reduce heat transfer from the environment to the liquid air flowing through it.

During Phase I, OSS tested various vaporizer designs in a small vacuum chamber to evaluate their performance. The data obtained was also used to size the vaporizer.

OSS also developed the components needed to complete the backpack. Brief descriptions of these components are provided in the following paragraphs.

LCG Pump ad Vaporizer: The LCG Pump drives the water through the Vaporizer and the Liquid Cooling Garment. The pump is a positive displacement gear pump driven by a DC motor. The pump head and gears are made from plastic to minimize the pump's weight. A spring energized Teflon shaft seal is used to seal the motor shaft as it enters the pump head. The Vaporizer is specially designed to protect it from damage that could occur when the water freezes, and for forced de-icing of the vaporizer so that the AWPS can be put back into service quickly if a freeze occurs.

Ambient Heat Exchanger: If, due to a LCG Pump failure, the Vaporizer water stops flowing, the liquid air flowing through heat exchanger would freeze the water. As a result, the air exiting the Vaporizer would get progressively colder. The Ambient Heat Exchanger (AHX) is located outside of the dewar and is connected to the Vaporizer outlet. The AHX ensures the air exiting the Vaporizer is warmed to a breathable temperature prior to delivery to the user. It consists of a length of finned tubing and relies of natural convection with the ambient air to warm the air to a breathable temperature.

Pressure Control System Components: As liquid is drawn from the dewar, the pressure would normally drop. Therefore, a method known as self-pressurization is used to maintain the system pressure. In addition to the Liquid Line from the Liquid Hub, there is also a small Self-Pressurization Line. Cryogen is withdrawn from the dewar and vaporized below the liquid level in the vessel. This gas is at a pressure differential higher than the pressure in the vessel equal to the hydrostatic head between the two levels. This gas flows to the Pressure Closing Valve (PCV). The PCV remains closed until the pressure in the dewar drops below the operating point. When this happens, the PCV opens, allowing the higher pressure self-pressurization gas to flow into the dewar through the Vent Hub.

In the line between the PCV and the Vent Hub is a Relief Valve and a Burst Disc. The Relief Valve vents excess pressure due to cryogen boil off. This is most likely to occur when the backpack has been filled with liquid air and set on the shelf. Heat leak into the inner vessel will cause the liquid air to boil and the pressure in the inner vessel to rise. If the Relief Valve were not present, the pressure would eventually climb high enough to rupture the inner vessel.

The use and sizing of relief valves was a particular concern with this dewar. The all aluminum construction of the Phase I prototype resulted in a relatively large heat leak rate, compared the materials used in the Phase II backpack. The Burst Disc provides redundant pressure relief in the event of a relief valve failure.

Valves: A Shutoff Valve after the AHX is used to control the flow to the Face Mask/Regulator and Metering Valve, turning the system on and off. An Interspiro Face Mask/Regulator was used for the Phase I AWPS because its ability to operate at the 60 psig inlet pressure, the operating pressure of the inner vessel.

The Metering Valve is used to control the cooling rate by adjusting the cryogen flow through the Vaporizer. Higher breathing flow rates result in larger cryogen flows and therefore more heat exchange with the LCG water. The user's breathing rate will be a function of the work rate and the cooling level will track the work rate. However, additional cooling may be desired. The Metering Valve allows the user to increase cryogen flow through the Vaporizer and therefore his/her cooling rate.

The 3-Way Valve also in that section of tubing has two positions. In one, it routes the self-pressurization gas to the ullage. In the other, it is used to vent the dewar as it is filled. The AAPD is filled through a cryogen compatible Fill Check Valve to a separate port in the side of the Inner Vessel.

Sensors and Electronics Board: Several sensors were packaged in the dewar to monitor system performance. A pair of pressure switches monitored the system pressure and indicated if it rose too high or dropped too low. A temperature sensor was located in the LCG loop after the vaporizer to monitor the outlet water temperature. If the outlet water temperature drops too low, the vaporizer is in danger of freezing.

These sensors, the pump, and the capacitance were all interfaced with a custom electronics board developed by OSS during Phase I. The electronics board was housed in a small plastic case and mounted below the dewar. The electronics board also controlled the user display discussed in the following section and an audible alarm. When the liquid air in the dewar reached the ¼ full level, the electronics board triggers an audible alarm located in the backpack, per NIOSH requirements. For the AWPS, this occurred with 30 minutes of time remaining when breathing at the standard NIOSH rate. Consequently, a "snooze" button has been added. However, when the volume reached 1/8 full, the button was disabled and the audible alarm remained on.

4.2.2 Face Piece, Regulator, Helmet, Communications

An Interspiro face piece, regulator, and hose assembly were selected to supply the user with air from the backpack, as required. This equipment was selected because of the regulator's ability to operate with a source pressure of 60 psig, and because the equipment was already used in existing NIOSH certified SCBAs. A picture of the equipment is presented in Figure 4.2-4.

The Interspiro equipment was tested on a breathing machine to ensure it could deliver the required flows and maintain positive pressure at the low operating pressure of the AWPS. The testing indicated the regulator maintained a positive pressure at the standard NIOSH breathing rate of 40 SLPM. However, the regulator could not maintain a positive pressure at much higher breathing rates, such as the at the maximum NFPA rate of 100 SLPM. This was judged acceptable for Phase I, and did not effect any manned testing.

During Phase I, OSS integrated an off-the-shelf helmet and communication system with the face piece. The communication system was modified to mount directly to the Interspiro face piece. The communications system (a standard commercial grade VHF radio set) was modified with a mask mounted microphone and a harness mounted push-to-talk switch. These were tested for operation and integration. The switch, while large enough and with sufficient tactile feel to be operated through the protective garments, was difficult to mount where it would not interfere with other items of the ensemble. The microphone was found to be too sensitive and mounted too close to the face piece speaking diaphragm.

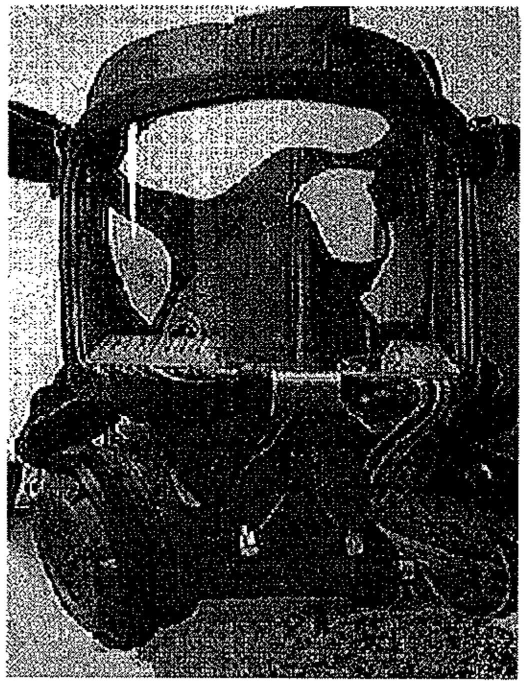


Figure 4.2-4: Interspiro Face Piece

A System Status Display was also mounted on the face piece to allow the user to monitor the system. The display consisted of a series of LED bars. A red or yellow LED illuminated if the pressure in the dewar became too high or too low respectively. A blue LED illuminated to warn the user the vaporizer may be in danger of freezing and that the metering valve should be closed.

The display also used 8 green LEDs to indicate the quantity of liquid air in the dewar. The LEDs turned off as the dewar was emptied. When the liquid air level reached 3/8 full, the last LED turned red and the other two LEDs, the ones for the ¼ and the 3/8 level, turned yellow.

Testing during Phase I indicated that the display was easy to understand. However, the size of the display must be reduced to block less of the user's field of view. Brighter LEDs will also be needed to ensure the user will be able to see the smaller display. The position of the display also needs to be optimized. The position may need to be adjustable to accommodate both users who are right-eye and those who are left-eye dominant.

4.2.3 Liquid Cooling Garment

A new patch liquid cooling garment was developed during Phase I. This LCG consisted of stretchable material with plastic patches sewn to the inside and connecting tubing located on the exterior of the garment. Water was circulated through parallel flow passages in the patches. A picture of the LCG is presented in Figure 4.2-5.

Figure 4.2-5: Phase I LCG

During Phase I, OSS characterized the heat transfer capability and other performance aspects of the new LCG and compared them to other LCGs. In addition, we evaluated several construction techniques and design concepts for the patches. While the patches developed in Phase I were acceptable for the manned testing, a more robust design and construction technique developed as part of an OSS internal research project will probably be used in the Phase II system.

The comparisons with other LCGs showed that the AWPS LCG has a much lower pressure drop (which allows a smaller pump and battery) than the tube LCGs. The comparisons also showed that the new patch LCG was able to remove more metabolic heat then any of the commercially available tube type garments. The performance of NASA's tube LCG was comparable to the patch garment. The NASA LCG is custom made and used by NASA astronauts during spacewalks. It has approximately twice the length of tubing and number of circuits as commercially available tube type LCGs. Consequently, the suit is much more expensive than other tube suits. It also costs considerably more than the projected sales price for the new patch LCG.

4.2.4 Protective Garments

Based upon the three DOE site visits, OSS decided to test both a Level A and a Level B suit in the KSU evaluation. The two suits are described in the following two sections.

4.2.4.1 Level A Suit

A review of existing vapor protective suits currently on the market showed that the commercially available Chemfab "Challenge 6400" met the requirements of the AWPS. A training version of the Chemfab suit was obtained and used for prototype testing. Figure 4.2-6 is a photo of the Chemfab suit.

Figure 4.2-6: Level A Suit

A standard "Challenge 6400" vapor protective suit is reusable with the following characteristics:

1. Integral visor, detachable gloves, and sock-like booties and will be worn over the worker and the PLSS.

2. The hood area of the suit provides ample room for a worker to wear a hard hat, respiratory face mask, and communications set.

3. The back area of the suit has an expanded pouch-like protrusion to accommodate wearing of the PLSS backpack.

4. An inner and outer glove system is used. Outer gloves are Brunswick neoprene gloves with North Silver Shield inner gloves. Gloves are mounted to a hard ring fastened to the end of the suit sleeve. Glove mounting will be accomplished by using a low profile nylon or acetal tie down strap. The glove interface area is covered by a splash shield consisting of the garment material and extending three inches down over the interface area from the forearm area.

5. Booties are fully integrated into the termination of the suit leg. Splash guards consisting of the garment material are provided to prevent liquid accumulation into the outer boots. Bata Shoe HazMat boots will be used as the outer boots.

6. Garment seams (on full production units) are heat sealed and taped on both sides. The garment to visor interface is heat sealed with heavy duty taping on both sides of the seam.

7. The suit closure consists of a gas sealing (on full production units) zipper located on the suit back. The zipper begins at the head region and extends to the upper left thigh region of the suit.

8. Suit sleeves allow the wearer to withdraw his or her hand into the suit interior.

9. The visor consists of 10 mil Teflon FEP sized to provide adequate side-to-side and top-to-bottom vision.

4.2.4.2 Liquid Splash Protective Suit (Level B/C)

The liquid splash protective suit was designed by OSS specifically for the AWPS and has the following characteristics. An initial pre-prototype liquid splash-protective suits incorporating these features was fabricated by OSS. Subsequent prototype suit were fabricated by Mar-Mac Manufacturing Company, an established maker of chemical protective clothing in the industry. Mar-Mac Manufacturing was chosen because of the access to and experience with the chosen material (available from E.I. DuPont deNemours & Company) together with their specialized protective clothing heat sealing capabilities. Mar-Mac Manufacturing is one of two companies which routinely fabricate suits from the Tychem 9400 material for commercial applications.

All components used in the construction of the liquid splash-protective suit are commercially available. These choices were made to keep the manufacturing cost of the suit in line with similar products. What is unique about the liquid splash-protective suit prototypes is the design that is currently not found on any product available in the market place.

1. It is a two piece garment with coverall and hooded shroud consisting of overalls with suspenders and splash hood with visor and full sleeves with gloves. It will be worn with the PLSS outside the overall but inside the splash hood.

2. The suit hood has a 20 mil PVC visor.

3. Brunswick coated knit neoprene gloves are used with the suit. Gloves are mounted to a light-weight, plastic hard ring fastened to the end of the splash hood sleeve. Glove mounting is accomplished using a Delrina or acetal cable tie. The glove interface area is covered by a splash shield consisting of the garment material and extending three inches down over the interface area from the forearm area.

4. Booties are fully integrated into the termination of the suit leg. Splash guards consisting of the garment material are provided to prevent liquid accumulation into the outer boots. Bata Shoe HazMat boots are used as the outer boots.

5. Garment seams are sewn and taped on the outside.

4.2.4.3 Comparison of Liquid Splash Protective Suit Configurations
A comparative study was conducted to determine the optimum configuration of the project liquid splash protective suit. Three different options were selected and compared in terms of different features and their affect on wearer comfort and job effectiveness:

1. Option 1 involved a two-piece design. The first piece was a standard coverall with full sleeves and attached gloves and sock-like extensions of the trouser legs (booties). The second piece was a hooded cover with integrated visor, half length elasticized sleeves, and a bottom hem positioned near the waistline of the wearer.

2. Option 2 also involved a two-piece design. Unlike Option 1, the first piece was an bib-style overall with adjustable suspenders and no sleeves. This overall did include booties as in Option 1. The top piece was hooded top with integrated visor, full sleeves, attached gloves, and a bottom hem positioned near the waistline of the wearer.

3. Option 3 was a one piece design similar to the Level A Vapor-Protective Suit but not of a gas-tight construction. This design included an integrated visor, full sleeves with attached gloves, booties, and rear-entry closure provided with a cover flap.

Each option used outer boots worn over the booties for providing physical protection to the wearer's feet. Figure 4.2-7 illustrates each of the liquid splash suit configurations considered.

Each option was evaluated in terms of:

- cost (simplicity),
- mobility in terms of reaching, bending, and kneeling,
- relative comfort during operational use,
- relative comfort during non-operational use, such as before connection of the PLSS/LCG systems,
- ease of donning and doffing
- ability for wearer to don and doff suit without assistance,
- potential for contamination of wearer during operation,
- ability to prevent contamination of wearer and PLSS during doffing,
- number of sizes needed to achieve appropriate fit of most wearers,
- potential problems with PLSS and LCG interfaces, and
- overall relative fit.

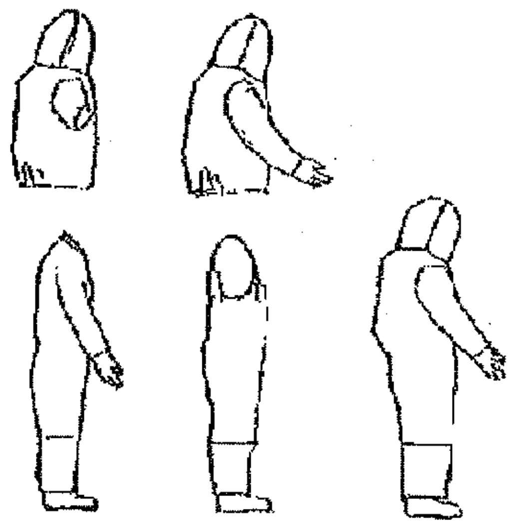


Figure 4.2-7: Level B Suit Configurations

A weight between 0.3 and 1 was assigned to each rating area based on OSS's perception of DOE requirements and needs in combination with project objectives. Each characteristics of the considered design configurations was rated using a 1 to 10 scale. A composite score was calculated using the product of the weight for each characteristic and the rating. This composite score was used to rank the three options. Using this system, Option 2 (full hooded top with bib-overall) yielded the highest score, followed by Option 1 (standard overall with short-sleeved hooded top. The encapsulating suit (Option 3) provided the lowest score-primarily because low relative comfort compared with other options and the inability to perform self donning and doffing. The individual scores and results are provided in Table 4.2-1.

4.2.4.4 Planned Garment Testing

Initially, a number of tests were designed to evaluate each of the protective clothing suits and their components. Planned evaluations of the Level A Vapor-Protective Suit Prototype included seam and closure strength, gas-tight integrity of the overall suit, and ensemble integrity, fit, function, and comfort.

Similar evaluations were established for the Level B Liquid-Splash Protective Suit Prototypes, including seam and closure strength liquid-tight integrity of the overall suit, and ensemble integrity, fit, function, and comfort.

However, the selection and design of the protective clothing obviated the need for all but the ensemble integrity, fit, function, and comfort tests. The vapor-protective suit chosen was a modification of existing commercial design, which has already been evaluated for the performance requirements of NFPA 1991, Standard on Vapor-Protective Suits for Hazardous Chemical Emergencies. Likewise, the selected liquid-splash protective suits uses a material where seam strength has already been demonstrated to meet the requirements of

NFPA 1993, Standard on Support Function Protective Clothing for Hazardous Chemical Operations. Since the liquid splash-protective suit has designed without a closure system, no testing of closures is necessary.

Table 4.2-1: Level B Suit Evaluation Results

		OPTION 1 Two-Piece Coverall w/Gloves and Sep. Splash Hood w/Short Sleeves		OPTION 2 Two-Piece Overall w/ Suspenders and Sep. Splash Hood w/ Gloves		OPTION 3 One-Piece Integral Hood and Gloves in Full Coverall		
Considerations	Weight	Score 1-10	Weighted Score	Score 1-10	Weighted Score	Score 1-10	Weighted Score	Comments
NFPA 1992 Water Spray Test	1	10	10	10	10	8	8	Opt. 3: Difficulty expected in sealing "ziplock" top end
Cost (Simplicity)	.8	8	6.4	9	7.2	10	8	Opt. 1: Coverall requires zipper, "ziplock", upper torso and collar plus splash hood Opt. 2: Suspenders required plus splash hood Opt. 3: Zipper/"ziplock" required
Mobility - Reach, bend, kneel	1	8	8	10	10	8	8	Opt. 1 and 3: One piece design may be restrictive during bending, kneeling, squatting motions Opt. 2: Two piece design and elastic section in suspenders should aid mobility
Comfort During Operational Use	1	9	9	10	10	9	9	Opt. 1 and 2: Two piece design allow some upper torso rotation w/respect to coverall or overall Opt 2: Sleeveless overall is less restrictive under splash hood
Comfort During Non-Operational Use i.e. before PLSS/LCG connection	.8	8	6.4	10	8	6	4.8	Opt. 1: Wearer will quickly become uncomfortable with closures open since hands, arms, and most of upper torso is not cooled Opt. 2: Wearer may remain in overalls and don PLSS/splash hood immediately before leaving suit-up area. Opt. 3: Since PLSS is donned before suit, wearer will have added weight plus have most of body covered with hood open and PLSS not operating.
Ease of Don/Doff	.8	5	4	10	8	10	8	Opt. 1: Some interference expected at shoulders during don/doff. Difficult to operate zipper/"ziplock" and adjust harness/mask with gloved hands Opt. 2: Splash hood donned after PLSS harness/mask installed and removed first during doffing. Opt. 3: Wearer can adjust PLSS and mask before donning suit. Assistant required for suit donning and closing zipper/"ziplock".
Self Don/Doff (yes/no)	1	10	10	10	10	0	0	Opt. 1 and 2 can be donned/doffed by wearer Opt. 3 cannot be donned/doffed by wearer

Table 4.2-1: Level B Suit Evaluation Results (cont.)

		OPTION 1 Two-Piece Coverall w/Gloves and Sep. Splash Hood w/Short Sleeves		OPTION 2 Two-Piece Overall w/ Suspenders and Sep. Splash Hood w/ Gloves		OPTION 3 One-Piece Integral Hood and Gloves in Full Coverall		
Considerations	Weight	Score 1-10	Weighted Score	Score 1-10	Weighted Score	Score 1-10	Weighted Score	Comments
Contamination protection of user during operation	1	8	8	9	9	8	8	Opt. 1 and 2: Slight potential for leakage exists due to two piece design Opt. 1: Slight potential exists for leakage at bottom of entry zipper/"ziplock" Opt. 3: Slightly greater potential exists for leakage at top of entry zipper/"ziplock"
Contamination prevention of user and PLSS during doffing	1	8	8	8	8	8	8	Scored on degree of difficulty to turn contaminated exterior surfaces inside-out and away from wearer during egress Opt. 3 requires assistant
Sizing - Number of sizes required	.5	6	3	6	3	10	5	Opt. 1 and 2: 4 coverall or overall sizes + 3 splash hood sizes Opt. 3: 4 one piece suit sizes
Interface problem: pass-throughs for air and water connections	.7	8	5.6	8	5.6	10	7	Opt. 1 and 2 require pass-throughs for LCG and venting in coverall/overall. Opt. 3: No pass-throughs needed
Fit	.7	8	5.6	10	7	7	4.9	Opt. 1 and 3: No torso length adjustment Opt. 2: Some torso length adjustment provided with suspenders Opt. 3: Large torso to accomodate PLSS and don/doff may shift in position relative to wearer
Totals (weighted)			84		95.8		78.7	(103 possible total)
RANK		2nd		1st		3rd		

Initial testing of the garments indicated that specifically qualitative assessments of the garments' integrity, fit, function, and comfort, should postponed until Phase II where sizing schemes were incorporated in the suit design and thus provide a more appropriate evaluation of these suit characteristics.

4.2.5 Recharge Station

The sub scale recharge station underwent extensive development testing to optimize efficiency. Operating pressures and components were adjusted to minimize the amount of consumables (industrial grade liquid nitrogen and compressed breathing air) used and time required for a recharge of the AWPS backpack. Times for a recharge varied from 40 minutes with both the recharge station and backpack warm to 7 minutes with both already chilled (i.e. - after a previous test). The consumable usage rates were also used to estimate the amounts needed for testing at KSU.

The oxygen percentage of the air at the user's mask was also tested. This is concern because in a liquid oxygen / nitrogen mix (liquid air) the nitrogen, because it has a lower boiling point, will boil off preferentially to the oxygen, resulting in an enriched air mixture. This is not an issue while using the AWPS, because the air mixture is forced through the vaporizer and all of the components are forced to boil at once, with the user receiving the same percentage of oxygen as the mixture stored in the backpack. However, when filling the backpack, the backpack must first be cooled down to liquid air temperature. While the initial liquid air is cooling the backpack, more nitrogen boils off than oxygen, causing the mixture stored in the backpack to be a slightly higher oxygen percentage than the compressed air source. The testing demonstrated that, with an air source (~ 21% oxygen), the oxygen concentration in the backpack would not exceed the regulatory definition of air - 23.5%.

4.2.6 In-House Manned Testing

Once the ensemble for the KSU evaluation was developed, OSS performed a series of manned tests with the system. During these tests, subjects exercised on a Nordic Track or a treadmill wearing the LCG, the backpack, and a Level B suit. A picture of the test is presented in Figure 4.2-7.

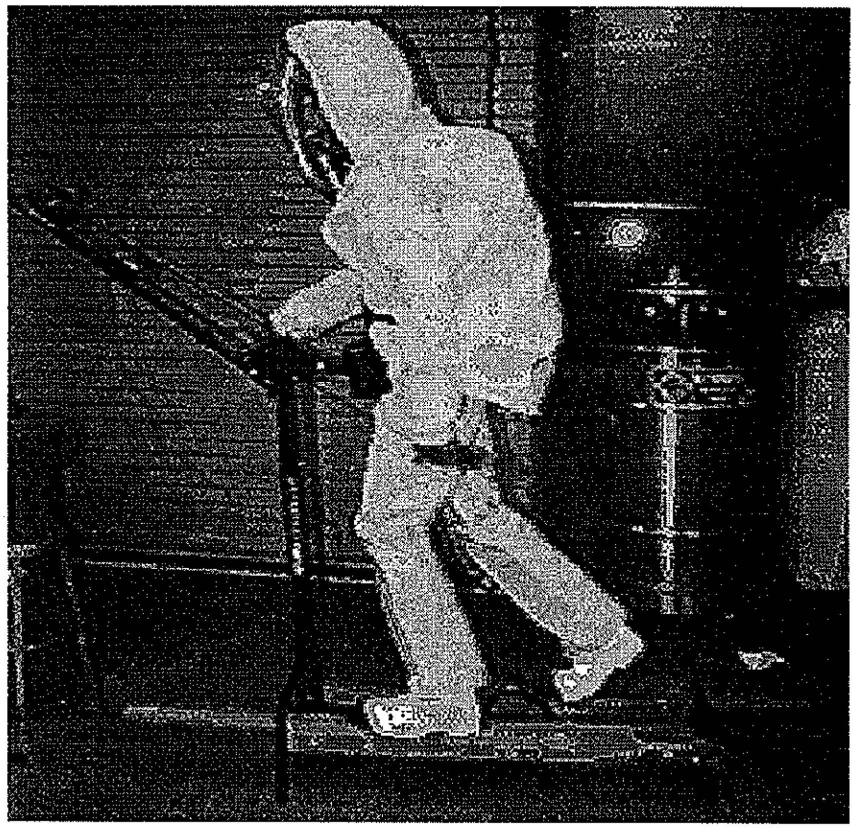


Figure 4.2-7: Phase I In-House Manned Testing

Data was taken and analyzed to evaluate the system's performance. However, the testing was mainly intended to verify operation of AWPS with human user, work out logistics and procedures for KSU testing, and evaluate integrated system operation. The system worked well during the in-house testing and by

4.3 Failure Mode and Effects Analysis

During Phase I, a Failure Modes and Effects Analysis (FMEA) was conducted on the AWPS to identify failures or combinations of failures that could allow the user to be injured, damage the backpack, or cause a user to withdraw from an operation early. The FMEA documents each component or component assembly in the system, along with function, failure modes and causes, failure effects, detection methods, corrective actions, and criticality category for each failure mode. The worksheets created for this analysis can be found in Appendix A of the AWPS Phase I Final Topical Report.

The FMEA was performed using Requirements for Preparation and Approval of Failure Modes and Effects Analysis (FMEA) and Critical Items List (CIL), NSTS 22206 Rev C as a guideline. Failure modes for the analysis were determined regardless of likelihood and show the worst case failure. The effects on the backpack unit, user, and operation are also worst case. The following are definitions of the terms used in the analysis.

- Hardware Criticality: The categorization of the singular effect of the identified failure mode of a hardware item using the rankings in the following table.

Hardware Criticality	Potential Effect Of Failure
1	Injury to user.
2	Halt operation, or next failure of any redundant item could cause injury.
3	All others.

- Functional Criticality: The categorization of the effect of loss of all redundancy for a given function using the rankings in the following table.

Functional Criticality	Potential Effect Of Failure
1	Single failure could result in injury.
1R	Redundant hardware item(s), all of which if failed could cause injury.
2	Single failure could result in halting operation.
2R	Redundant hardware item(s), all of which if failed could result in halting operation.
3	All others.

During the analysis, the failure modes for all of the components were identified, and the impact of that failure assessed. Any loss of functionality due to the failures was also identified. Failures that caused loss of functionality were than grouped together and the failures were assigned a hardware and functional criticality.

The criticality summary of the AWPS is as follows:

Criticality	Number of Failure Modes
2/1R	1
2/2	30
2/2R	2
3/1R	3
3/3	7

The only failures identified that can result in injury involve multiple failures in pressure control components or combined failures that overload the Ambient Heat Exchanger. In order for a failure of the pressure control components to cause injury, some failure, such as loss of vacuum, would have to be coupled with the Relief Valve failing closed and the Burst Disc failing to burst at the design pressure. This could cause enough pressure top build up in the Inner Vessel to cause a rupture. However, this could be prevented by opening the Vent Valve or Metering Valve to vent system pressure. The High Pressure Warning light also gives the user indications that the equipment is not performing within normal parameters and that they should remove themselves from the operation.

In order for the Ambient Heat Exchanger to be overloaded, the Metering Valve would have to fail open or be left open and the Mask Regulator would have to fail open after a Pump failure causes the Vaporizer to freeze. This could cause more cold gas flow through the Ambient Heat Exchanger than it was designed to handle therefore the gas coming to the user could become very cold.

The rest of the backpack failure modes do not result in any harm to the user but indicate that the backpack is not performing properly. In these cases, the user should go to a designated area, and take the pack off for servicing. The backpack could continue to provide life support but should be doffed. This is similar to a regulator failure on an SCBA. The bypass valve can be opened the system would still provide air for a much shorter duration so the pack should be removed. With the AWPS, cooling could be lost or the Relief Valve could be venting excess pressure, but the system will continue to support life. Electronic systems failures will not effect system performance at all, but the ability to monitor the system is lost.

4.4 Life Cycle/Cost Benefit Analysis

Visits to three DOE remediation sites (Fernald, Oak Ridge, and Hanford) yielded the information necessary for determining the life cycle costs for Personal Protective Equipment (PPE) used in the existing ensembles. This information has was entered into a life cycle cost model to predict the LCC of current ensembles. The same model was used to calculate the LCC for the proposed AWPS , and the numbers were compared.

A detailed derivation of the model and all component costs is included in the first Phase I topical report, "Performance/Design Criteria Review Topical Report - Advanced Worker Protection System". Also included in that report is a sensitivity analysis of all the major variables. Following is a brief description of the model, and updated costs based on current design and testing data.

Specific life cycle cost information was gathered at each of the sites using an elaborate survey and interview process. This information included:

The number of missions (sorties) involving PPE;
The number of individual PPE uses;
The expected number of uses for each PPE item (service life);

The number of PPE uses for each maintenance cycle;
The proportion of PPE use activity involving high, moderate, or low work rates;
The proportion of PPE use involving Level A or B protection;
The specific PPE items in use and their purchase costs or sources;
Consumable and their costs associated with each of the PPE items; and
Labor costs associated with each of the PPE items.

In some cases exact data was not available for an item, and estimates were used.

4.4.1 Development of Model

The life cycle cost of PPE is based on costs associated with:

Purchase;
Operations;
Cleaning or decontamination;
Maintenance and repair;
Storage; and
Disposal.

Incumbent in these costs are both labor and material costs. For example, the purchase price for the PPE includes not only the price paid for the item, but the time spent ordering the item, receiving the item, and putting the item into service. Operating costs include both labor and supplies needed to replenish the system. The same is true for maintenance (repair), storage, and disposal costs.

In its simplest form, the total support cost (T) is the sum of each of these costs:

$$T = P + O + C + M + S + D$$

where:

T	=	Total support cost
P	=	Purchasing costs
O	=	Operating costs
C	=	Cleaning and decontamination costs
M	=	Maintenance and repair costs
S	=	Storage costs
D	=	Disposal costs

For the complex PPE ensembles used in DOE remediation operations, these costs are calculated for each major item of the ensemble, i.e. the respirator, the protective clothing, the cooling system, the communications device, and the support equipment. In comparing ensemble costs, only those items that are different need be considered. Furthermore, the costs for the different items must cover an equal amount of work to provide a correct comparison of the LCC for a given project. In this study, the total PPE support costs for a specific job (with a defined amount of actual work) was chosen as the basis for providing the LCC estimates.

4.4.2 Model Variables

Different variables affect each of the cost areas identified in the previous equation. Some costs are based on the number of uses, while others are based on the number of missions involving PPE use or the total number of items in use. In addition, since tasks and consequent PPE item selection vary, the model must account for differences in work activity. For example, heavy work activity will more rapidly consume breathing air supply (for SCBA), increase clothing wear, and create the need for maintenance or disposal. Costs also vary based on the type of worker protection needed, i.e., EPA Level A versus Level B protection. Table 4.4-1 below lists the different variables involved in determining the costs in each PPE cost area.

Table 4.4-1: Model Variables for Each Cost Area

Cost Area	Item Specific?	Model Variables
Purchase	Yes	Number of PPE uses per year Number of uses per PPE item PPE item purchase price PPE purchasing hours Purchasing hourly labor rate
Operations	Yes	Number of PPE uses per year Ratios of low, moderate, and high work level activity Consumable costs Worker labor hours Worker hourly labor rate Indirect labor hours Indirect hourly labor rate
Cleaning and Decontamination	Yes	Number of PPE uses per year Number of missions per year Consumable costs Proportion of Level A/B use Decontamination labor hours Decontamination hourly labor rate
Maintenance and Repair	Yes	Number of PPE uses per year No. uses per maintenance cycle Ratios of low, moderate, and high work level activity Consumable costs Maintenance labor hours Maintenance hourly labor rate
Storage	Yes	Number of PPE uses per year PPE item purchase cost
Disposal	Yes	Number of PPE uses per year Number of uses per PPE item PPE item purchase cost

4.4.3 Determination of Specific Benefits

After the total support costs for the ensemble are calculated, these costs can be factored with benefits achieved from the improved system. Benefits are quantitatively determined in two areas:

1. Improvements in worker productivity allowing employees to spend more time actively performing tasks, and

2. Improvements in worker protection and thus lower costs in medical care and long term liability costs.

4.4.3.1 Worker Productivity

Improvements in worker productivity can be directly determined by comparing the number of additional work hours afforded by the AWPS. The operational life cycle costs show the average number of hours for each level of work activity. These hours are based on the combination of both rest and actual work time. The proportion of actual work to rest time can be determined for each ensemble. This ratio can then be used to calculate the amount of additional actual work that may be accomplished with the AWPS from measures of the total work time required to complete specific tasks at the different work levels. It is important that the level of work activity be considered since the provision of cooling from the AWPS is expected to have somewhat different impacts on increasing actual work time.

4.4.3.2 Worker Protection

The benefits of increased worker protection require several assumptions, specifically:

- Prediction of the proportion of workers who will receive various exposure-related injuries;

- An estimate of the average costs associated with treatment for exposure-related injuries; and

- Determination of probable liability costs for exposure-related injuries.

Calculation of this benefit was determined independent of the life cycle cost due to less defined basis. For the purposes of this study, values were assumed for each of the above three areas based on historical chemical process industry statistics.

- It is estimated that between 500,000 and 1,000,000 workers will be engaged at one time or another in D&D activities at DOE sites. Of this number, only 5 percent are expected to come in contact with hazardous materials which are capable of causing long term health hazards. Of this latter number, only 0.2 percent are expected to develop long term medical disorders such as cancer which may be attributed to site exposures. Using the higher end of estimated DOE worker population (1,000,000 x 0.05 x 0.002), a total of 100 workers are expected to have long term disabilities or medical disorders as the result of clothing and equipment which fails to provide adequate protection (based on existing technologies).

- Insurance industry statistics show that the average cancer case cost $250,000 in medical bills. This amount varies with the severity of the cancer and the methods of treatment available for the specific disorder.
- Of cases where long term illnesses are suspected to be the result of work place exposure, the American Bar Association estimates that 20 percent of these will be brought into the court system with settlements made in half of the cases. The average settlement is $1,000,000.

Based on these estimates, the total benefit becomes:

= 100 workers x ($250k in medical costs + 0.1 x $1,000k in liability costs)

= $35 million

4.4.4 Basis for Comparing Different Ensembles

Since the principal utility of the AWPS is for worker protection during Level A and B operations, life cycle costs have been computed for these operations only. Initial visits to the Fernald Environmental Management Project, Hanford, and Oak Ridge DOE sites showed an increase in both Level A and B clothing ensemble uses as decontamination and decommissioning processes fully begin.

For the purposes of this study, a total of 5,000 man-hours are assumed to require self-contained breathing air for a specific remediation function. Ninety five percent of this time is assumed to require Level B protection (4,750 man-hours), while 5% of that total (250 man hours) is assumed to require Level A protection. Both of these figures are based on the actual number of man hours required to complete the work and not time spent in non-work activities such as donning, doffing, decontamination, and rest periods.

The analysis of life cycle costs is therefore based on the costs needed to affect the indicated number of work hours. A comparison is made between conventional Level A and B systems and the AWPS Level A and B systems.

The current Level A ensemble used in the DOE weapons complex includes a limited use totally encapsulating suit constructed of a lightweight plastic laminate-based material, attached gloves, and a 30 minute or 60 minute Self Contained Breathing Apparatus (SCBA). While other items may be worn with the ensemble such as over boots, a cooling system, a communications device, and a hard hat, none of these items were considered in estimating total ensemble purchase costs.

The suit in this scenario is used only once before requiring disposal. SCBAs have a 5 year service life under heavy use conditions (approximately 1000 uses). The encapsulating suit purchase price is approximately $400, while the SCBA costs $2200.

The AWPS Level A ensemble includes a reusable totally encapsulating suit constructed of a durable material, attached gloves, an inner cooling garment, and a liquid air backpack. The suit in this scenario is expected to provide five uses before requiring disposal and costs $3500. The backpack also is estimated to have a 5 year service life (1000 uses) with a purchase price of $7,500.

The Level B scenario includes the same ensembles but a liquid splash protective suit is substituted for the totally encapsulating suit. For the existing ensemble, this clothing costs $25 and is disposable after a single use. In the AWPS Level B ensemble, the purchase price for the splash suit is $150 and is designed for only one use.

Since each ensemble consists of two separate parts having different service lives, the individual life cycle costs must be calculated for each.

4.4.4.1 Methods of Estimating Costs

While some information was obtained during the site visits, the majority of costs have been estimated using related data for EPA remediation activities. Specifically, a series of equations have been developed by Schwope and Renard, "Estimation of the Cost of Using Chemical Protective Clothing," which define the individual costs and labor requirements of protective clothing as a function of its purchase price. These relationships were used for determining labor requirements for both existing and AWPS ensembles.

4.4.4.2 Assumptions

Despite information gathered on site visits and methods of estimation provided above, a number of assumptions were necessary to calculate life cycle costs. In the first set of calculations, several simplifications of the model were used. These included:

1. All work is conducted at a moderate workload;
2. All operational labor is at a rate of $40/hour (includes overhead);
3. All other labor, including labor for purchasing, storing, and disposal, is at a rate of $25/hour (includes overhead).
4. Decontamination costs are the same for Level A as they are for Level B; and
5. Decontamination labor costs are based on the protective suit only. This include decontamination of gloves, outer boots, and other accessory clothing items but not the respirator. Protection of the breathing apparatus within the suit excludes decontamination (but not maintenance) costs for this item.

Under a moderate work load, the SCBA offers a maximum of 20 minutes useful work time, while the PLSS is assumed to provide 120 minutes useful work time. Table 4.4-2 below shows the individual times associated with operational uses of each ensemble (applies to both Level A and B).

Table 4.4-2: Time Required in Ensemble Operation

Activity	Amount of Time Per Activity (minutes)	
	Current Ensemble	AWPS
PPE Donning	15	25
Pre-entry Inspection	0	10
Working Time	20	120
Decontamination	10	10
Rest Time	30	30
Total Time Required	75	195
Ratio of Working Time to Total Time Required	0.27	0.62

Other specific assumptions were required for other costs, particularly purchasing labor consumables for different activities. The following estimates were used:

- Purchasing labor for the existing ensemble is considered to be twice as much for the AWPS due to myriad of choices affecting current clothing purchases. The AWPS purchase labor requirement is 20 hours per year.

- Operation consumables vary between ensembles primarily due to the difference between compressed and liquefying air. The AWPS uses 270 cubic feet of compressed air at $0.05/scf and 12 lbs of liquid nitrogen at $0.38/lb for a total consumable cost of $16.65. In comparison, the SCBA uses 30 scf of compressed air for a total cost of $1.35.

- Cleaning/decontamination consumables have been previously estimated (by Schwope and Renard) at $50/entry for disposable supplies and $25/entry for reusable supplies.

- Maintenance costs are assumed to be the same for AWPS PLSS and the existing ensemble SCBA at $25 with a total of 10 uses per maintenance cycle for each item. Likewise, the principal maintenance for protective clothing is replacement of gloves at $25/pair with a total of 20 uses.

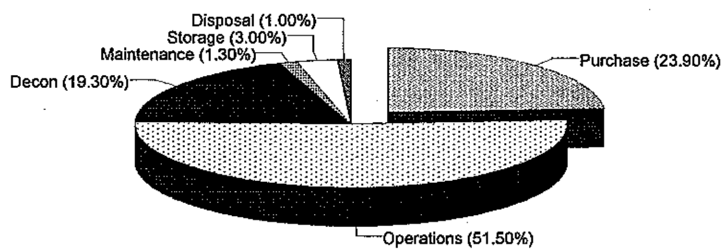
4.4.5 Life Cycle Cost Calculations (Base Case)

Table 4.4-3 shows the values used for each variable in the model based on the estimates and assumptions above. The overall life cycle cost for the existing ensemble was calculated as $1,676,851. For the AWPS, a LCC of $980,886 was obtained. This represents a difference or savings of nearly $700,000. Note that while the acquisition (purchase) costs of the AWPS hardware are significantly higher than for the existing ensemble, much lower costs were estimated for the other expense areas. The majority of the AWPS LCC was the purchase cost, which had roughly the same contribution as the operational cost. Over 50% of the LCC for the existing ensemble was due to operational costs. Figure 4.4-1 shows the relative proportion of costs for each the LCC. Note that while the acquisition (purchase) costs of the AWPS hardware is significantly higher than for the existing ensemble, significantly lower costs are demonstrated for the other expense areas.

Table 4.4-3: Cost Model Variable Values

Variable	Existing Ensemble	AWPS
Level A Suit Purchase Cost	$400	$3500
Level A Suit Purchase Cost	$25	$150
SCBA Purchase Cost	$2200	$7500
Labor Rate	$25/hour	Same
Purchasing Hours	20/year	Same
Actual Time per Use	20 minutes	120 minutes
Support Time per Use	55 minutes	75 minutes
Total Time per Use	75 minutes	195 minutes
Ratio of Actual Time to Total Time	0.27	0.62
Operations Labor Rate	$40/hour	Same
Consumable per Use	$1.35	$16.65
Decontamination Consumable per Mission	$25	$50

Existing SCBA Ensemble - ($1,676,851 total LCC)



AWPS - ($980,885 total LCC)

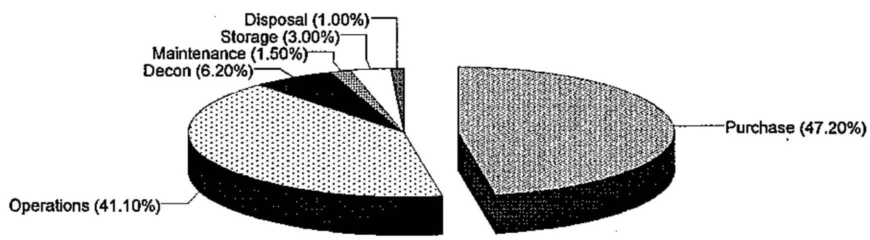


Figure 4.4-1: Distribution of Life Cycle Costs

The LCC analysis also provided estimates on the increase in productivity for the AWPS. Since the assumption has been made that PLSS can provide at least 120 minutes of air and cooling, the actual time on site is six times higher than achieved with a conventional SCBA. Nevertheless, use of the AWPS is considered to require more support time. As a consequence, the best way to examine increases in productivity (separately from the life cycle costs) is to compare actual work times. On that basis the AWPS provides more than a two fold increase in worker productivity. Use of the AWPS allows completion of the 5,000 hour job in 156 days as opposed to 625 days for the existing protection technology.

4.4.6 Sensitivity Analysis

Key variables were selected for ascertaining their effect on the life cycle costs, including:

- AWPS purchase costs;
- the number of reuses for the Level A garments;
- the relative amount of support labor time;
- the expected lifetime of the PLSS; and
- actual work time provided by the AWPS.

With the exception of the AWPS actual work time, a relatively low and high value was chosen as compared to the base case assumption or estimate. Several different actual work times were evaluated ranging from 40 minutes to 160 minutes. The values of these variables are show in Table 4.4-4. Calculation worksheets for each of these cases are provided in the final topical report for Phase I.

Table 4.4-4: Range of Key Variables Investigated

Variable	Base	Low	High
Level A suit cost	$3,500	$3,000	$4,000
Level B suit cost	$150	$100	$200
PLSS Cost	$7500	$5000	$10,000
Level A suit reuse	5x	Once	10x
Support labor time	35 minutes	15 minutes	55 minutes
PLSS service life	1000 uses	500 uses	1500 uses
Actual work time	120 minutes	40 minutes	160 minutes

The largest effects on the AWPS LCC were demonstrated by the reusability of the Level A suit and the actual work time provided by the two-hour backpack. Since the AWPS purchase cost is relatively high, the largest benefit is seen from longer stay times for conducting actual work. This increase in productivity is the single largest factor contributing to the more favorable LCC for the AWPS. Figure 4.4-2 shows how LCC varies with actual work time. The AWPS must provide approximately one hour of actual work time (3 times that of the existing ensemble) in order to match the LCC cost of the existing ensemble. A relatively high LCC was calculated for the case when a expensive Level A suit is used only once. Repeated use of this suit, even in its limited applications has a profound effect on the overall AWPS LCC.

While varying purchase cost had some effect on the AWPS LCC, increasing Level A and B suit costs to $4000 and $200, respectively, in combination with raising the PLSS cost to $10,000 still provided a lower LCC than the existing ensemble.

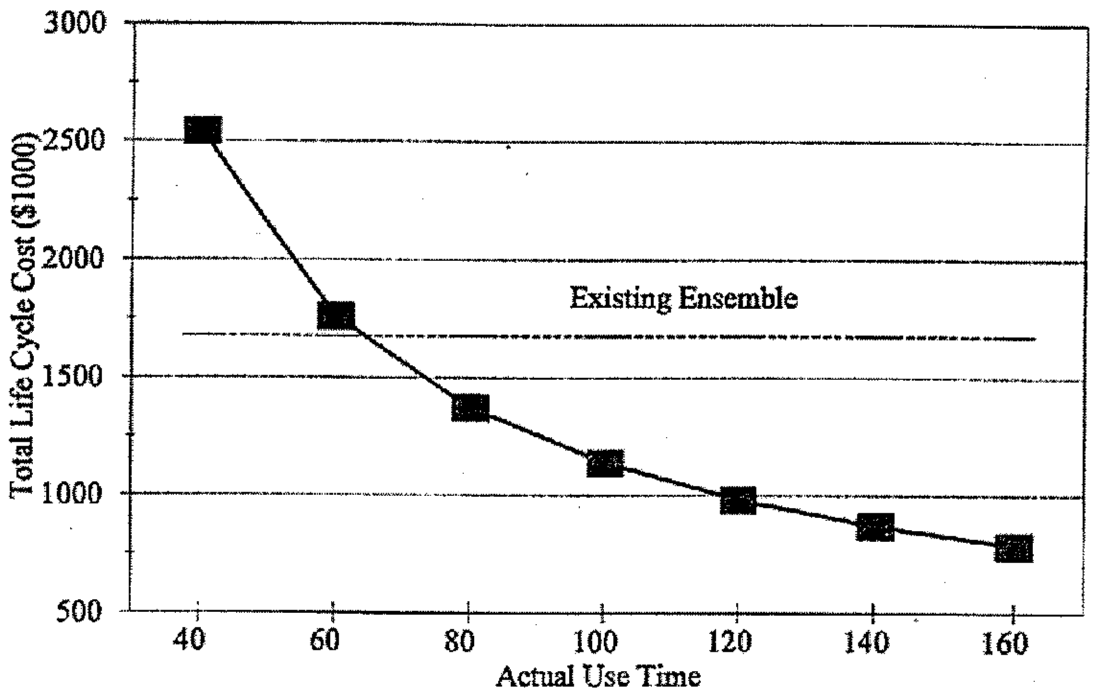


Figure 4.4-2: Life Cycle Costs Versus Work Duration

Requirements for less or more support time for AWPS operations had little effect on the LCC. The LCC was still lower than the existing ensemble when the support time increased to 55 minutes (donning and preentry inspection).

Varying the service life of the PLSS by fifty percent either up or down has the least effect on the LCC for the AWPS.

The life cycle cost analysis indicated the AWPS could save $700,000 over current PPE during a 5,000 man-hour job. A sensitivity analysis performed on the LCC model indicated the AWPS would still provide substantial savings using the worst possible assumptions in the cost model.

It is expected that numerous remediation projects of the size used in the LCC analysis will occur over the next 30 years. As a result, the AWPS can save the DOE several millions of dollars in direct costs, not to mention the indirect benefits to worker health and safety. These benefits more than justify the development costs of the AWPS.

4.5 Kansas State University Independent Evaluation

The Institute for Environmental Research (IER) as Kansas State University was subcontracted to independently evaluate the Advanced Worker Protection System in a series of human subject, controlled environment tests. The principal objectives for testing the AWPS at KSU's Institute for Environmental Research were:

- To provide an independent assessment of the AWPS specifically with the intent of evaluating how the system and its components affect the physiology and perceptions of human subjects wearing this system in both a Level A and B configuration;

- To allow a comparison of the effects on worker endurance for the AWPS liquid air based breathing system with liquid cooling garment versus a traditional, compressed air-based, breathing system with no provision for cooling; and

- To investigate the differences in AWPS performance under different environmental conditions likely to encompass the working situations of end users.

The Institute for Environmental Research at Kansas State University (Manhattan, Kansas) was chosen based on the availability of its highly controlled environmental chambers and their experience with conducting human subject tests involving prototype personal protective equipment.

4.6.1 Test Plan

A two-part test program was designed to achieve these objectives. The first part of this test program involved using a single set of environmental conditions to compare the performance of the AWPS and SCBA-based protective ensembles.

4.6.1.1 Ensembles Tested

The following four different ensembles were evaluated.

1. The first ensemble consisted of the prototype backpack, the prototype LCG, and prototype Level A vapor-protective suit. The protective suit was a ChemFab totally-encapsulating training suit which includes attached Neoprene gloves and booties. Industrial PVC outer boots were worn over the booties. The diaphragm type suit exhaust valve was removed and used for a pass-through for the sensor leads.

2. The second ensemble also consisted of the prototype backpack and LCG but included a two-piece Level B splash-protective suit. A prototype splash-protective suit was fabricated using the TyChem 9400 material in a two piece design. Sensor leads were passed under the hooded top.

3. The third ensemble used the Level A suit described in the first ensemble with a Interspiro Spiromatic 9030 SCBA. There was no provision of cooling.

4. The fourth ensemble used the Level A suit described in the first ensemble with a Interspiro Spiromatic 9030 SCBA. There was no provision of cooling.

Hard hats and communications sets were worn with each ensemble.

The second part of the testing involved the evaluation of the second ensemble (Level B AWPS) with two different sets of environmental conditions with the intent to determine how human subjects wearing the system would respond to colder and hotter situations.

4.6.1.2 Test Conditions

The first part of testing was conducted at the following conditions:

Temperature:	85 F (29.4 C)
Relative Humidity:	75%
Air Velocity	< 30 fpm (0.15 m/s)

The environmental conditions chosen for the second part of testing included:

Low temperature condition:	45 F (7.2 C)/75% relative humidity
High temperature condition:	100 F (37.8 C) 95% relative humidity

Environmental conditions were maintained using a controlled chamber having the following specifications:

Size:	11.2 ft by 11.2 ft x 9 ft (3.4 x 3.4 x 2.7 m)
Temperature:	0 to 140 F (-18 to 60 C)
Humidity Range:	20 to 95% RH at moderate temperatures
Air Velocity:	< 30 fpm (0.18 m/s)

4.6.1.3 Test Subjects

A total of four different human test subjects were used in these evaluations. Test subject ages ranged from 18 to 30 and each was an experienced fire fighter from the local fire department familiar with the use of SCBA. Since only one size of the AWPS was prototyped, all test subjects were of average build and dimensions, able to fit large-sized prototype protective clothing. All test subjects were volunteers in good physical condition as demonstrated in baseline testing (without protective clothing or equipment).

Each test subject wore underpants, a T-shirt, sweat socks, and a full body cotton coverall under protective clothing.

4.6.1.4 Exercise Protocol and Test Measurements

The test subjects maintained a constant work rate of 400 to 500 kcal per hour throughout all tests. The work rate was maintained by adjusting the rate and incline of the tread mill they were walking on.

The following physiological measurements were monitored during each test:

Core temperature
Skin temperature
Heart rate
Temperature inside the protective garment

In addition, test subjects were asked to rate aspects of their comfort using a qualitative scale. An overview of the instrumentation for each of these measurements is provided below.

Core temperature was measured using a rectal sensor inserted 8 cm into the test subject's rectum. The wire from the rectal sensor was taped to the test subject's waist to prevent it pulling out during the test. The lead from the rectal sensor was routed through the respective suit pass-through fitting.

Skin temperature was measured at left side of the test subject's neck, right side of chest, center of back, lower left thigh, left calf, and left forearm using skin temperature sensors. The lead from the six sensors were routed through the respective suit pass-through fitting.

Heart rate was measured by preparing the test subject's chest for attachment of five different electrodes. Locations for these electrodes included:

At the indention below the clavicle on the left and right sides,
Below the last rib in line with the nipple on the left and right sides; and
Right of center between the fourth and fifth ribs.

The test subject's skin was shaved in these areas, rubbed with dry gauze, and cleaned with an alcohol gel pad. Electrodes were attached to the skin with gel. The leads from these sensors were routed through the respective suit pass-through fitting.

Internal suit temperature was measured in the neck region of the protective garment using a thermocouple. The lead from this sensor was routed through the respective suit pass-through fitting.

At five minute intervals during the test, test subjects were asked to rate their thermal comfort using a nine point scale. Subjects were also asked to fill out the ensemble comfort evaluation at the end of the test.

The test subject's weight and the ensemble weight were measured both before and after each test. These measurements allowed the calculation of the test subject's average sweat rate.

4.6.1.5 Test Matrix

All test subjects under went baseline testing in shorts and T-shirt to establish physiological parameters and to become accustomed to the exercise protocol. Each test subject wore each ensemble once. The order of wearing the four different ensembles was randomized for each test subject.

A total of twenty tests were undertaken, including the baseline, for comparing AWPS and SCBA-based ensemble testing. Eight (8) additional tests were also conducted using the liquid splash-protective ensemble at the two extreme environmental conditions.

Test duration was for a maximum of two hours (once actual exercise started) or when the test subject wished to stop for any reason. The test was also halted if the test subject's core temperature or heart rate exceeded prescribed exercise levels (39°C or [220 - subject's age] beats per minute, respectively).

4.6.2 Test Procedures

Prior to each test, the AWPS backpack was filled with liquid air. This was done with the recharge station using compressed breathing air and commercial grade liquid nitrogen as consumables. The backpack was placed on the fill stand, connected to the fill station, and warm water was circulated through the vaporizer. The recharge station was filled with liquid nitrogen and then the backpack filled with liquid air. Once full the backpack was pressurized to 60 psig using gaseous air.

Meanwhile, the test subject was getting ready. As discussed in Section 4.6.1.4, EKG and skin temperature sensors were attached at various locations on the subject's body. For AWPS tests, the test subject donned the liquid cooling garment (LCG) before continuing with a pair of coveralls, sweat socks, the protective suit pants, and boots. Each piece of clothing was weighed before and after the test. Once suited to this stage, the test subject would proceed to the fill area to don the AWPS or SCBA. The SCBA donning was very straightforward, according to the manufacturers recommendations.

The AWPS required that any air in the LCG be removed before starting the test. The test subject would don the backpack, very much like the SCBA. The LCG lines were then connected such that any air trapped in the patches was removed. After this procedure, the LCG was reconnected such that it was operating as a closed loop.

The test subject then returned to the chamber to don the upper portion of the protective garment and begin the test. After returning to the environmental chamber, the test subject began breathing from the mask, donned the hard hat, and donned the upper portion of the protective garment. A final weight was taken, and recorded. This weight was used to program the treadmill. The weight was rounded up to the nearest 5 lbm increment, (maximum 250 lbm) and entered into the treadmill. This measurement allowed the treadmill to calculate how much work was being done. The treadmill velocity was increased until the caloric expenditure was approximately 7 cal/min. This usually gave a walking speed of ~3 miles/hour. This process was intended to ensure that all test subjects were working at approximately the same rate.

As the test subject began walking, they were asked to rate their thermal comfort from 1 to 9 (1=very cold, 9=very hot). Every five minutes, they were again asked to rate their thermal comfort overall, and to report any distribution of hot or cold across various body parts. The test subject was also requested to indicate any change in operation, status indicator lights, or personal comfort whenever those things happened. The comments were recorded in a log book along with heart rate, core temperature, and LCG temperatures as the test progressed.

The test subject was instructed at the beginning of the test and whenever their physiological indicators showed signs of stress that they could stop. They were also instructed that they should stop if they experienced headaches, dizziness, nausea, shortness of breath, or other discomfort. Other termination criteria used by the test conductor included heart rate, core temperature, breathing gas supply, and hardware malfunction. During the first two tests, heart rate was limited to 80% of (220 – subject's age). It was realized that the work rate expended by the test subjects was fairly intense, and it was decided that this heart rate limit was too conservative. The limit was raised to 100% of (200 – subject's age), with the understanding that the test subject was to be carefully monitored if his heart rate went above the 80% level. In addition, the EKG showed fluctuations and irregularities particularly as the test subjects became fatigued. It is believed that these artifacts were caused by chest muscle contraction. If the artifact became so severe that the EKG machine could not reliably count the heart rate, the test was terminated. The final test termination criteria was depletion of the air in the pack.

After the test, the subject was weighed and then removed the top of the protective garment and the mask, and filled out an ensemble rating evaluation. Then the backpack was removed and taken to the fill station to vent any remaining cryogen and warm the vaporizer in preparation for the next test. As at the beginning of the test, weights were taken as each type of clothing was removed. Additional comments were solicited from the subjects and recorded in the log book. The LCG and coveralls were laundered and the protective garments were allowed to dry before the next test.

The tests were conducted in an environmental chamber as described in Section 4.6.1.2. The chamber provided the test environment and housed the test apparatus, test conductors and test subject. All data except the EKG/heart rate information was recorded by a PC with custom data acquisition hardware and software. Data values were updated, displayed on the screen, and recorded on disk once per minute. In addition, every fifteen minutes a thermal comfort vote was recorded. Data recorded included: 6 skin temperatures, core temperature, LCG in/out temperatures, air temperature in the suit, the thermal vote, and several room temperature and humidity measurements.

The test subject's heart rate was determined using a 4 lead EKG. The EKG machine interpreted the heart rhythm and calculated a heart rate. Since the test subject was moving and carrying a backpack, spurious electrical signals caused by sweat and fatigue in the chest and shoulder muscles sometimes caused a fluctuating EKG trace (artifact). These fluctuations often caused the EKG machine to calculate incorrect heart rate readings. In these cases, the test was continued at the test directors discretion based on test subject condition, and direct observation of the EKG trace.

The test subjects walked on a Precor USA Ergo Smart 9.5 electric treadmill. As described previously, the test subject's weight with the backpack and all protective gear was entered into the treadmill, and the velocity was increased until the caloric expenditure was approximately 7 kcal/min. This resulted in a walking speed approximately 3 mph. This speed varied with the test subject and type of backpack. In several cases, the total test weight was more than 250 lbm. Since this was the maximum entry possible with the treadmill, 250 lbm was used for these cases.

Servicing of the backpack required the use of several pieces of support equipment. These included the vacuum pump, fill station, power supply, and various consumables.

The vacuum pump was used to check and maintain the insulating vacuum in the AWPS dewar. The current AWPS is a prototype system and uses a large o-ring as a vacuum seal to allow the dewar outer vessel to be easily re-entered. This o-ring allows a very small leakage of gas into the insulating vacuum space. In addition, when a dewar is opened, contaminants such as water vapor, fingerprints, and various gasses enter the system and are "absorbed" by the materials in the dewar. These contaminants must be pumped out of the dewar using the vacuum pump.

The fill station consisted of an insulated box and a series of heat exchangers, valves, and regulators in the box. The box was filled with liquid nitrogen which acted as a heat sink. Compressed air was flowed through the plumbing in the box and was liquefied by the liquid nitrogen. The Liquid air then flowed into the AWPS backpack.

The power supply was used to power the water pump in the AWPS to conserve batteries during the fill and donning process. Consumables used included: industrial grade liquid nitrogen, compressed air, and 9V and C cell alkaline batteries.

4.6.3 Test Hardware Performance and Description

The AWPS hardware performed remarkably well during the evaluation. Several hardware and procedural modifications were made during testing. It was evident after the first couple of tests that the test subjects were having difficulty with their feet. The boots used for testing were procured at a local hardware store and had very inferior footbeds. As a first step to reducing blistering, the booties on the level B suit were removed. They tended to bunch up under the feet and rubbed causing blisters. In addition, the seams were not completely smooth and added to the irritation. In addition, the insoles were replaced with commercial "sport" insoles that nearly eliminated the problem.

A thigh patch developed a leak during donning and was replaced. Later inspection showed several places on the patch that were stressed indicating places where future tears might occur. These stress locations were eliminated in the design of the next generation patch.

An electrical problem caused the pump motor to stop during one test, which caused the LCG water to freeze in the vaporizer. The problem was solved by replacing an electrical connector in the system.

Three temperature sensors were added to the backpack in addition to those on the test subject. The new temperature sensors measured LCG water temperature into and out of the LCG and temperature of the ambient cryogen heat exchanger. All of these sensors were attached to the outside of their respective tubes using thermal mastic and aluminum tape. They helped indicate what was happening with the backpack, and quantitatively how much cooling the test subject was receiving.

During one test run, the LCG water froze in the vaporizer. This occurred with the metering valve open 6.5 turns, providing several standard cubic feet per minute of gas flow in addition to what was being breathed by the test subject. The symptoms of LCG water freezing are loss of body cooling, and a gradual decrease in the temperature of the air being vented to the suit through the metering valve. When these symptoms were identified, the test was terminated. This aborted test was rescheduled for a later day. During Phase II, the metering valve was eliminated because it was seldom used and because of potential failures such as this one.

Test subject access to the metering valve control was fairly limited. When wearing the level B suit, the subject could reach under the "hood" at the waist and actuate the valve. When wearing the level A suit, the subject could manipulate the valve handle through the garment, or withdraw his hand from the sleeve, and manipulate the valve from within the suit. Backpack controls will be much more integrated in future versions of the AWPS.

Gas exhaled into the suit from the mask tended to cause fogging of the outside of the facepiece, and the inside of the suit visor. Commercially available anti-fog solution nearly eliminated this problem at the 85 °F temperatures. At the 45 and 100 °F temperatures, the fogging was much more pronounced. Venting of exhaled gasses outside the suit would greatly improve fogging problems, as well as heat build-up in the head area.

A fluctuation in the system pressure was noticed during the first third of each test. Before the tests started, the backpack was pressurized to 60 psi (operating pressure). Shortly after the test subject began breathing, the pressure dropped to approximately 40 psi. The pressure then gradually built back up to the operating pressure during the next 20 minutes. This issue was addressed early in Phase II during breadboard testing of various pressure control system configurations.

Due to variations in body shape and LCG sizing, different test subjects noticed varying amounts of cooling in different body parts (particularly arms and legs). These variations are due to changes in LCG water flow through the patch garment. As the body position is changed, the pressure drop through the patches varies, thus causing changes in water flow. Future LCG designs minimized the effects of body movement on flow variations.

One of the tests was terminated in part due to a complaint from the test subject of a headache. It was later determined that the test subject overly tightened the mask and hard hat straps.

The capacity display on the mask indicates quantity in eighths. The indicators show from a single red light to eight green lights. During this testing, the empty indication was closer to 2 lights, while the full indication was 7 lights. Updating this display is a simple matter of reprogramming the decoder proms.

Integration of radio communications was fairly clumsy during these tests. There were basically two problems, clarity and accessibility. The microphone was positioned outside and very near the speaking diaphragm in the mask. This placement added distortion to the speech. Typically, SCBA users talk very loudly to be heard. This tendency also added to the speech distortion. The other problem was the location of the push-to-talk button. This was a large (1" diameter) button with excellent tactile feedback located on the radio body. The radio was attached to the shoulder strap near the waist. With all of the other things located at the waist, it was difficult to locate the radio switch. During Phase II, this problem was solved through the use of a Scott facemask and microphone specifically designed for this application. Scott's design does not require a push-to-talk button.

4.6.4 Test Observations

An extensive amount of data were collected during this evaluation. While much of this data is presented in the topical report completed at the end of Phase I, additional observations and findings are offered in this section.

There were a number of contributing factors which affected the outcome of some tests, and in some cases, these factors caused tests to be prematurely terminated. Some examples include, blisters developing on the feet of one test subject, headache due to overly tight mask straps, and failure to increase cooling. The latter problem was more an artifact of the testing given the unfamiliarity of the test subjects with PLSS technology. In general, cooling was increased at 15 intervals and at the request of the test subject. This led to variable cooling levels for individual test subject; however, cooling perception is subjective and needed accommodation during these tests.

There were relatively few physiological response differences between the two different types of suits for each test subject. Since the materials used in the construction of each suit were impermeable, the environment immediately next to the test subject's body became rapidly saturated as expelled humid air was released from the breathing mask (of PLSS or SCBA) into the suit. The Level B ensemble should allow for better air exchange with the outside environment compared to the Level A ensemble since it is not of an air-tight design. Relative humidity inside the suit was not measured in any of the tests but no difference between different ensembles on the basis of humidity was perceived. In general, the inside of the protective garments were soaked with perspiration following each test.

Figures 4.6-1 and 4.6-2 illustrate the dramatic improvements in duration and thermal comfort possible with the AWPS. The two graphs show skin temperatures for the same test subject wearing a level A suit with an SCBA and the AWPS respectively.

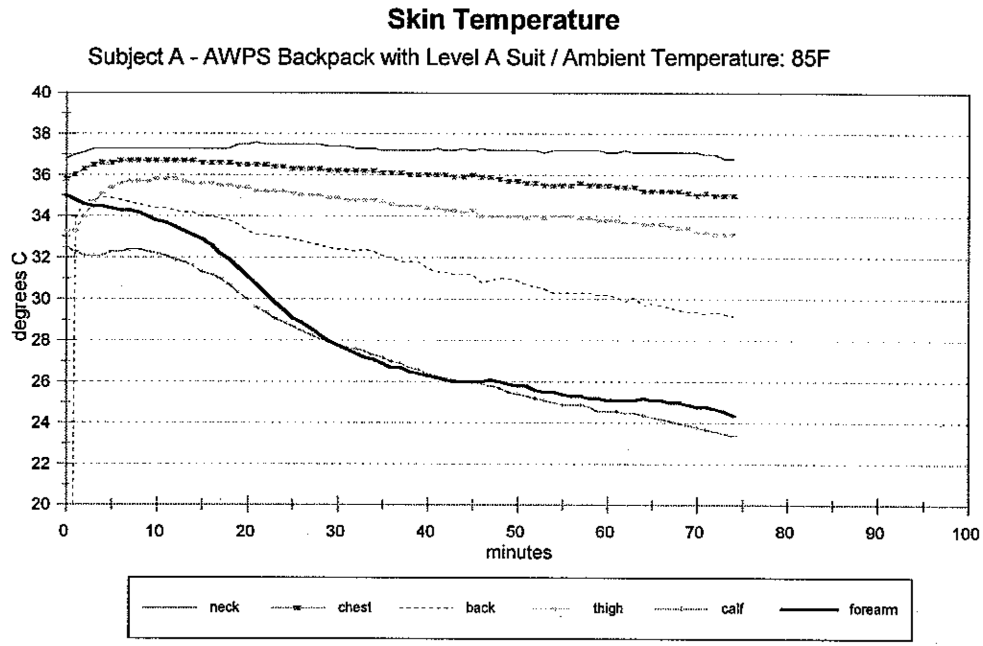


Figure 4.6-1: Representative Skin Temperature Graph with AWPS Backpack

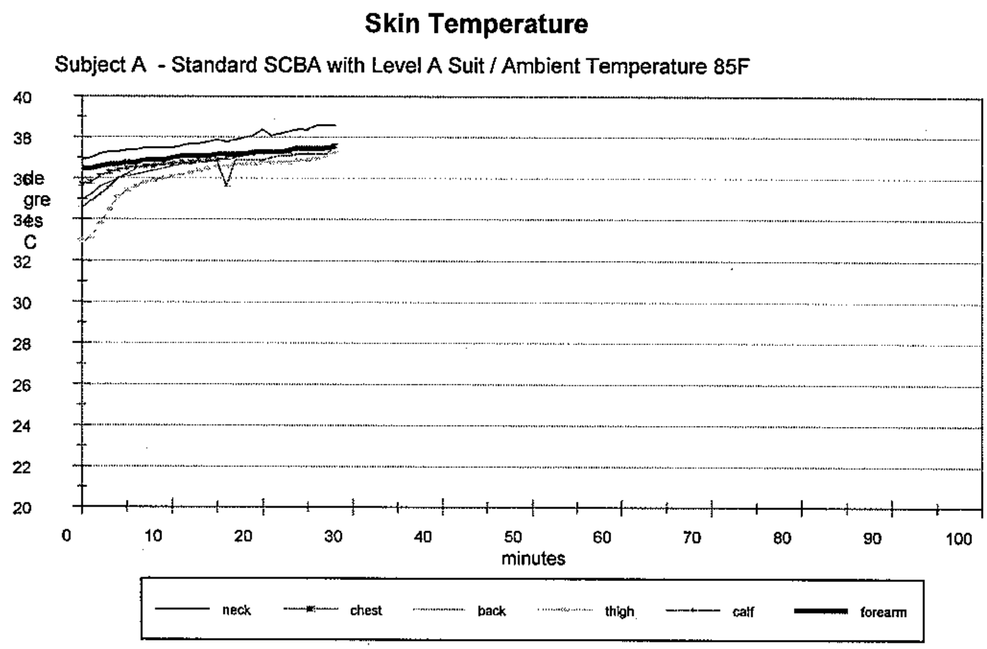


Figure 4.6-2: Representative Skin Temperature Graph with SCBA

Two major observations from these graphs are the overall duration and the rise (or fall) of skin temperatures. The first graph (SCBA) shows a duration of approximately 30 minutes, and all the skin temperatures show an increase. In comparison, the AWPS graph shows a duration of approximately 75 minutes, with a much smaller rise in skin temperatures. In fact, several of the measurements consistently decrease.

Skin temperatures are a good indication of perceived thermal comfort. Core temperature is a much better measure of actual thermal condition and shows how much heat the body is losing or storing. People naturally have different core temperatures, and that temperature varies throughout the day. In addition, the important information from core temperature is how it changes. For both of these reasons, core temperature difference is shown on the next graph. The core temperature at the beginning of the test was taken to be zero, and all subsequent temperatures were plotted as a difference. This graph is for a level B suit and includes five different tests, baseline, SCBA and AWPS at 85 °F, and AWPS at 100 °F and 45 °F. Again, the observations to be made from this graph are duration and rate of temperature change.

The baseline test was conducted with the test subject wearing only shorts, a T-shirt, and running shoes. The other tests (on this graph) were conducted with the test subject wearing coveralls, the cooling garment (for the AWPS tests only) the backpack and a level B suit.

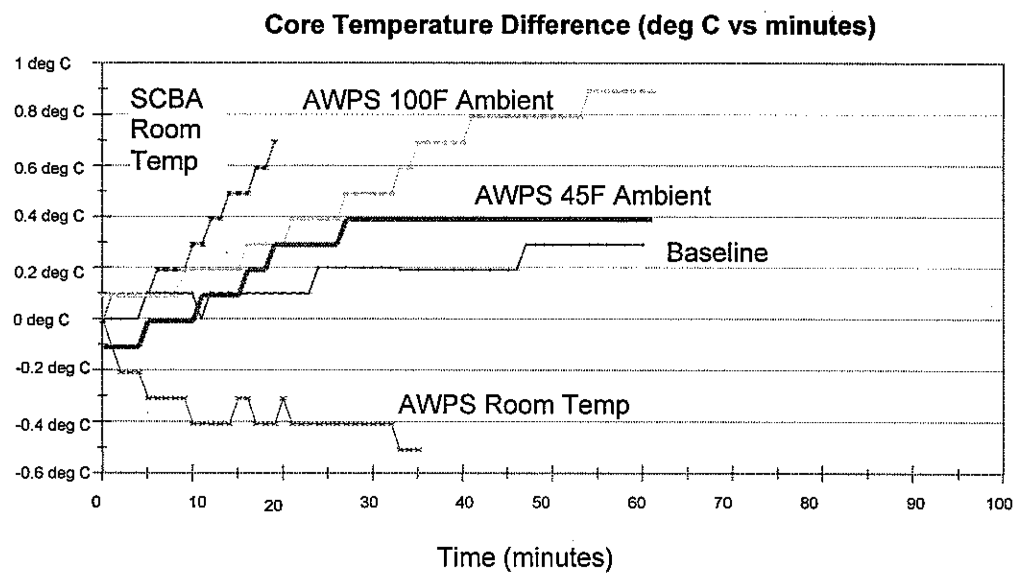


Figure 4.6-3: Representative Core Temperature Graph

Looking at the slopes of the core temperatures, the 85F AWPS test actually shows a decreasing core temperature. This test lasted for approximately 35 minutes and was terminated early due to fatigue and sore feet. The baseline and 45 °F AWPS had the smallest core temperature rise. Both tests lasted approximately 60 minutes and had similar core temperature increases. The 100 °F AWPS had the next fastest core temperature rise (~0.9C) and a duration of 65 minutes. The SCBA (with no cooling) had the steepest core temperature rise of 0.7 °F in 20 minutes. A good indication of thermal stress is a core temperature rise of 1 °C. The SCBA test would have reached this level at approximately 28.5 minutes, less than half the duration of the 100 °F test that had a 15 °F warmer environment.

The design of the Level A encapsulating chemical protective suit posed no problems on any of the test subjects during the evaluation. The Level A design follows a commercial product and incorporates many features which have been accepted by the industry for suits of this type. Nevertheless, these suits are bulky, present wide profiles, and are relatively difficult to don, requiring the assistance of at least one helper. Test subjects were able to freely move with the Level A suit but did have some restrictions in mobility and field of vision. Other observations included:

- Donning difficulties appeared to be affected by the placement of the closure in combination with the PLSS profile. A lower profile PLSS will substantially improve ease of donning. A second donning problem occurred when inner plastic gloves became displaced from the outer rubber glove. This problem was obviated in the testing by cutting the inner glove out of the suit so that testing could be continued. The suit should be designed with a single layer glove system or multiple glove system which does not allow the inner glove to pull away from the outer glove.

- Fogging of visor, from release of humid air inside ensemble, was particularly a problem at the elevated test conditions. This problem was minimized with the application of a anti-fogging agent on the inside of the visor. One other possible design change would be to route some air from the PLSS to flush across the visor to sweep humid air from depositing moisture on the visor's inner surface.

- While the test subjects were of average build, the one size concept did not appropriately accommodate each tests subject for proper fit. Improvements in fit could be achieved by providing a wider range of sizes. However, since Level A suits are primarily for use during chemical emergency response, and would be less frequently used as compared to Level B ensembles, the additional sizing for this suit may not be cost effective.

The two-piece Level B Liquid Splash-Protective Suit appeared to provide a better fit than the Level A suit and resulted in less mobility and field of vision problems. Two test subjects had problems with the sleeve length and gloves. Additional problems were encountered with the outer boot/bootie design. Even with proper donning, the bootie seam sometimes would be a location next the foot causing blisters or discomfort. As these observations were made during early tests, the booties were removed and outer boots used exclusively for foot protection. The Phase II splash suit will have re-designed booties, possibly enlarged to allow street shoes to be worn inside the suit, with a larger outer boot.

The incorporation of sizing, in addition to the improvements identified above, for the Level B suit should allow for improved comfort, fit and mobility. Currently, liquid splash suits may be offered commercially in standard sizes, often small, medium, large, and extra large. The two-piece design afforded by the prototype Level B suit provided flexibility in fitting the size ranges of the study test subjects, because different heights could be easily accommodated by the movement of the upper torso protective part in relation to lower bib-coverall with adjustable suspender-like straps.

4.6.5 KSU Evaluation Conclusions

The Independent evaluation conducted at Kansas State University verified the AWPS' positive effect on user safety, health and productivity. The test subjects were able to work for twice as long using the prototype AWPS compared to the standard SCBA, even with the weight and footwear problems. The testing also provided important design information on operations in a variety of environments. The backpack, the most complex part of the AWPS worked well throughout the testing, with no significant hardware failures.

The independent evaluation also revealed important findings on the design of the two prototype chemical protective suits. Following the evaluation, OSS identified several design improvements. For the Level A system, these include a provision for expelling breathing air to outside the suit, using a single glove, and flowing air across the visor. For the Level B system, proposed design changes will encompass modified glove and boot interfaces together with the incorporation of sizing.

4.7 Phase I Summary

The performance criteria for the AWPS was developed during Phase I with both an understanding of the AWPS capabilities combined with the identification of DOE Decontamination and Decommissioning activities protection needs. Testing of a prototype AWPS demonstrated the system's ability to meet these criteria.

The unique features of the AWPS will allow it to be used in environments and situations beyond the capability of current systems. Furthermore, a review of current DOE practices has identified several areas of concern which can be rectified with the introduction of the AWPS. The AWPS can reduce DOE inventory needs, reduce selection problems (by providing DOE with a single system that will be suitable for most needs), enhance personnel protection, safety, and provide significant gains in worker productivity.

During Phase I, OSS identified all applicable regulatory requirements with regards to the respirator, pressure vessel, protective suits, helmet, and support equipment. Regulatory requirements for DOE use, as well as those that govern the use of the AWPS once in production, have had a bearing on the design of the AWPS. In-house testing of various components and subsystems provided OSS with the information needed to modify the designs during Phase II to ensure the AWPS meets all of the applicable requirements.

Compliance with these regulatory and similar requirements will be demonstrated through an extensive battery of testing, and certification of individual components by the appropriate authorities.

Visits to three key DOE remediation sites yielded the information necessary to perform a cost benefit analysis, with positive results. A model was developed to determine the equivalent life cycle costs of various configurations of the AWPS. This information was used to compare the AWPS with systems currently in use. Using a specific scenario deemed representative of DOE D&D activities, the determination of life cycle costs has shown the

AWPS will provide a savings of over $700K (based on a total life cycle cost of $1.7 Million) for a 5000 man hour job when compared to similar costs for existing protective clothing and equipment. This type of scenario is likely to be repeated many times over the 30 year period as the DOE undertakes specific D&D tasks at its various sites which require self-contained breathing air. Through a similar analysis, productivity gains of 100% or better were shown as well as lower potential medical and liability costs through better worker protection.

The prototype hardware developed in Phase I served to verify the design approaches for the AWPS, and gathered manned operations and integration information. The testing at KSU provided the performance data needed to optimize the Phase II hardware, as well as providing independent verification of the AWPS' effectiveness. Technical problems highlighted in the testing, particularly the weight of the backpack, are being solved in an independent research program nearing conclusion at OSS. This work, along with the Phase I activities, lowered the technical risk for Phase II of the AWPS project.

Independent testing at the KSU's Institute for Environmental Research provided a comprehensive test subject evaluation of the AWPS, showing significant increases in human subject endurance and comfort when compared to traditional SCBA-based ensembles. These tests also demonstrated continued performance of the backpack without any major failure and the efficacy of the liquid cooling approach when integrated with chemical protective clothing. The duration that human subjects were able to sustain as compared to the SCBA-based ensembles validated assumptions made in the life cycle cost study, where major benefits are realized from increased extended mission performance and increases in productivity.

At the completion of Phase I, OSS possessed the confidence in the AWPS design to proceed with full-scale AWPS development during Phase II.

5.0 Phase II

5.1 Overview

OSS refined the AWPS design during Phase II to address the issues identified during Phase I. Specifically work focused on verifying the system would meet all applicable requirements, reducing the system weight and production costs, increasing system performance, and improving system reliability and robustness. During this phase, OSS also entered into a business agreement with Scott Health and Safety Products, the leading supplier of Self Contained Breathing Apparatus (SCBAs) in the United States. Scott was to develop the design for all backpack components external to the dewar, head up the certification of the system, and market the units. A more thorough discussion of Scott's participation is provided in Section 5.7.

Initially, OSS began to resolve the design and fabrication issues associated with a plastic cryogenic pressure vessel and a titanium vacuum vessel. Many of the fabrication issues, such as attaching stainless steel tubes to a plastic vessel and forming the titanium outer vessel in a cost effective manner, were resolved within the first six months. However, the

LCP (plastic) inner vessel at that time did not provide an adequate factor of safety on burst pressure.

As a result, OSS built a smaller, one-hour duration engineering development unit that had been designed in support of the NASA Kennedy Space Center (KSC) contract discussed in Section 2.2. This unit was used to test different pressure control schemes and operating pressures. It was hoped the operating pressure could be dropped to 25 psig to avoid the need for a DOT certification of the pressure vessel and to provide an ample factor of safety on burst pressure. The testing indicated that the operating pressure could not be lowered below 40 psig and still maintain a positive pressure in the mask while breathing, a NIOSH requirement. During these tests, OSS switched from the Interspiro mask and regulator used during Phase I to a commercially available Scott mask and regulator that Scott had modified to operate at lower pressures.

During this time, OSS also performed a second FMEA and then updated the basic schematic to accommodate changes in the pressure control system and to incorporate needed safety features identified in the FMEA.

In early 1996, Scott began to take an active interest in the backpack design. They tested one of the one-hour development units and identified some drawbacks in the design. OSS worked to improve the design to eliminate these drawbacks and to reduce the system weight. OSS also worked on maturing the designs of the LCG and the outer protective garment, and on increasing the burst pressure of the inner vessel.

A Preliminary Design Review was held in April 1996. At this review, the inner vessel was the only component considered to still need a significant amount of work. The previous work indicated the vessel could not be strengthened without making it thicker and thereby exceeding the weight budget for the inner vessel.

Shortly following the design review, a new inner vessel shape was identified which could reduce the inner vessel weight and provide an adequate factor of safety on burst pressure. The new shape affected most of the dewar components and required several components, such as the pickup mechanism, the capacitance gauge and the outer vessel, to be completely redesigned. OSS spent the following seven months updating the design to accommodate the new inner vessel shape and to incorporate design features identified during testing of the one-hour development units. OSS also changed the design of the suspension system from the cones developed during Phase I to a spoke tension system. The spoke tension suspension system more easily integrated with the new vessel shapes, reduced the backpack weight, and reduced heat leak into the inner vessel.

During this time, OSS developed two one-hour systems to be used in a system evaluation by the International Union of Operating Engineers (IUOE). One-hour systems were used in the evaluation because the one-hour design was preceding the two-hour design; the one-hour system was being developed in parallel for use by fire fighters at the NASA Kennedy Space Center. New LCGs and outer protective garments, as well as a recharge station for filling the backpack with liquid air were also developed. The evaluation was conducted in

September of 1996 and provided useful information that was used to improve the design of the APWS and the support equipment.

A formal agreement between OSS and Scott was also signed during this time. Scott was to finish the design of the bottom box, pursue NIOSH certification of the system, and market the units. Minnesota Valley Engineering (MVE) also agreed to join the team. MVE is the nation's largest manufacturer of commercial dewars. MVE was brought on board to produce the dewars for commercial units. It was not expected that MVE would play a significant role in the AWPS project.

Initial testing of the new inner vessel design was not promising. The vessel burst at much lower pressures than predicted. The vessel design was modified slightly and stiffening rings added. The new design was tested in January of 1997 and proved to have an adequately high burst pressure.

Two two-hour prototype units were then assembled and tested at OSS. These units were used in a series of manned tests at OSS. The tests focused on evaluating the performance of the LCG and outer protective garment. Based upon this testing, OSS improved both of the garment designs by eliminating patch pinch points and increasing the garment comfort. The two-hour prototype units were then used in a second IUOE evaluation conducted in October of 1997. Minor improvements were made to both the backpack and garment designs based upon the IUOE evaluation.

The design documentation, such as drawings and assembly procedures, was then completed and 6 dewars were built and tested with quality controlled hardware and procedures. These dewars were to be used for NIOSH certification. During checkout of the qualification dewars, problems were encountered which led to a redesign of the pickup mechanism.

Scott became increasingly concerned about the projected dewar production costs, its weight, and the slippage in schedule as a result of the design modifications. As a result, the agreement between OSS and Scott was terminated. This left OSS financially responsible for not only completing and testing upgrades of the dewar, but also of completing the development of the remaining backpack components that were Scott's responsibility and of NIOSH certifying the system. The cost for this work would have far exceeded the remaining AWPS budget. As a result, OSS aggressively pursued other partners to fill the void left by Scott. At the writing of this report, OSS has not been successful in locating a partner with which to team.

In parallel, OSS worked on upgrading the dewar and LCG designs. OSS also documented the work performed under the AWPS contract and compiled this final report. The following sections of the report discuss the specific work and progress made on the individual sub-systems during Phase II. An overview of the IUOE evaluations is also presented along with a discussion of the remaining design issues.

5.2 Dewar Development

The dewar is the heart of the AWPS. It stores and supplies air to the user via the bottom box, in any orientation. The design of an all position dewar which meets all of the performance specifications within the given weight budget represents the greatest technical challenge in the AWPS project. As such, much of Phase II focused on dewar development. The dewar consists of seven primary subsystems; the inner vessel, the pickup mechanism, the capacitance gauge, the outer vessel, the suspension system, the vaporizer and tubing, and the dewar insulation. The evolution of each of these systems during Phase II is described in the following sections.

5.2.1 Inner Vessel Design and Certification

A significant effort during Phase II focused on the development and DOT certification of the LCP inner vessel. OSS first addressed the issue of sealing the metal tubes, which run between the inner and outer vessels. The tube used to fill the inner vessel was first moved from its previous position on the periphery of the inner vessel up into the metal center hub. Thus both the fill and vent tubes were each welded to one of the metal hubs which then had to be mounted in the center of each vessel half.

Several options, ranging from injection molding the hubs into the vessel halves to spin welding the hubs in place, were considered. The option that offered the greatest chance of success was gluing the hubs in place. Several different glue joints, epoxies, and surface preparation techniques were investigated. A breadboard fixture of the design was built to test different configurations. The final solution used a flexible metal diaphragm welded to the hub and then glued to the LCP. This design is presented in Figures 5.2-1a and 5.2-1b. The hub is located on the left of Figure 5.2-1a while the welded diaphragm/hub assembly is located on the right. Figure 5.2-1b shows the hub glued to an inner vessel.

Hysol epoxy was selected to glue the hubs in place due to its strength and durability at cryogenic temperatures. The flexible diaphragm was capable of flexing to accommodate differential thermal expansion between the metal hubs and the LCP inner vessel. The design also provided substantial surface area for the glue joint. The methods of preparing the surfaces and curing the epoxy were perfected and documented in a quality controlled procedure. Additional breadboard fixtures were built and then used to test the design's durability. The fixtures were continually cooled to liquid nitrogen temperatures and then warmed up, see Figure 5.2-2. Periodically, the fixtures were helium leak checked. In 600 cycles the only leaks detected occurred in braze joints used to connect tubes to the metal hub. No failures in the glue joint were detected.

Work also focused at this time on strengthening the inner vessel. A sketch of the original vessel shape is included in Figure 5.2-3. Mold modifications were first completed to prevent the warping of the vessel half edges observed during Phase I. It was expected this would increase the strength of the joint between the two vessel halves.

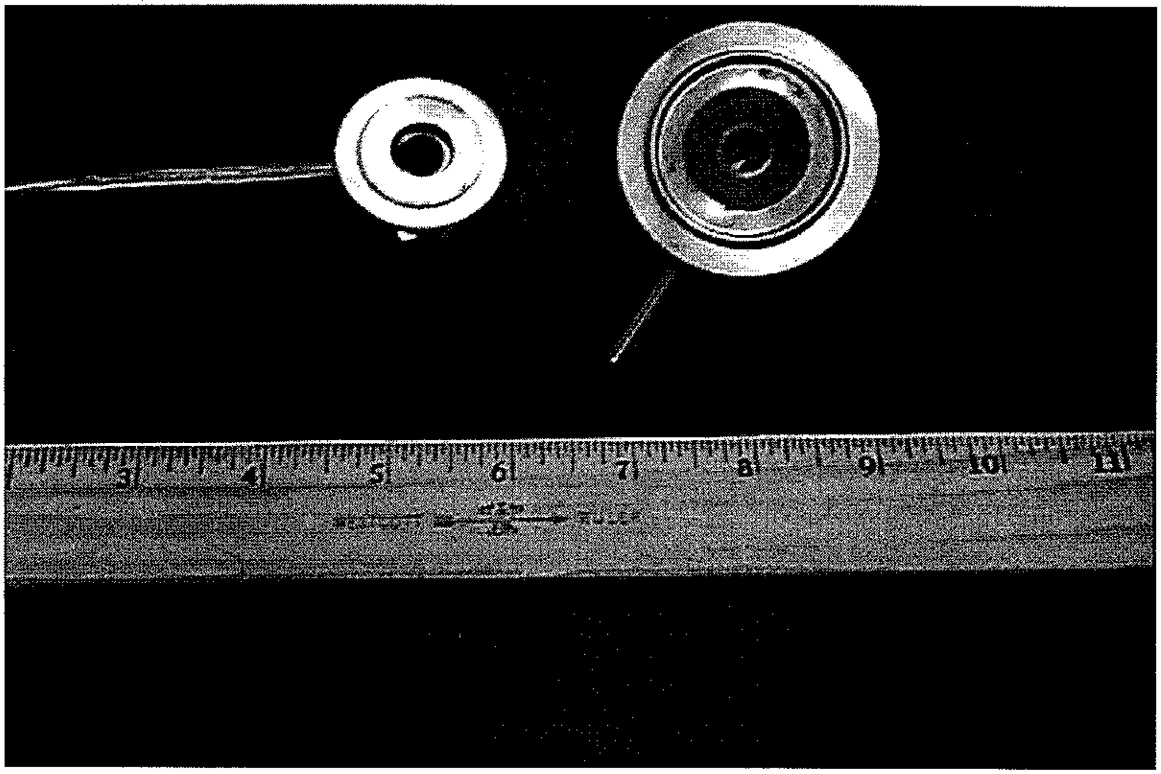


Figure 5.2-1a: Center Hub Joint

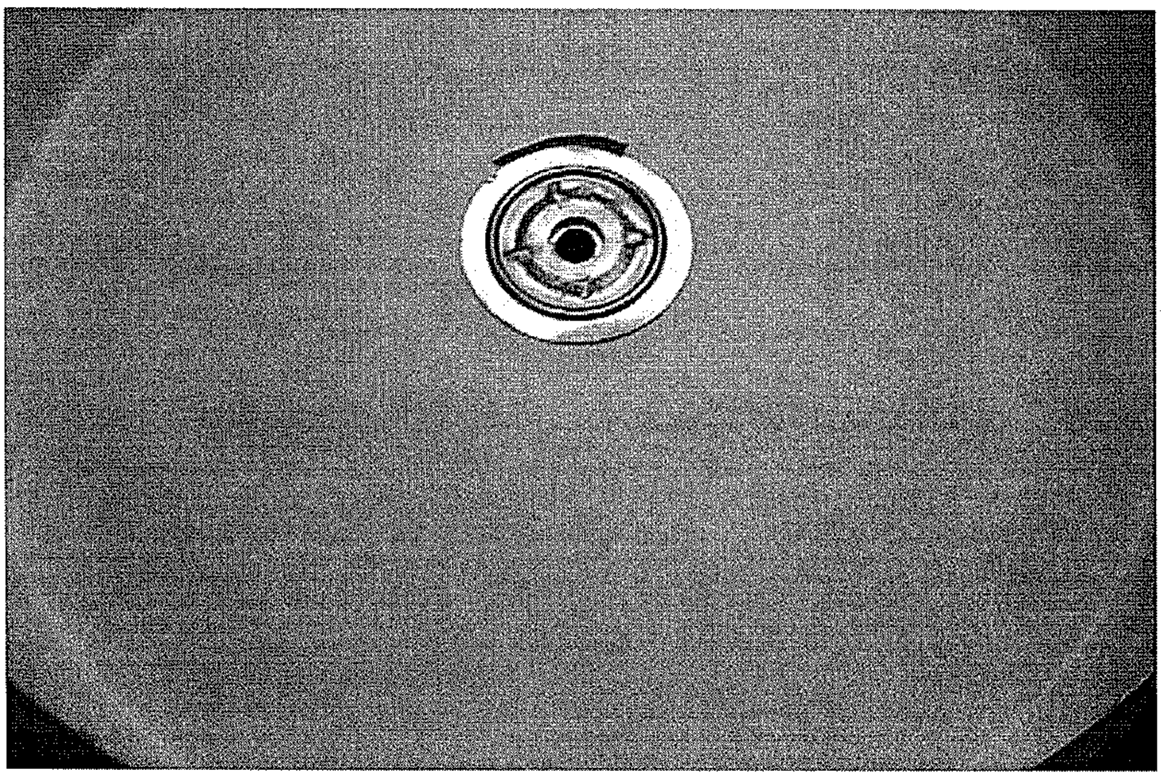


Figure 5.2-1b: Center Hub Glued to Inner Vessel Half

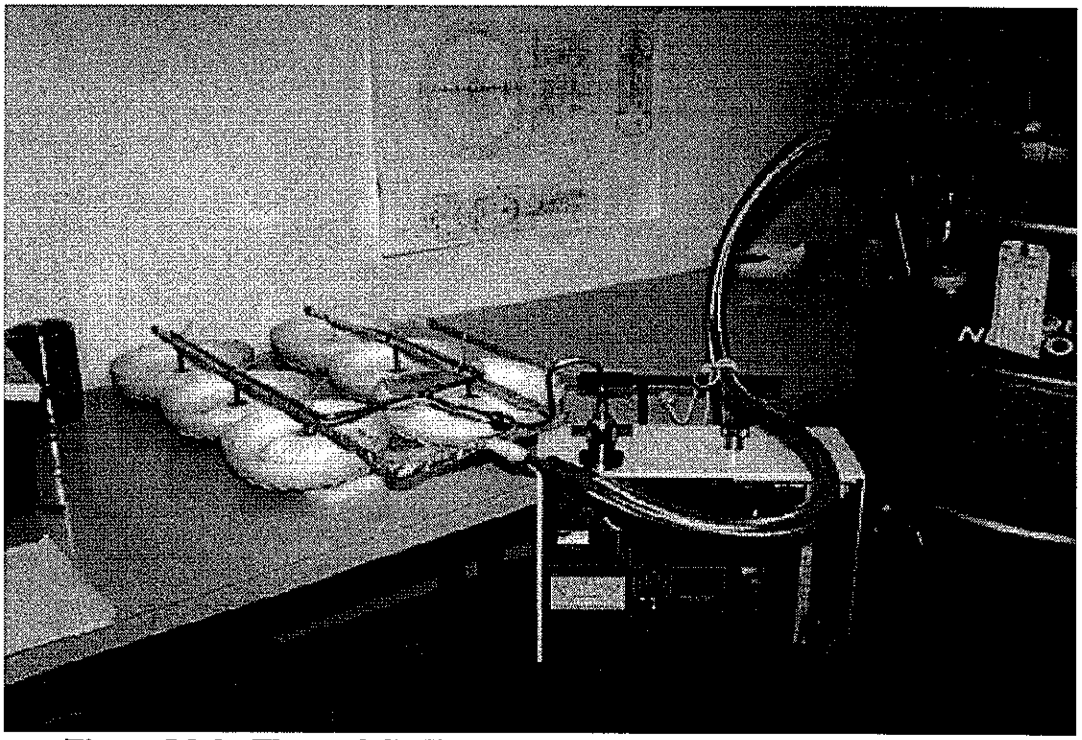


Figure 5.2-2: Thermal Cycling Testing of Inner Vessel Diaphragm Hub

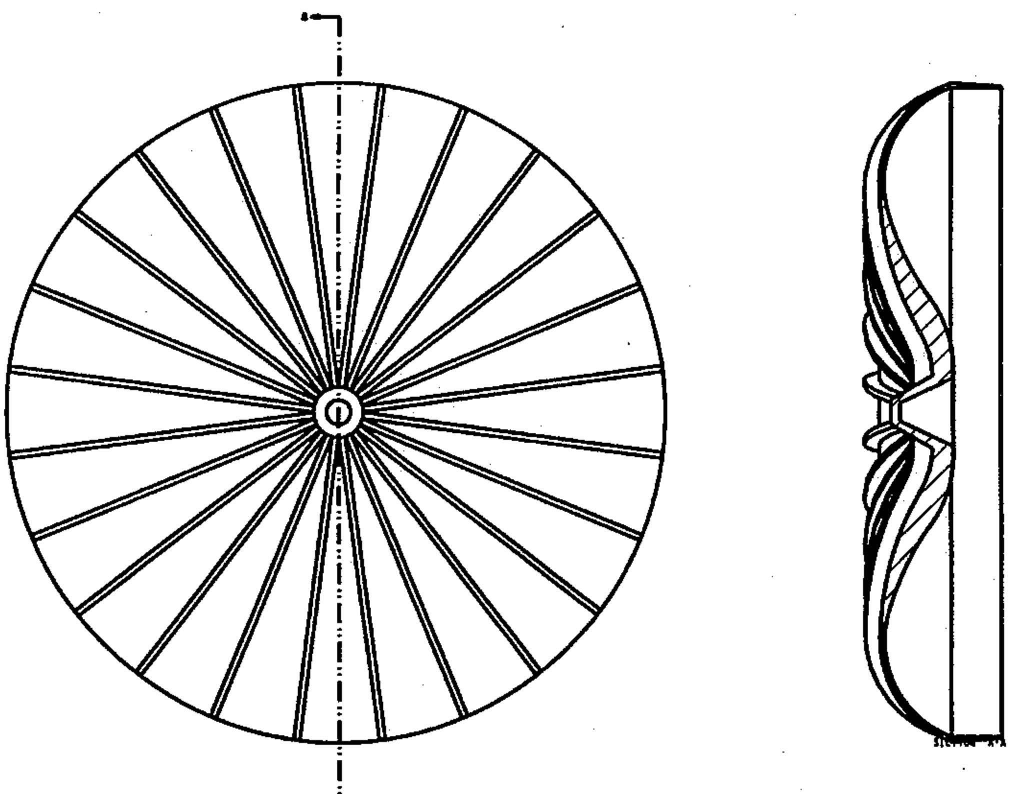


Figure 5.2-3: Original Inner Vessel Shape

Once the mold modifications were completed, a set of 20 vessels were injection molded. Several vessels were assembled and pressurized to failure in a burst test using liquid nitrogen. Unfortunately, the vessels burst at too low of a pressure; the average burst pressure for the vessels was 95 psi. As a result, additional finite element analysis was performed to further strengthen the design. The anisotrpoic properties of the LCP were more accurately modeled in this additional analysis. The parametric FEA model developed to analyze the inner vessel is presented in Figure 5.2-4. The model shows one quadrant of the inner vessel, the outer vessel, and the suspension system. The outer vessel and suspension system were included in the model because these structures helped carry the pressure loads on the inner vessel. During this process, we used our Pro-E models that were developed to fabricate the inner vessel mold and document the design to develop the finite element model, thereby reducing the time required to analyze the vessel.

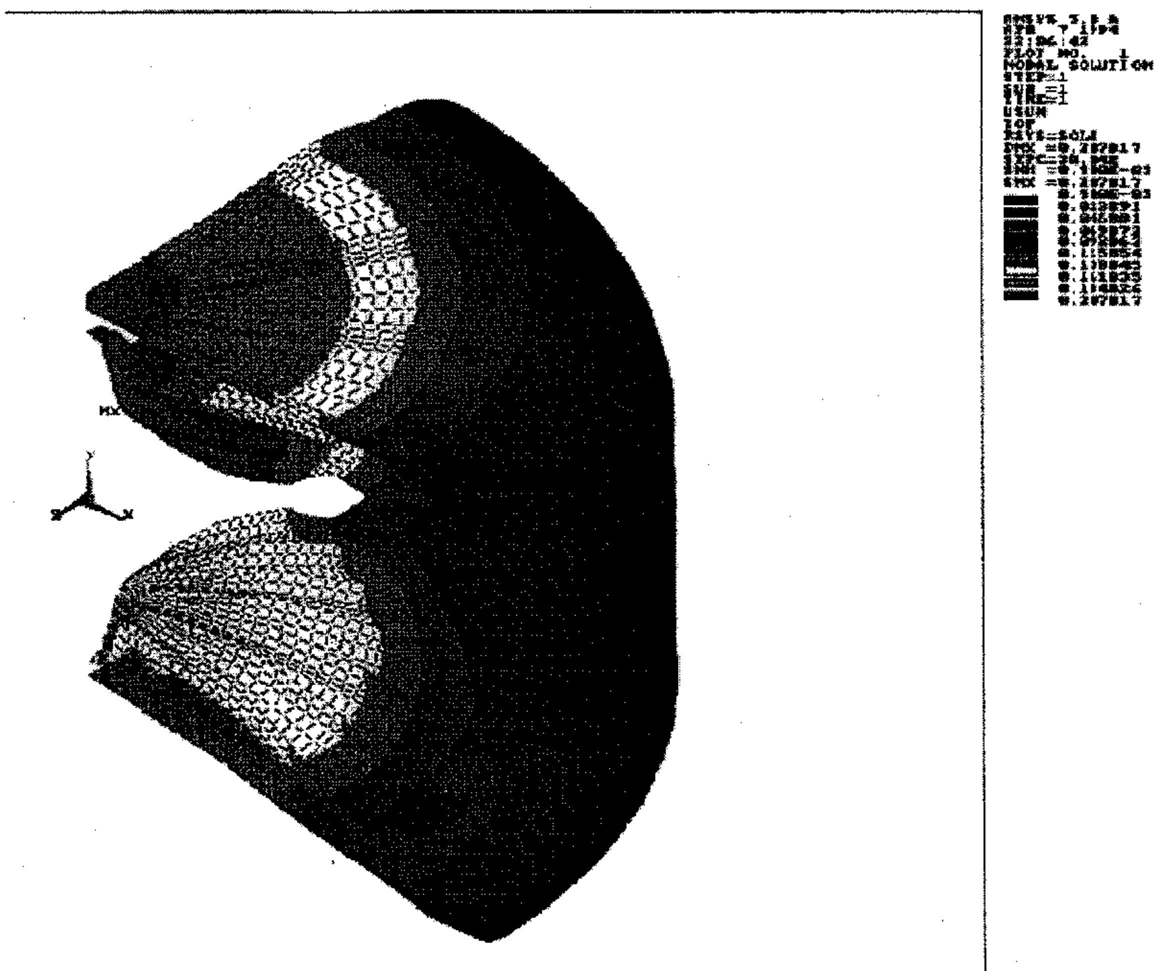


Figure 5.2-4: Inner Vessel FEA Model

We also consulted a mold flow expert for suggestions on eliminating knit lines and increasing the vessel strength. The consultant ran FEA flow models of the injection process to determine where knit lines, weak spots, may form. A sample analysis is presented in Figure 5.2-5. As indicated in the figure, knit lines were expected to form on the ribs.

However, the consultant believed that the extra material in the ribs would compensate for the weakness caused by the knit lines.

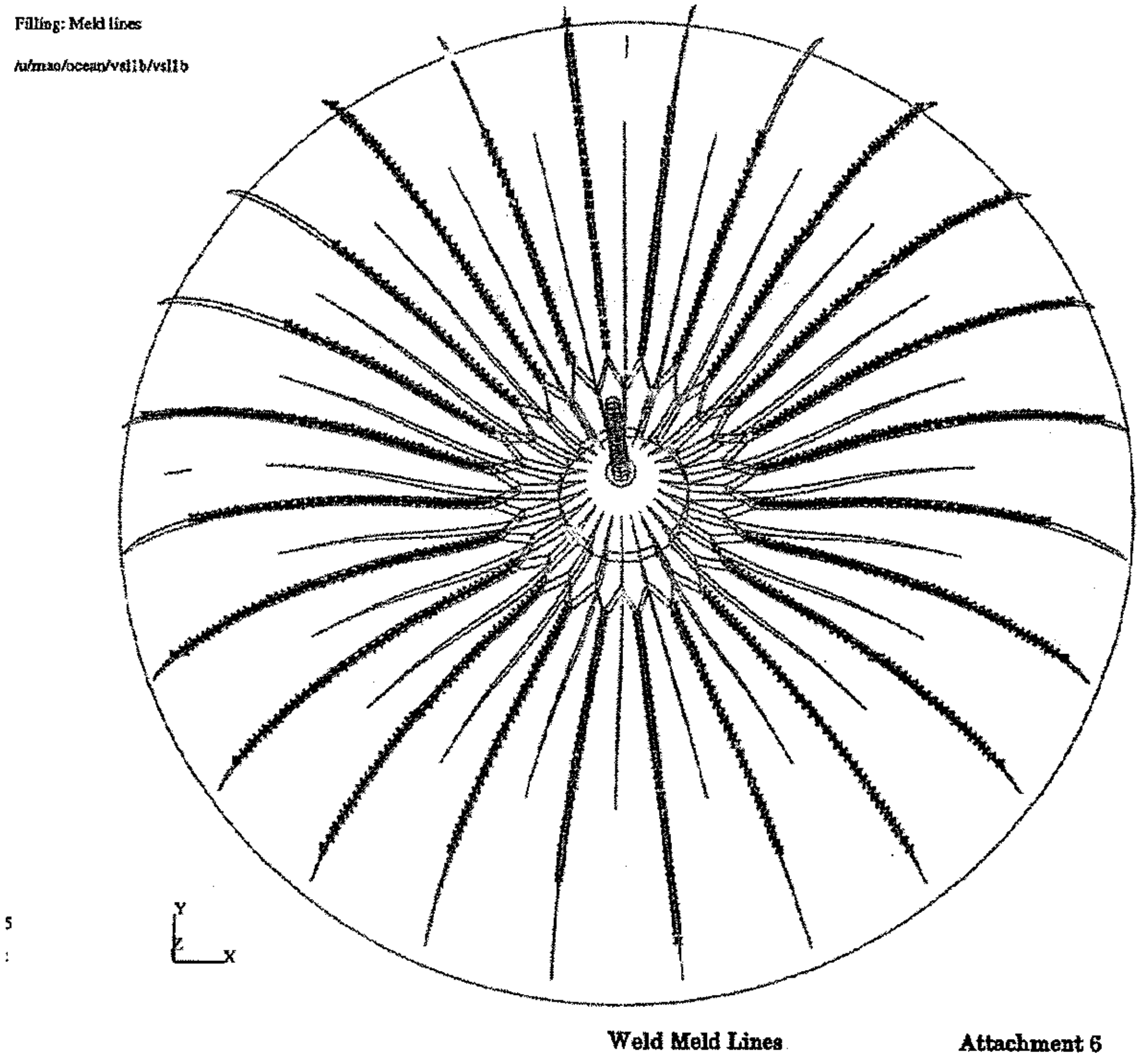


Figure 5.2-5: Mold Flow Analysis

After extensive analysis, we concluded the vessel could not be strengthened without significantly increasing the weight of the inner vessel. The projected backpack weight already exceeded the 40 pound NIOSH limit and so increasing the inner vessel weight was not an attractive option.

Shortly after this, in April of 1996, a new design for the AWPS inner vessel was conceived. After several months of analysis this new inner vessel shape was adopted. The new shape has a cross section of a double headed axe; a central sphere intersected by two opposing spheres. The central sphere makes up the side walls and the opposing spheres are the inverted end caps. The use of traditional pressure vessel shapes (sections of a sphere) allowed stresses to be reacted in compression in the dishes and tension in the side walls rather than in bending. A sketch of the new shape is presented in Figure 5.2-6.

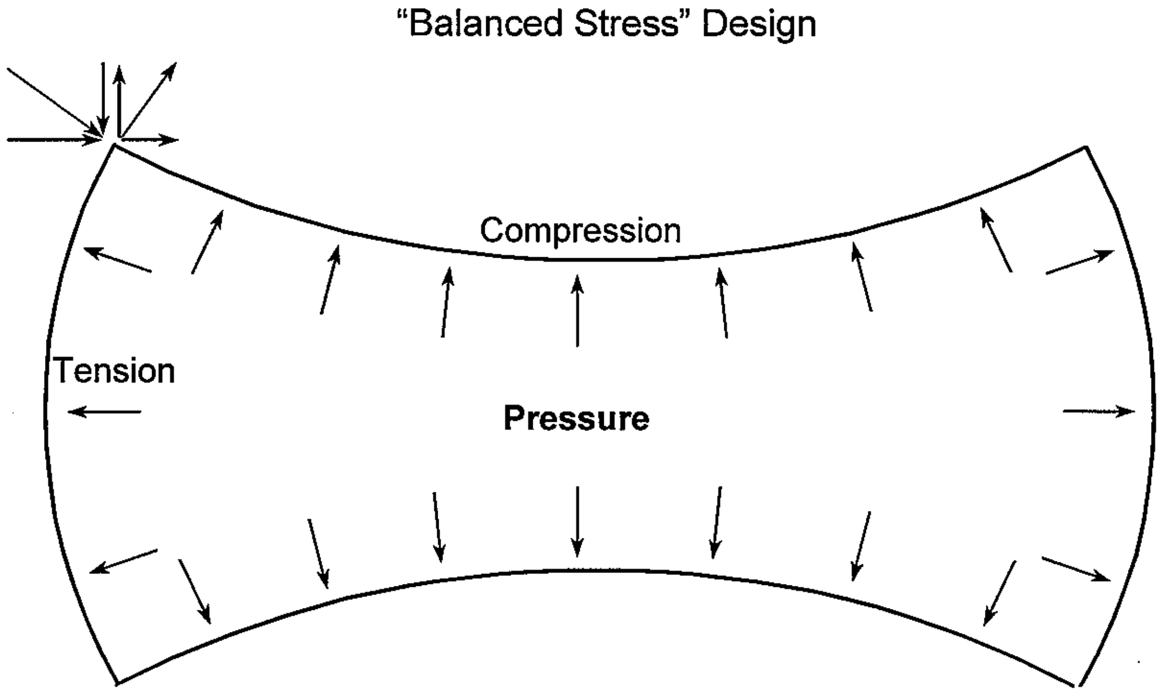


Figure 5.2-6: New Inner Vessel Shape

The new design looked promising for weight reduction and improved safety margins. However, it still required significant refinement. Design variations investigated included wall thickness, hub dimensions, corner dimensions, and size of sphere sections. The new shape also required the design of a tension ring that stiffened the vessel in the hoop direction at the intersection of the end caps and side wall. Incorporating a tension ring allowed us to investigate switching from our compression cone suspension system to a tension suspension system, see Section 5.2.5.

During this redesign effort, we also considered fabricating the inner vessel from a variety of metals, such as a 300 series stainless steel or Inconel. The new vessel is axi-symmetric and so could be readily manufactured using standard metal working techniques like stamping, deep drawing, or spinning. However, analyses indicated that a metal vessel would weigh at least 1.5 times the weight of an LCP vessel.

Manufacturing of the inner vessel mold commenced after a satisfactory design was developed. Due to the symmetry of the inner vessel and the expense of injection molds, both the male and the female halves were molded from the same tool with interchangeable inserts to form the male or female glue joint. This drastically reduced the cost of the tool by not requiring an entirely separate tool for each half. The basic lap glue joint design for the perimeter glue joint from the previous inner vessel mold was successful, therefore the same basic concept was used again in the new inner vessel design. It consists of feathering the edges of each half with the mating interface being 3 degree parallel surfaces. The male half fits inside the female half, and a hard stop provides accurate location of each half with respect to one another. When assembled, the glue joint design provides a relatively constant wall thickness throughout the side wall. The feathered edges allow the joint and glue to flex at each end of the joint where the glue is weakest. Without the feathered edge, the glue would be pulled in tension, it's weakest strength, by a stiff section of plastic. Lessons learned from the previous inner vessel glue joint allowed us to predict the molding induced warpage of the parts fairly well and to compensate for the warpage in the design of the glue joint inserts.

Initial tests of parts formed using the new injection molding tool resulted in disappointingly low hydrostatic burst pressures ranging from 68 psi to 83 psi. During these tests we measured displacement at various point on the inner vessel and tension ring. This data indicated that the ring was not stiff enough to prevent the edge of the vessel from rotating outward, as indicated in Figure 5.2-7. This placed significant bending stresses on the outer walls directly below the ring and caused the vessel to rupture at pressures lower than expected. Several materials and configurations of the tension ring were investigated and tested before an aluminum ring with an L shaped cross section was selected.

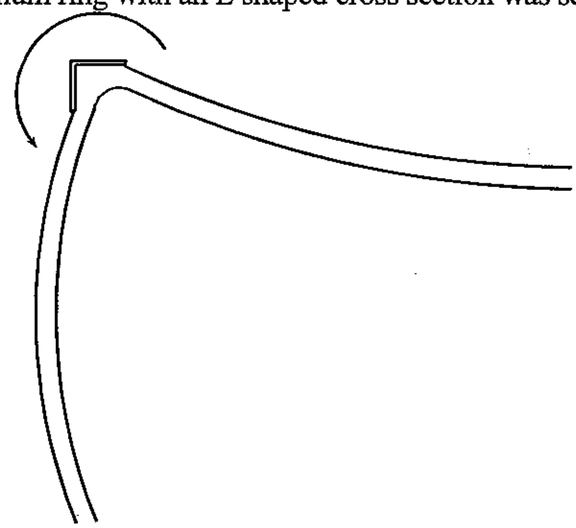


Figure 5.2-7: Rotation of Vessel Outer Edge Leading to Failure

The new ring design increased the burst pressure approximately 25 psi; the burst pressure ranged from 95 psi to 103 psi. Additional burst tests indicated that the dished end caps were now the weak point. The dished end caps were buckling in a low stress area that had been thinned to save weight. The injection molding tool was modified to increase the wall thickness in this area. New vessel halves were molded, assembled, and tested with the new rings. The new design provided the needed factors of safety. During hydrostatic burst tests the vessel burst between 145 and 155 psig, and during cryogenic burst tests the vessels burst between 165 and 190 psig. These burst pressures were acceptable because the dewar's operating pressure had been dropped from 60 psig to 40 psig; use of a Scott regulator modified to operate at lower pressures allowed the system pressure to be reduced.

During this process various epoxies were tested to identify the one best suited for gluing the two vessel halves together. The epoxy we had been using proved to be the best choice. The testing however highlighted the importance of following the proper procedures for cleaning the surfaces and gluing the vessel halves together.

Following successful burst testing, a prototype unit was built up and repeatedly tested to ensure the dewar contained enough liquid air to provide a two hour duration. There was some concern over the system's duration because the modifications made to prevent buckling on the outer dish slightly reduced the inner vessel's internal volume. During each test, the prototype system was filled and then connected to a mechanical breathing machine. The breathing machine was set to the NIOSH standard rate and allowed to operate until the prototype backpack was empty. The backpack provided sufficient duration. The tests lasted from 130 minutes to 140 minutes.

NIOSH requires that the AWPS pressure vessel storing the liquid air be DOT certified. The AWPS most clearly falls under the category of 49 CFR 178.57 Specification 4L; welded cylinders insulated. However, due to the materials of construction and the special nature of the overall system, exception was taken to almost every paragraph within this specification in one form or another. The main area of divergence from the specification comes from the use of an injection molded liquid crystal polymer inner vessel in place of stainless steel. For this reason, all references to the metallurgical properties, design criteria, and testing as they relate to the stainless steel inner vessel had to be revised. The shape of the vessel is complex due to the portable, all position nature of the system. Normal calculations are not sufficient to predict the actions of this vessel under pressure. For this reason, OSS has made use of FEA modeling and burst testing to establish design and acceptance criteria. OSS proposed a specification that encompassed the spirit of 49 CFR 178.57 Specification 4L while incorporating the changes necessary for the new material and design. This proposed specification was accepted by the DOT, resulting in DOT certification of the AWPS through the exemption DOT-E 11739.

The DOT exemption requires that the vessel design be proven safe through design qualification tests. These tests include:

- Ambient Temperature/Pressure Cycle Test - At ambient temperature, pressure cycle inner vessel from ambient to service pressure three vessels each for 0, 100, and 1000 cycles, then cycle from ambient to test pressure (5/3 service pressure) for 30 cycles, then fill with liquid nitrogen and pressurize to burst. Minimum allowable burst is 2.5 times service pressure.
- Cryogenic Temperature/Pressure Cycle Test - At cryogenic temperatures, pressure cycle inner vessel from ambient to service pressure three vessels each for 0, 100, and 1000 cycles, then cycle from ambient to test pressure (5/3 service pressure) for 30 cycles, then fill with liquid nitrogen and pressurize to burst. Minimum allowable burst is 2.5 times service pressure.
- Creep Rupture Test – At ambient temperature, pressurize inner vessel to service pressure and hold for 1000 hrs. Measure for permanent distortion before and after pressure hold, then cycle from ambient to test pressure (5/3 service pressure) for 30 cycles, then fill with liquid nitrogen and pressurize to burst. Permanent deformation prior to burst in excess of 0.1% not allowed. Minimum allowable burst is 2.5 times service pressure. Extrapolate burst pressure out to 50,000 hrs on a log scale graph.
- External Pressure Test - Externally pressurize an assembled dewar (inner vessel, suspension system, outer vessel) to 2 atmospheres and then check for permanent

deformation. Permanent deformation of 0.1% is not allowed. The outer vessel must show no evidence of buckling and shall maintain vacuum insulation. There must also be no evidence of inner vessel failure.

- Temperature Extreme Test - One representative pack shall be cycle tested at ambient temperature by pressurizing from ambient to service pressure for 1000 cycles, then cycled from ambient to test pressure (5/3 service pressure) for 30 cycles. Next, the representative pack shall be pressurized to service pressure and submerged in 200 °F fluid, soaked for 10 minutes, then transferred to 0 °F fluid and soaked for 10 minutes, repeated 20 times. The pack shall not show evidence of distortion, deterioration, or failure during these tests.
- Bonfire Test - A test unit shall be placed in the horizontal position over a fire, subject over its entire length to flame impingement, until completely vented. Inner vessel may fail, but resulting venting shall be contained within the outer vessel and vented through the outer vessel relief valve.

The DOT exemption also requires tests to ensure the vessels remain consistent during forming and assembly. As a result, the following tasks are part of the manufacturing process:

- After assembly, each inner vessel shall be pressured to 2 times the service pressure maintained for 30 seconds without evidence of leakage, distortion or other defect.
- ASTM standard slabs molded from the same lot of material shall be tested to determine yield strength, tensile strength, and elongation, which must meet specified limits.
- Following the gluing procedure, 2 pairs of ASTM standard slabs must be glued together, cured and pull tested. Failure can occur only in the base material.
- Three inner vessels taken at random out of each lot of 200 shall be subjected to ambient temperature pressure cycling from ambient to service pressure for 1000 cycles, then pressurized to 5/3 service pressure, then filled with liquid nitrogen and pressurized to burst.

Following the completion of the dewar design, we stepped through each of the these tests and tasks and documented the results in a preliminary report to the DOT. A copy of the report is provided in Appendix B. With the exception of the permanent deformation in the outer vessel following external pressurization, the dewar design passed all of the tests. The outer vessel deformation issue is discussed in Section 5.2.4.

5.2.2 Pickup Mechanism Development

OSS initially worked to optimize the original pickup mechanism designed during Phase I. Early in Phase II, OSS built up a one-hour backpack to evaluate different pressure control schemes. During this testing, a gradual decay in internal pressure occurred when the liquid level in the inner vessel fell below the below the level of the hub, the halfway point. Data showing this phenomenon is provided in Figure 5.2-8. During the testing, the backpack was filled and connected to a mechanical breathing machine. The machine was set at a breathing rate of 100 SLPM, the maximum NFPA (National Fire Protection Agency) rate, and allowed to operate until the internal mask pressure dropped sufficiently below the ambient pressure. Pressure sensors connected to the backpack's pressure control system recorded internal pressure during the breathing cycles.

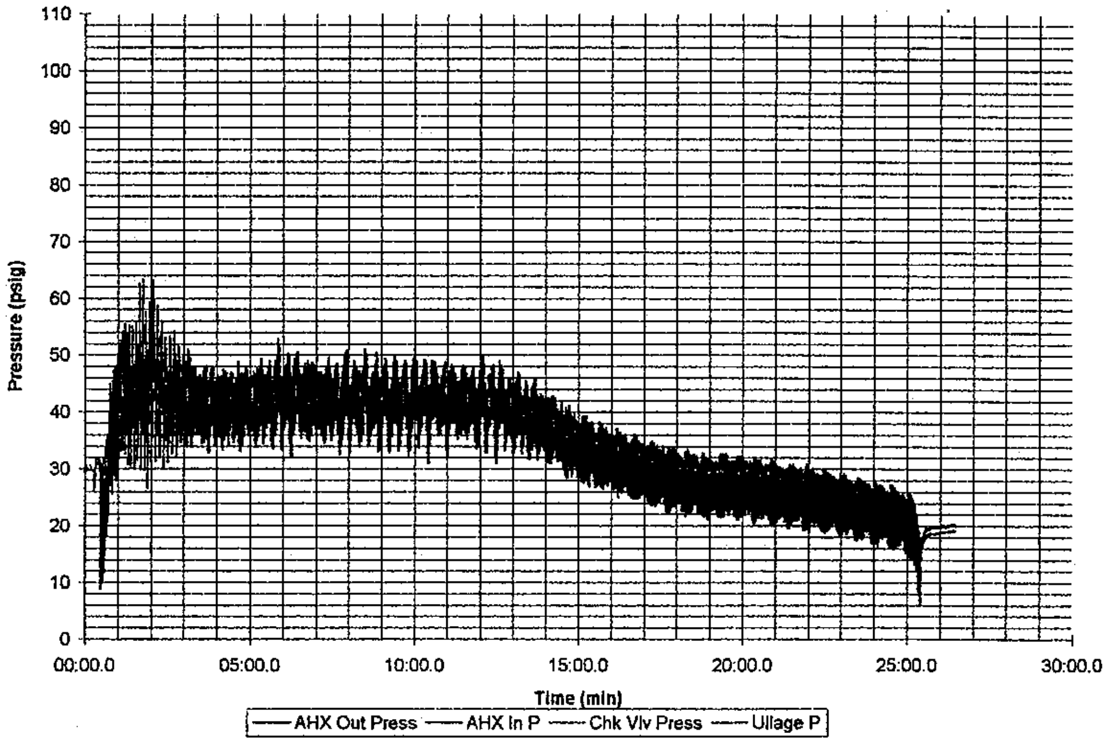


Figure 5.2-8: Test Data Showing Pressure Decay

The drop in pressure was attributed to a leak in the seal around the liquid pivot tube. This seal leak allowed gas into the liquid flow when the user, or breathing machine, inhaled. The pressure in the system began to drop as a result.

This phenomenon was repeated in a breadboard test performed to determine how large the seal leak must be to affect system performance. A cylindrical open mouth dewar, with a volume comparable to the AWPS inner vessel, was used during these tests. The top of the dewar was sealed and a straight withdrawal tube was inserted into the dewar through the top. A short vent tube was also inserted into the top cap. A breadboard pressure control system was connected to the dewar and the system connected to the breathing machine. An initial baseline run was performed during which no pressure drop was observed until the dewar was emptied. The test was then repeated after a 0.014" diameter hole was drilled midway down the liquid withdrawal tube. This hole simulated the leak that might be caused by the seal. Again, no drop in pressure was observed. The test was repeated with hole diameters of 0.026" and 0.060". These results are presented in Figures 5.2-9a and 5.2-9b. As indicated in the figures, the pressure began to drop in each test when the hole was exposed to the ullage gas. As expected, the larger the hole, the quicker the drop in pressure. Based upon this testing, we estimated that a gap between the pivot and the seal of approximately 0.002" would cause the drop in dewar pressure observed during testing.

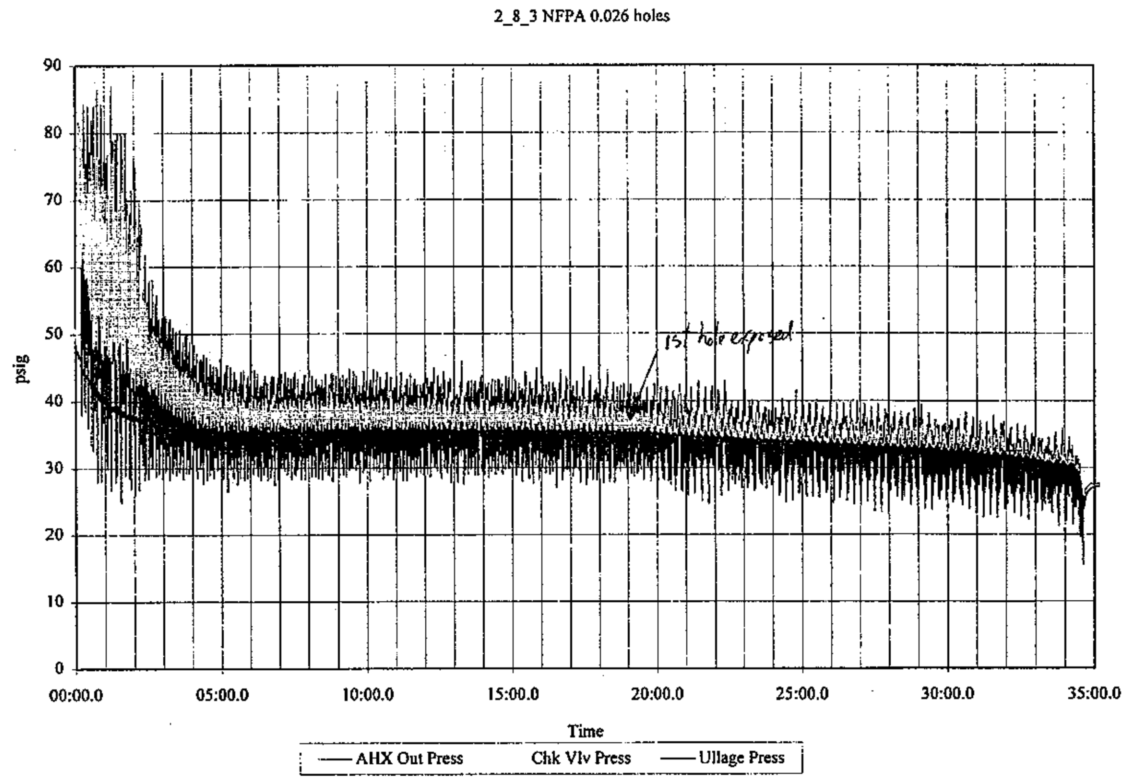


Figure 5.2-9a: Breadboard Testing of Liquid Line Having 0.026" Diameter Hole

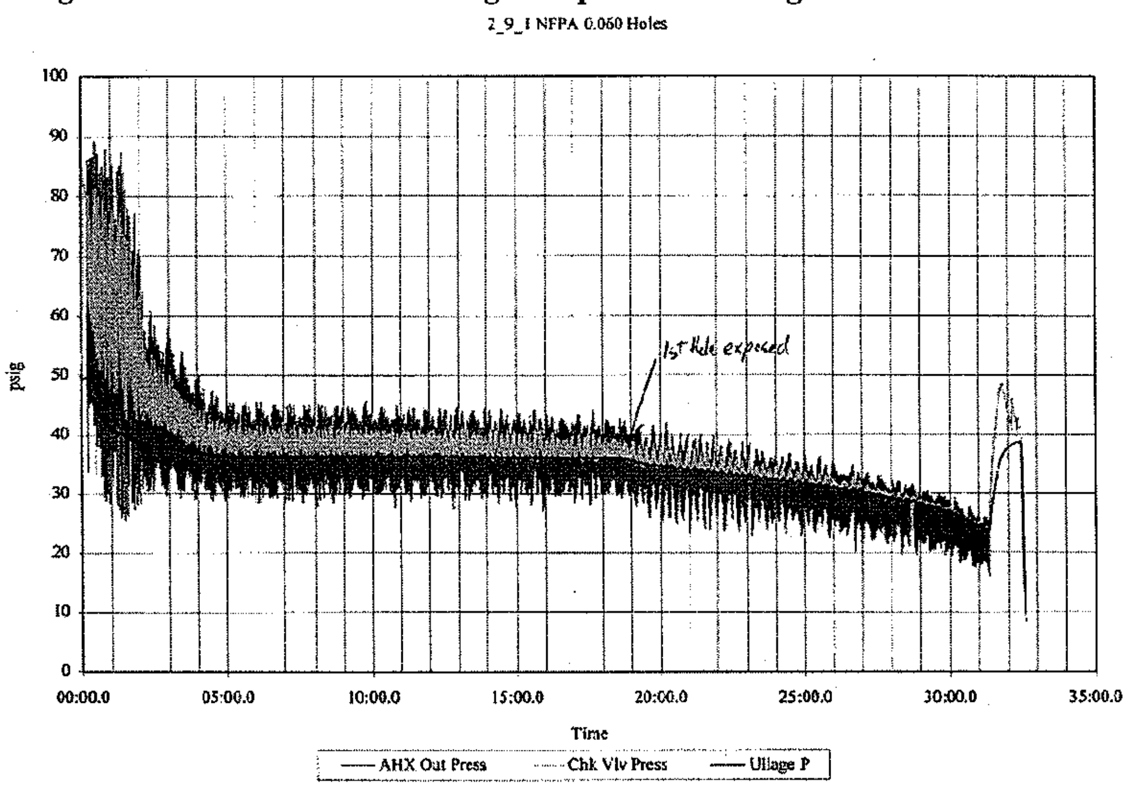


Figure 5.2-9b: Breadboard Testing of Liquid Line Having 0.060" Diameter Hole

Inspection of a breadboard assembly of the pivot mechanism and hub indicated the gap between the pivot and the seal exceeded 0.002" due to wear in the seal material. An alternative design was developed to resolve this problem. The circumference seal on the pivot tube was replaced with a flat face seal. The face seal is pressed against the bearing by the spring force of a small bellows to which it is brazed. The other end of the bellows is brazed to the pivot tube. A sketch of the new design is presented in Figure 5.2-10.

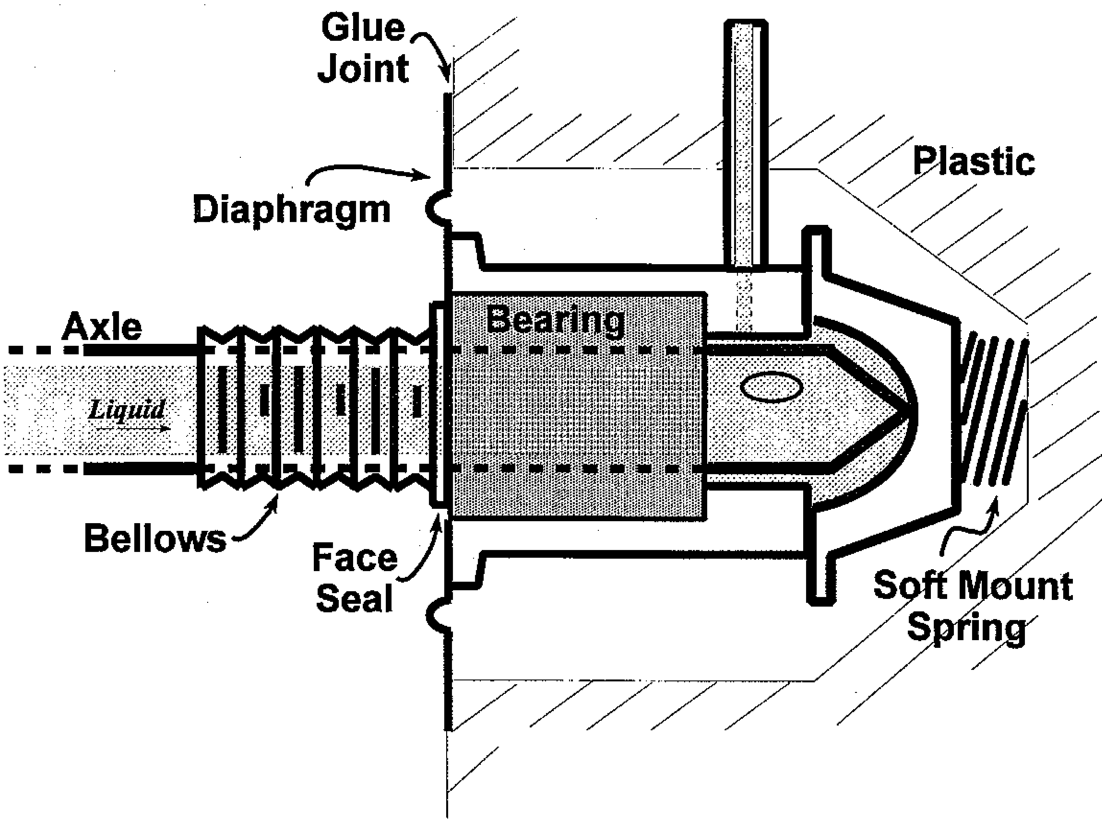


Figure 5.2-10: New Face Seal Design

As changes in the liquid pivot tube seal were being made, the pickup mechanism was also being modified to accommodate the new inner vessel shape. As discussed in Section 5.2.1, a new inner vessel was developed to provide a higher factor of safety. The outer edge of the new vessel design is a spherical sector with the radius of curvature located at the center of the inner vessel. In all orientations, the liquid air inside the vessel will be in contact with this outer surface. Consequently, a pickup/vent tube that pivots around the center of the vessel can access liquid air at any point along the outer surface and thus access all of the fluid in the vessel. Using this principle, the design in Figure 5.2-11 was developed. The figure shows a simple sketch of the pickup mechanism with the inner vessel in both a vertical and horizontal orientation.

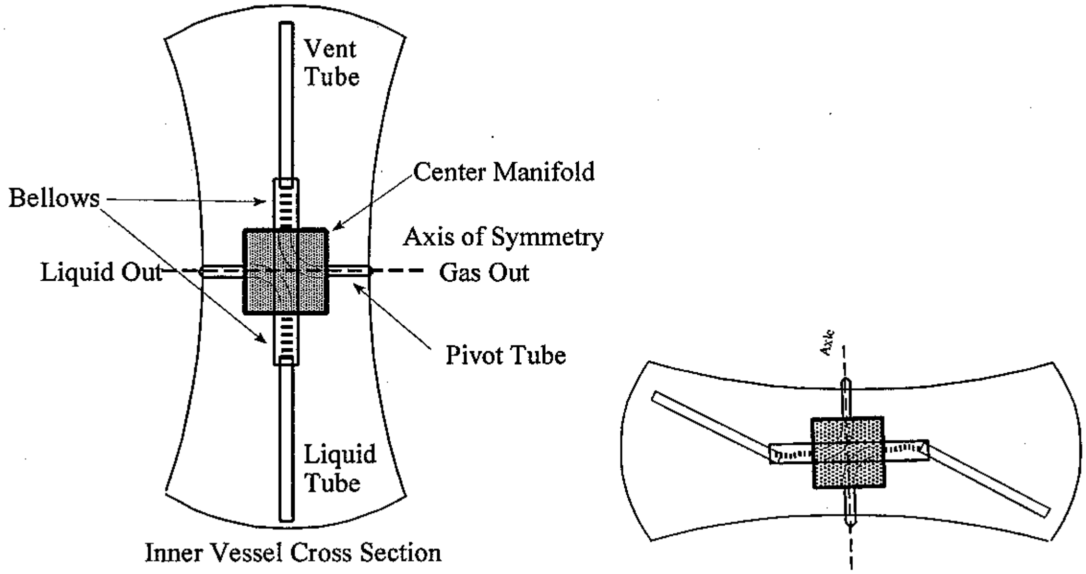


Figure 5.2-11: New Pickup Mechanism

The pickup and vent tubes are attached to a center manifold via metal bellows. These two tubes are connected by a linkage bar that is soldered to the middle of each tube. The metal bellows and the linkage bar allow the two tubes to pivot as a single tube around the center of the inner vessel. Note: the linkage bar is not shown in Figure 5.2-11.

The center manifold cross is a single piece made from Ultem, a cryogenic compatible polyetherimide. Two pivot tubes are glued to opposite edges of the manifold. These pivot tubes interface with hubs in the inner vessel and allow the center manifold, the pickup tube, and the vent tube to rotate about the vessel's axis of symmetry.

The new single piece manifold reduced the pickup mechanism's part count and provided features that aligned the pivot tubes during assembly. In the previous design, the manifold was made from two pieces of LCP that were glued together. In this design it was difficult to align the pivot tubes when the manifold and tubes were assembled. The new design provided close tolerance holes in which the pivot tubes are inserted. These holes ensure the tubes are properly aligned.

The pivot tubes also provide a flow passage for the liquid air and the vent gas. The outer ends of these hollow tubes taper to a point that interfaces with the inner vessel hubs. Small holes are machined into the sides of the taper to allow flow between the hubs and the pivot tubes. Two passages machined into the center manifold connect each pivot tube to either the pickup or vent tube. During operation, liquid is withdrawn up the pickup tube, through the manifold and pivot tube, and out of the inner vessel via one of the hubs. Gas is vented in a similar manner through the other pivot tube and hub; the gas flow path is shown in Figure 5.2-12.

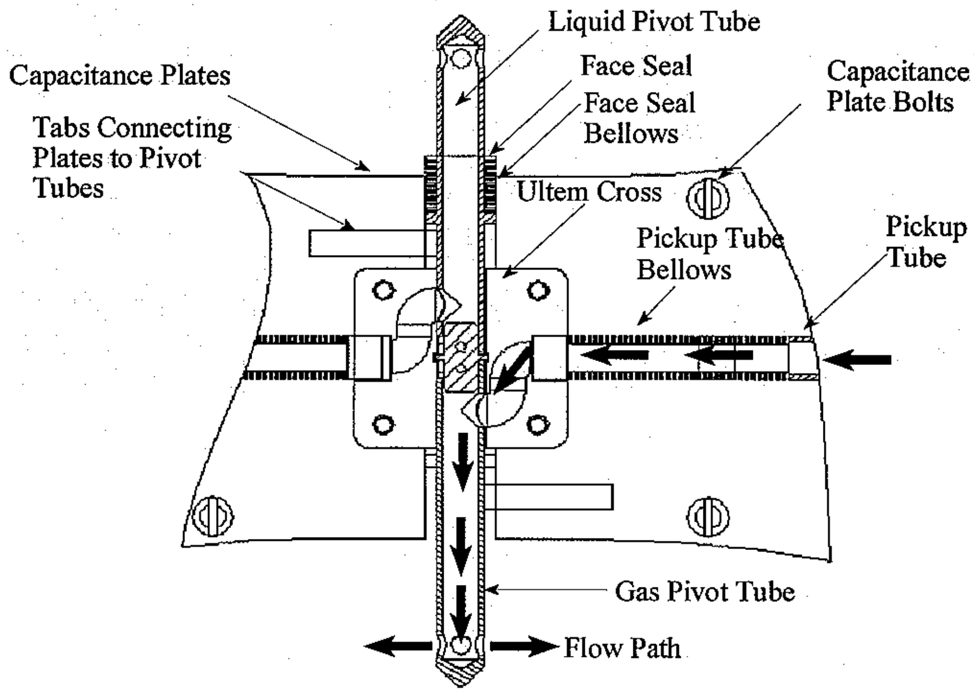


Figure 5.2-12: Pickup Mechanism Flow Path

The pivot tubes also conduct the capacitance gauge electrical signal to the hubs. The capacitance gauge is bolted to the center manifold and rotates with the manifold and the pickup/vent tubes. Each capacitance gauge plate is electrically connected to one of the pivot tubes via metal tabs soldered to each component. Since the center manifold is not an electrical conductor, the two pivot tubes are electrically isolated from one another.

The interface between the pivot tubes and the hubs is a critical feature of the design. The interface must allow the pivot assembly (pivot tubes, manifold, capacitance gauge, pickup/vent tubes) to rotate freely, must create a seal between the inner vessel and the hub, must pass the capacitance gauge signal, and must accommodate expansion and contraction of the inner vessel.

For this initial iteration, a spring-loaded metal cup interfaced with the pivot tube, see Figure 5.2-10. The interface formed a point contact between the cup and the tip of the pivot tube. The interface produced very little friction and allowed the pivot assemble to rotate freely. The spring soldered to the back of each cup accommodated the expansion and contraction of the inner vessel. The springs ensured the cups and pivot tubes remained in contact when the vessel expanded due to pressure loads, and also prevented the interfaces from being compressed too tightly when the vessel contracted as it was cooled to cryogenic temperatures. OSS discovered during development testing that if the interface is compressed too tightly, the friction at this interface increases significantly and prevents the pivot assembly from rotating.

The capacitance gauge electrical signal also passed through the point contact and down the spring. The spring on the liquid side of the pivot assembly interface was soldered directly to the hub. The gauge signal was conducted to the hub and out of the dewar through tubes welded between the liquid hub and the outer vessel. The spring on the vent side of the pivot assembly rested in an Ultem cup. This cup rested inside the hub and electrically insulated the spring and cup from the hub. A small insulated wire was soldered to the spring and routed through the vent tube that ran from the hub to the outer vessel. The end of the wire was attached to an electrical pass-through connected to the end of the vent tube, outside of the dewar. The pass-through brought the capacitance gauge signal out of the vent tube where it was carried to the electronics box via a coaxial cable.

A breadboard of this new design was built and tested. This testing showed that friction in the mechanism could prevent it from rotating into its proper upright position if the dewar is slowly turned upside down. The mechanism would be in a metastable position similar to an inverted pendulum. The mechanism would right itself if jarred or hit.

A new feature was added to the design to prevent the mechanism from sticking in this position, a kicker weight. A sketch of the kicker weight integrated with the pickup mechanism is presented in Figure 5.2-13. The kicker weight consisted of two tubes attached to the center manifold. A weight on roller bearings slid along one of the tubes. When the dewar was rotated, the slider weight easily moved, shifting the pickup mechanism's center of gravity (CG) and causing it to rotate into a vertical orientation. The other tube attached to the center manifold supported a counter weight. The counter weight ensured the pickup mechanism hung vertically, rather than at an angle, when the backpack was upright.

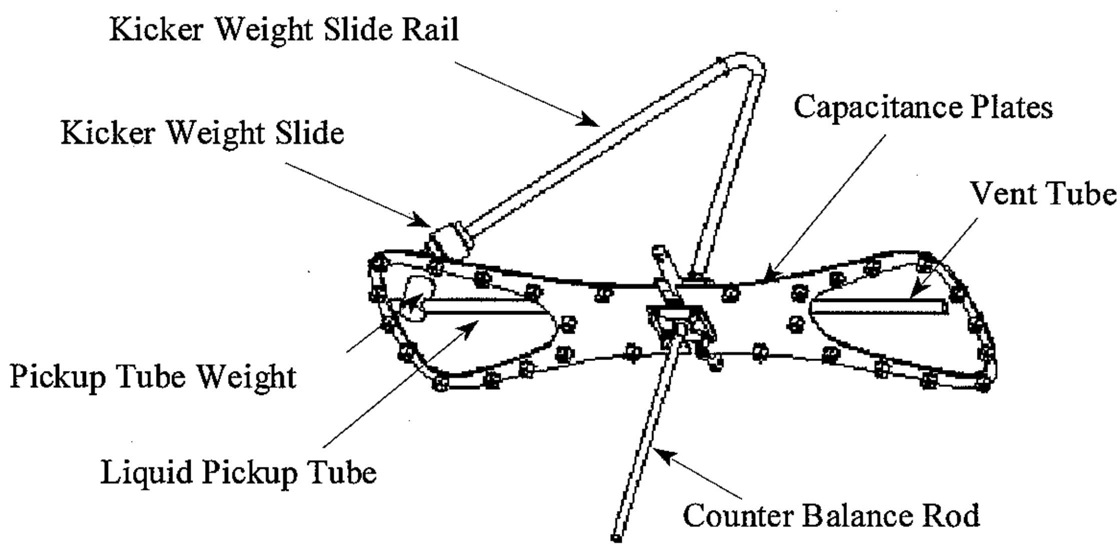


Figure 5.2-13: Sketch of Kicker Weight and Pickup Mechanism

This design was implemented in several prototype dewars. Initial testing of the prototype units indicated the design worked well. However, a problem was located in the design of the vent/pickup tubes and flex bellows. A failure was found in the bellows that connects the pickup tube to the center manifold. The bellows had split in one location.

A test fixture consisting of a complete inner vessel assembly was built to isolate the cause of the failure. Holes were drilled in the vessel so that the bellows deflection could be observed. The observed deflections were not great enough to cause problems during movement of the pickup mechanism. However, when the vessel was filled with cryogen the deflection was great enough to damage the bellows over several cycles.

These deflections occurred when the inner vessel and pickup mechanism first began to cool down during a fill. Slugs of cryogen would quickly boil and create a surge in the pressure inside the dewar tubing. These surges caused the bellows to deflect sideways far enough to fatigue them. This problem was solved by increasing the outer diameter of the pickup tube from ¼" to 3/8". Opening this flow passage eliminated the pressure surges and the bellows deflections.

This incident raised an important issue on the fatigue life of the bellows. A test fixture was built that automatically exercised the bellows through the full range of motion expected in the pickup mechanism. The bellows were also alternately dipped in cryogen and pressurized to simulate the other expected loading conditions for the bellows. Occasionally the bellows would be helium leak checked.

The test was allowed to run independently for days. No leaks were experienced after 15,000 cycles. As a result, the design was considered adequate.

Following the change to larger vent and pickup tubes, the 6 dewars to be used for NIOSH certification were assembled. During their assembly, the pickup mechanisms in the prototype dewars began to stick after repeated testing. This prevented the mechanism from rotating freely and when the dewar was inverted caused the pressure to drop rapidly. Furthermore, the capacitance signal began to drop out intermittently after repeated uses.

Unfortunately, the NIOSH dewars possessed even larger problems than the prototype units. The pickup mechanism did not rotate freely in these units from the beginning. One of the dewars was disassembled to inspect the pickup mechanism. Once removed from the outer vessel, a hole was drilled in the inner vessel. A bore scope camera was used to inspect the mechanism. We searched for components that might be interfering or contacting the inside surface of the inner vessel. No obvious interference was observed.

The inner vessel was then completely disassembled. Inspection of the pickup mechanism revealed the pivot tubes were slightly out of alignment. This may have caused them to bind to the point where the mechanism would not rotate freely. Divots were also found in the brass cups that interface with the tips of the pivot tubes. A small amount of debris and discoloration was also present in the brass cups.

It was believed that the inner vessel was compressing the pickup mechanism too tightly, causing the springs behind the brass cups to bottom out and the pivot tubes to dig into the cups. The discoloration and debris in the cups were thought to be the cause of the intermittent capacitance signal drop out. A thin oxide layer on the cups could cause the signal to drop out. The resistance of the pivot tube/cup interface was found to vary randomly by over an order of magnitude when the pickup mechanism was rotated or the connection between the pivot tubes and cups broken and reconnected.

The first action taken following the disassembly and inspection of the inner vessel and pickup mechanism was to accurately measure the inner vessel deflections during different load cases. Two vessel halves were glued together and the deflections were measured as the vessel was pressurized and cooled to cryogenic temperatures. Table 5.2-1 presents the deflection data recorded.

Table 5.2-1: Inner Vessel Deflections

Pressure (psig)	Temperature	Hub to Hub Deflection (in)
0	Room Temp	0.000
-14.7	Room Temp	-0.119
0	Room Temp	-0.059
14.7	Room Temp	-0.030
29	Room Temp	0.000
55	Room Temp	0.058
0	Cryo Temp	-0.075
14.7	Cryo Temp	-0.053
29	Cryo Temp	-0.063
55	Cryo Temp	-0.031

Condition	Hub to Hub Deflection*
With Rings	0.084"
With Rings; -14.7 psig IV Pressure	0.124"
With Rings; @ Cryo Temp; 0 psig IV Pressure	0.164"

* Deflection as measured from initial glued inner vessel dimension.

Once this deflection information was collected, a new pickup mechanism design was developed. The new design was based upon a design developed for the one-hour dewar. The design implemented face seals on both of the pivot tubes. This eliminated the seal around the outside of the vent pivot tube and reduced the chance the pivot tubes would bind. The combined length of the pivot tubes was also shortened to ensure the design could accommodate the inner vessel deflections.

New electrical connections for the capacitance gauge signals were also added. These new connections were developed following an extensive design study. In this study, a wide variety of concepts were developed. Several breadboards were developed of the most promising designs. Sketches of several of these concepts are presented in Figure 5.2-14.

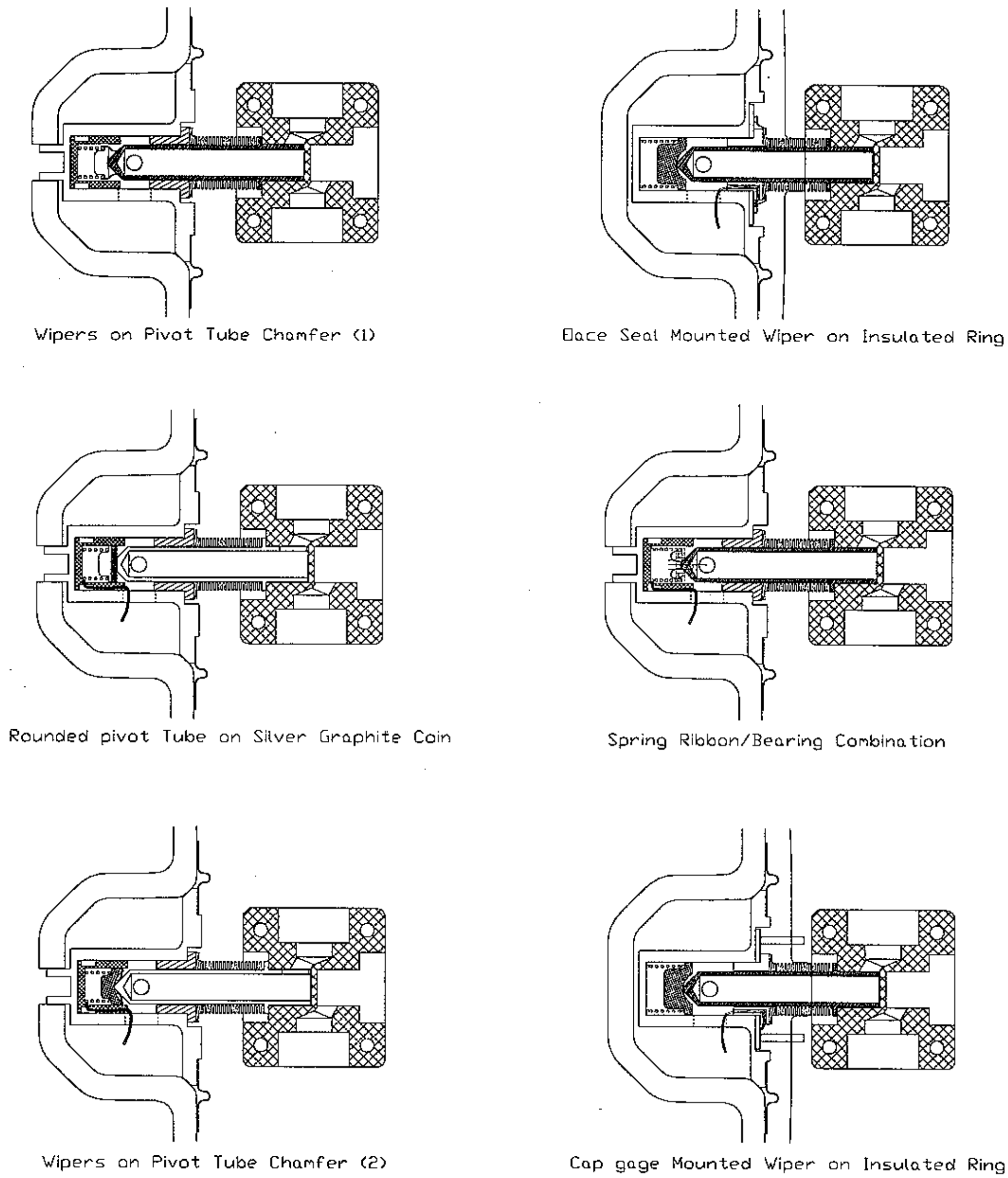


Figure 5.2-14: Electrical Connection Concepts

A fixture was developed to automatically cycle these breadboards. The resistances of the various interfaces were periodically recorded. After hundreds of cycles, modifications were made to the designs and the cycle testing repeated. After several thousand cycles with no change of resistance, a new concept was adopted and integrated into the pickup mechanism design. A sketch of the new design is presented in Figure 5.2-15.

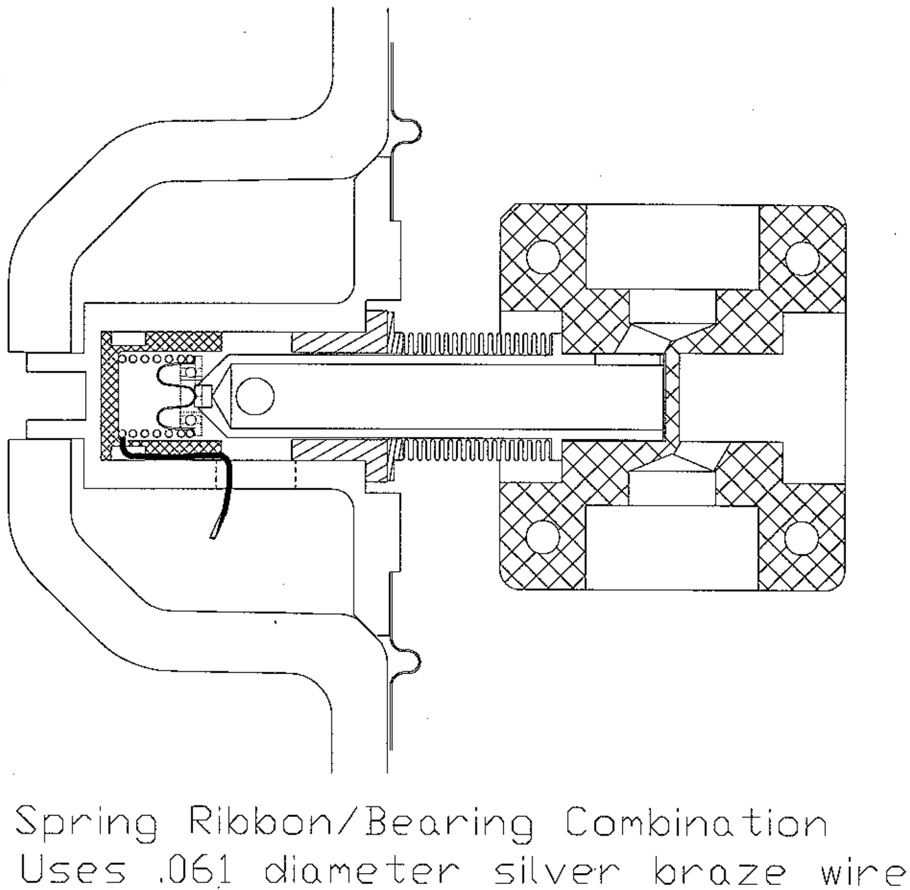


Figure 5.2-15: New Electrical Connection

In this new design, the brass cup has been replaced with a spring ribbon and bearing. The tip of the pivot tube rests inside a bearing that is soldered to the pre-load spring. The bearing reduces the friction in this interface and allows the pivot tube to rotate freely. A piece of silver braze wire is inserted into a hole drilled into the tip on the pivot tube. The wire contacts a spring ribbon that has also been soldered to the pre-load spring. This interface forms the dynamic electrical connection. The spring ribbon provides a light pre-load on the braze wire to ensure the electrical connection remains intact.

During the redesign of the electrical connection and the pickup mechanism seals, a more thorough analysis was performed on the kicker weight to estimate the amount of torque the weight could exert if the mechanism became stuck. This analysis indicated a couple configurations in which the kicker weight would not operate as expected.

Consequently, another study was conducted to refine the design. A series of concepts were developed and analyzed, several of them built and tested, and a final design selected.

Testing of this design showed that the kicker weights will always move, shift the pickup mechanism CG, and cause the mechanism to rotate regardless of the dewar position and motions. A sketch of this design is presented in Figure 5.2-16a and pictures of the prototype kicker weight and pickup mechanism are presented in Figures 5.2-16b and 5.2-16c.

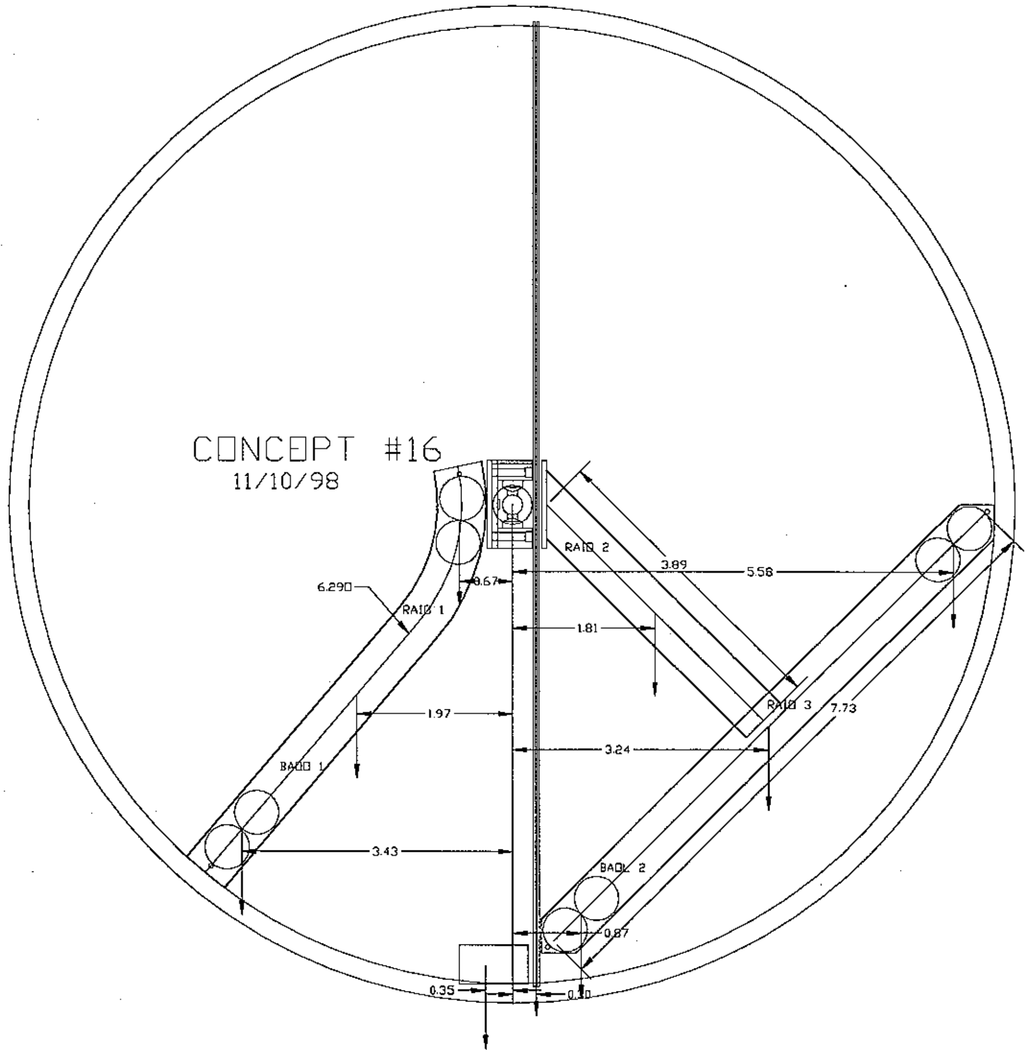


Figure 5.2-16a: New Kicker Weight

This new design consists of two sets of two ½" diameter ball bearings rolling inside hollow tubes attached to the center manifold. The new design did not utilize roller bearings as did the first design and was therefore much less expensive. The new design also provided a slight weight savings. Note: the static counter weight added in the initial kicker weight design to ensure the pickup hung vertically when the dewar was upright has been replaced by a set of ball bearings. This change increases the kicker weight's response; i.e. it produces a greater CG shift when the dewar is turned over.

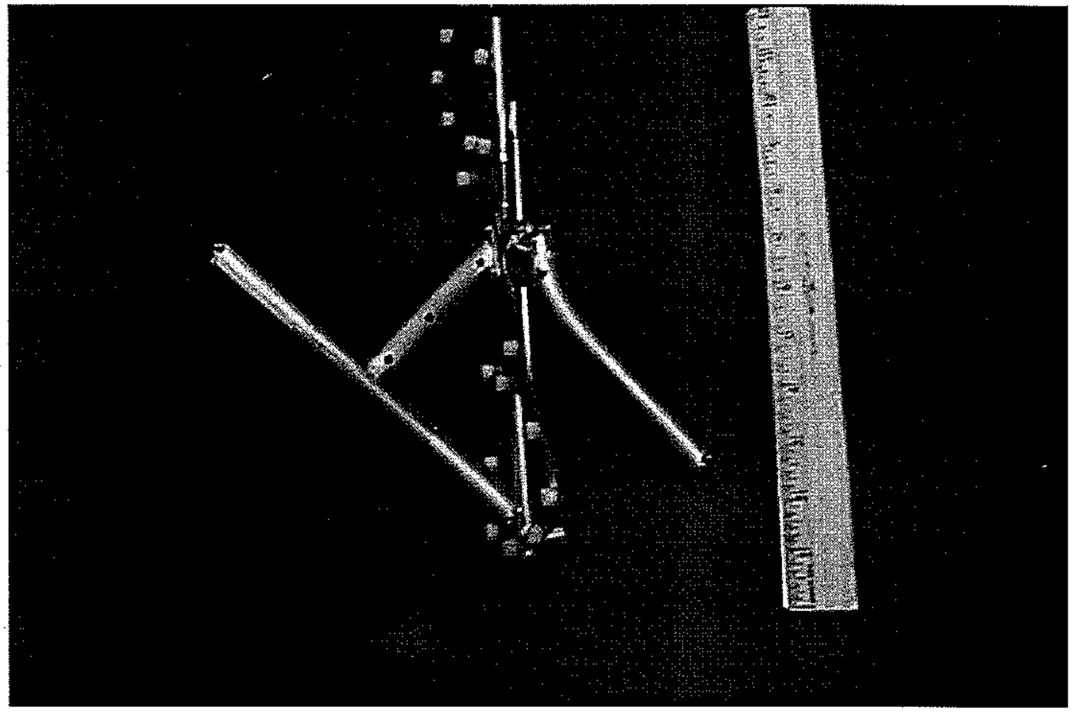


Figure 5.2-16b:New Pickup Mechanism and Kicker Weight

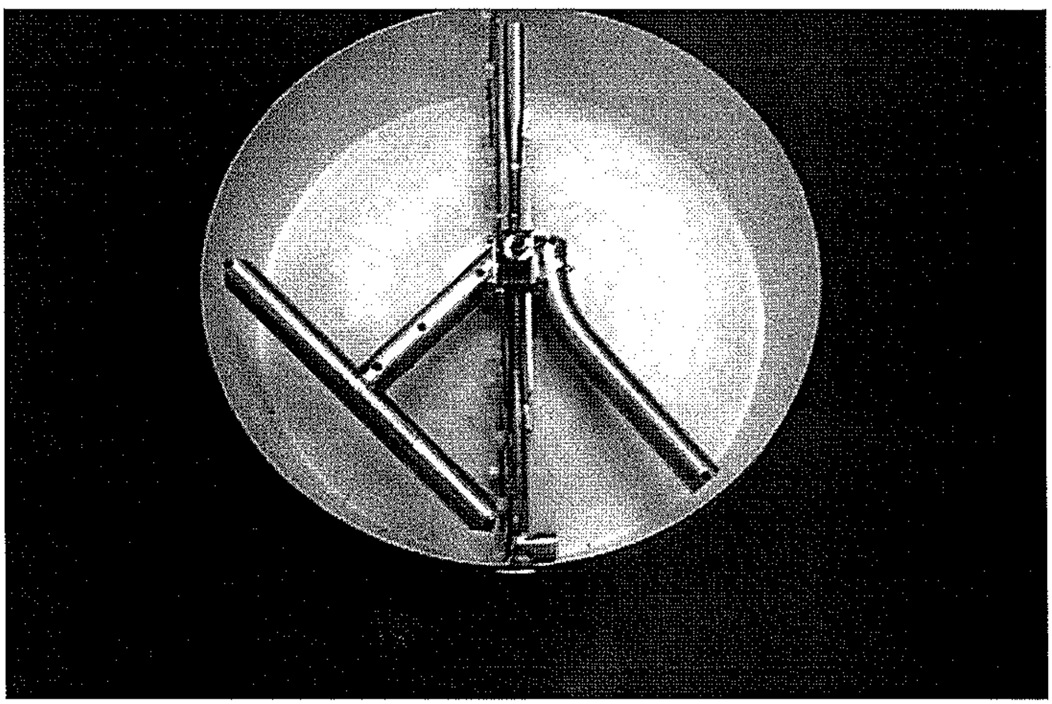


Figure 5.2-16c: New Pickup Mechanism and Kicker Weight in Inner Vessel

The details of a new pickup mechanism design that incorporated new seals, new electrical connections, and a new kicker weight was completed early in 1999. Unfortunately, a complete system could not be built and tested within the budget and schedule constraints of the AWPS project. However, during the design process the individual components were extensively tested; these components were tested more thoroughly than the previous design was. The results of this development testing have provided us with confidence in the new pickup mechanism design.

5.2.3 Capacitance Gauge Development

The capacitance gauge measures the amount of liquid remaining in the dewar. The gauge consists of two parallel plates that form a capacitor. The capacitance of the gauge increases as its wetted surface area (the surface area in contact with liquid air) increases. This change in capacitance is measured by the backpack electronics, which displays to the user the amount of air in the backpack.

As mentioned in the previous section, the gauge rotates with the pickup mechanism and so is always in a vertical orientation. The key to the capacitance gauge design is to ensure the wetted surface does not change for a given fill level, when the backpack is pitched forward and backward. If the wetted surface area changes, the gauge will provide a different reading when the user goes from standing to crawling on their hands and knees.

An initial gauge design was developed for the dumb bell shaped inner vessel. A picture of this initial design is presented in Figure 5.2-17. Note: the initial pickup mechanism is also shown in this picture. The gauge shape was laid out to provide relatively constant surface area at all orientations for a variety of fill levels using CAD software.

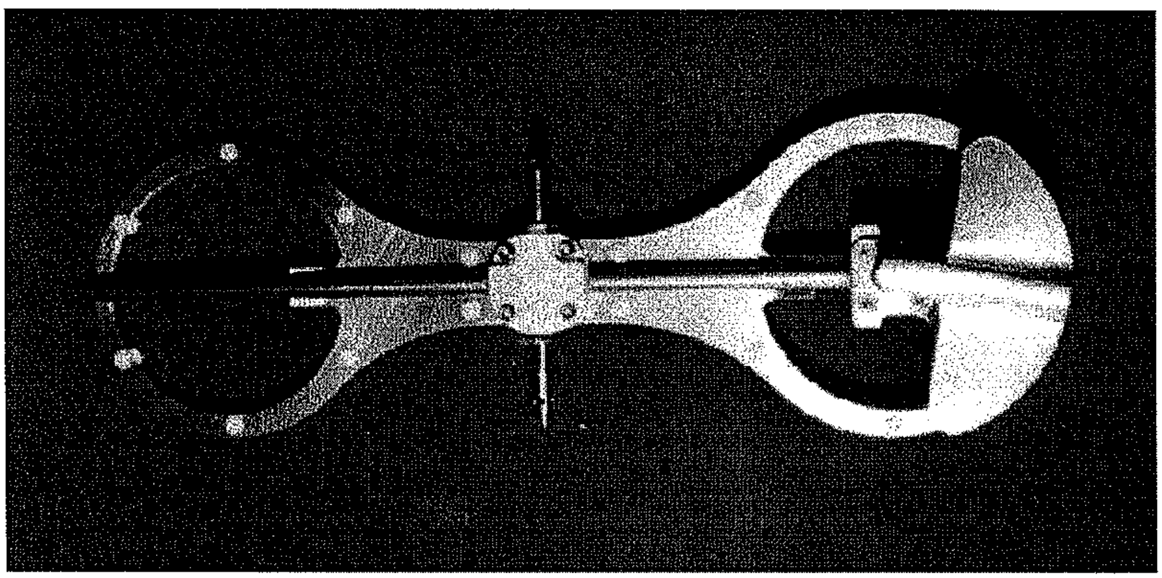


Figure 5.2-17: Phase I Capacitance Gauge Design

When the shape of the inner vessel changed, a new capacitance gauge had to be designed. As in the design of the previous gauge, a shape for the gauge was assumed and then analyzed. The initial shape assumed for the new gauge was based upon an enlarged version of the gauge developed for the 1-hour duration backpack. The shape was then modified based upon analysis results and the new shape analyzed. This iterative process was followed until the predicted gauge performance satisfied the gauging requirements outlined by NIOSH.

In each iteration, AutoCAD was used to calculate the wetted gauge surface area for different fill levels and different orientations. Some graphical outputs from this analysis are presented in Figure 5.2-18. The final gauge shape is presented in Figures 5.2-19a and 5.2-19b. The predicted results are shown in Figure 5.2-20.

Figure 5.2-10 shows the predicted wetted surface as a function of orientation for various fill levels from 1/8 to ½ full. As indicated in the figure, the wetted surface area remains fairly constant except when the dewar is between 20% and 30% full and is laid down flat (orientation of 90°). However, these predictions indicate the gauge would meet the gauging accuracy required by NIOSH, and so the design was incorporated into the first two-hour development unit.

During testing of this unit, the capacitance reading continually drifted, thus requiring constant calibration. When the dewar was disassembled, the gauge was inspected. The signal drift was associated with distortion of the aluminum capacitance plates and creep of the nylon washers that maintain the plate spacing. The nylon washers were replaced with Teflon ones and the plate material was changed from aluminum to stainless steel.

The new gauge design was incorporated into another two-hour development unit. Each capacitance plate was also modified to include a short tab that was soldered to one of the pivot tubes when the pickup mechanism and capacitance gauge were assembled. These tabs formed the gauge electrical connection.

As with the previous design, the gauge worked well initially. The gauge readings tracked the fill level. However, no detailed tests were performed to quantify the gauge accuracy during this initial testing. During repeated testing, the gauge signal drifted and dropped out intermittently. As previously discussed, the problem was tracked down to the dynamic electrical connection in the pickup mechanism.

During the redesign of the pickup mechanism, the gauging analysis was expanded to include the effects of surface tension. Surface tension forces cause liquid air to wick up a short distance between the capacitance plates; the wicking height for the gauge plate spacing we selected was estimated to be 0.15". This effect results in a slightly greater wetted surface area than would be expected. The updated analysis also utilized Pro-E models rather than AutoCAD to improve the accuracy of the analysis and decrease the amount of time required to estimate the wetted area at various orientations. A sample of the graphic outputs generated in the updated gauge analysis is presented in Figure 5.2-21.

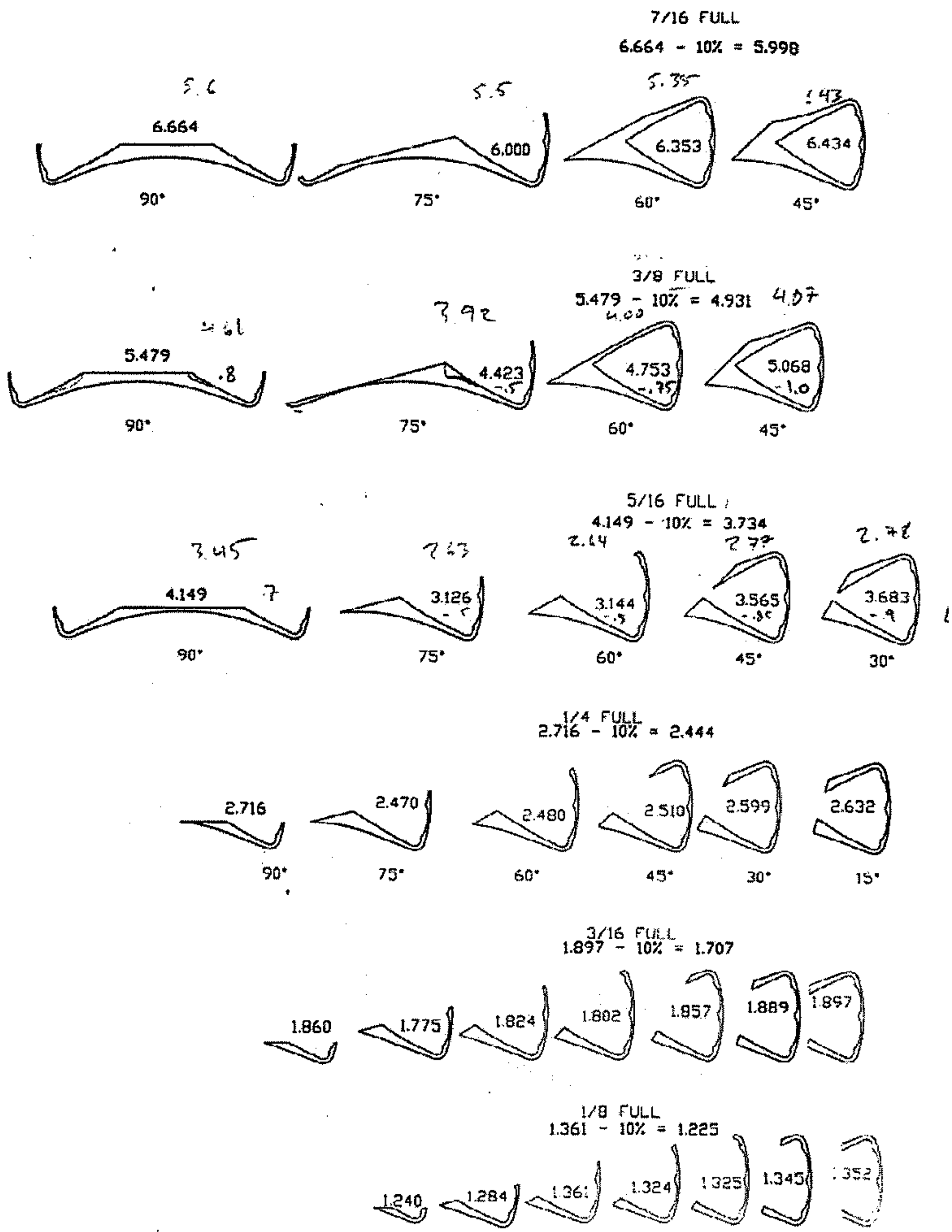


Figure 5.2-18: Graphical Analysis of Capacitance Gauge

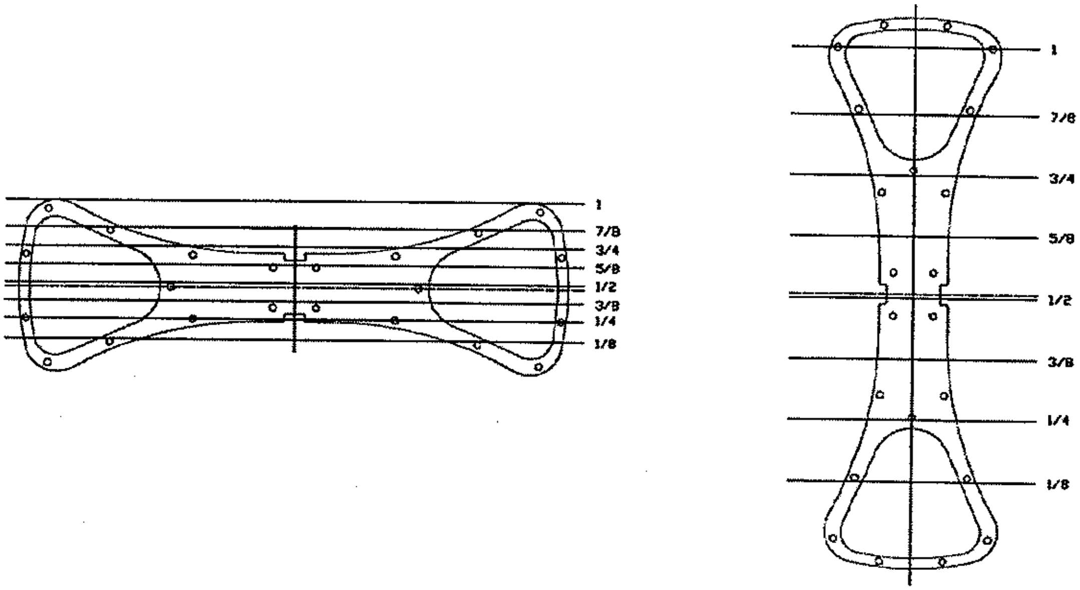


Figure 5.2-19a: Sketch of Final Capacitance Gauge Shape

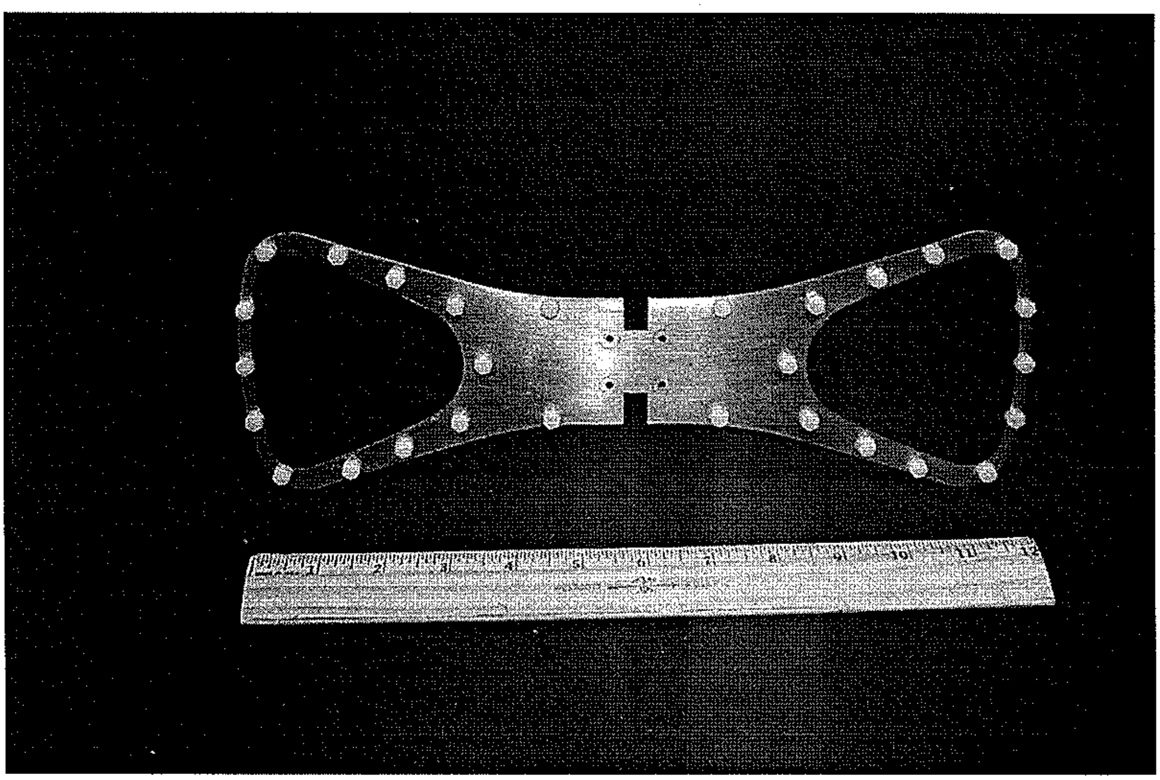


Figure 5.2-19b: Final Capacitance Gauge Shape

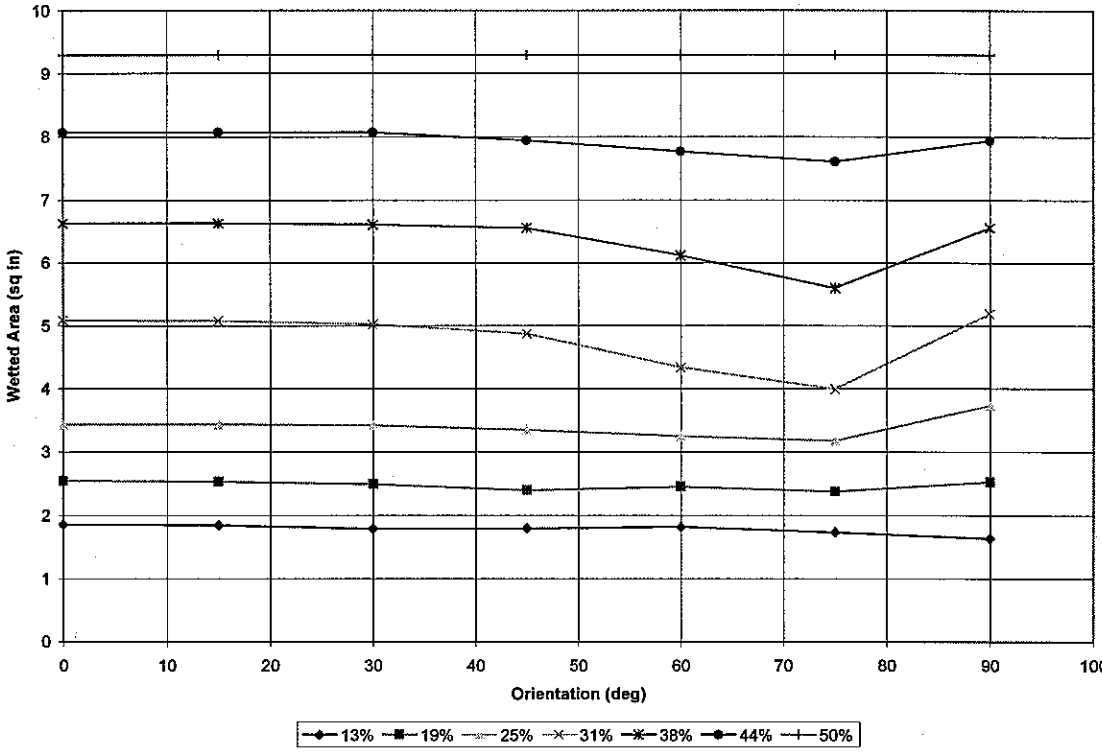
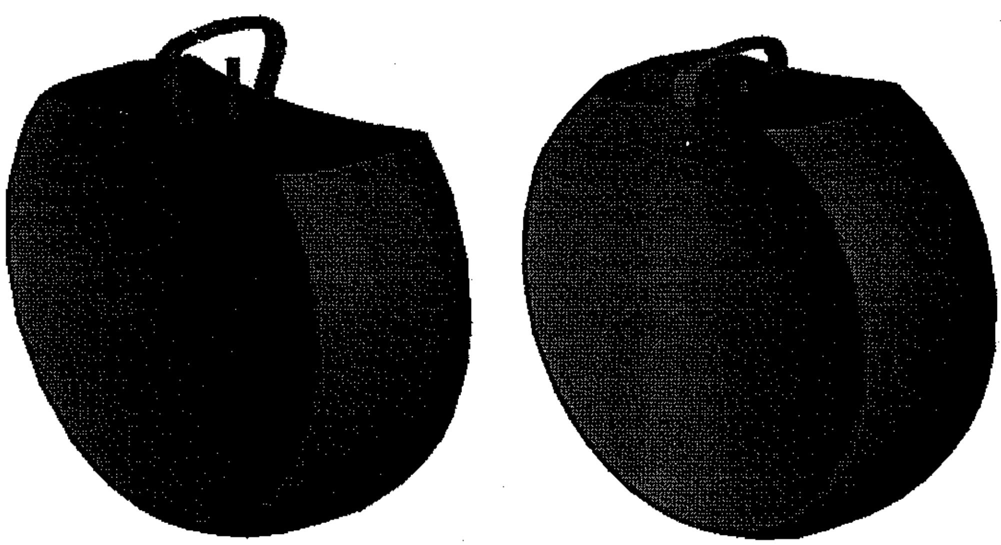


Figure 5.2-20: Initial Capacitance Gauge Predictions



6.5 lbs Liquid Air **7.2 lbs Liquid Air**

Figure 5.2-21: Graphical Analysis of Capacitance Gauge

The results of this new analysis are presented in Figure 5.2-22. As indicated in the figure, the gauge will meet the NIOSH accuracy requirements of +/- 5% when over a quarter full and +/- 2.5% when less than a quarter full.

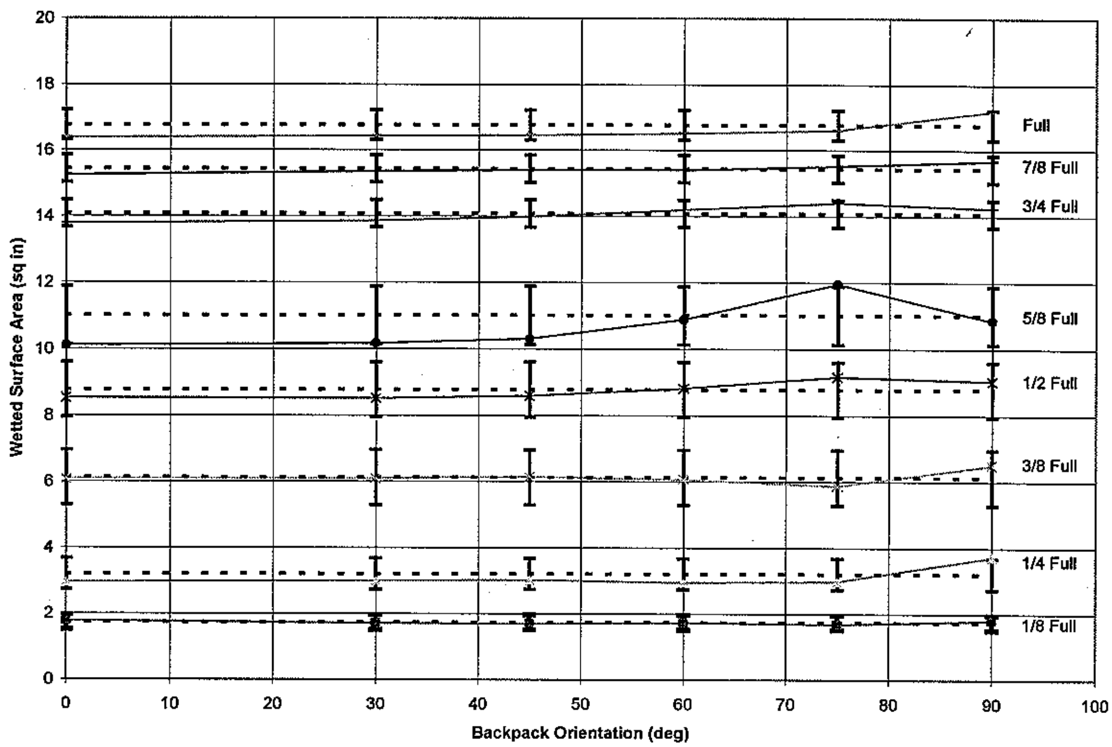


Figure 5.2-22: Capacitance Gauge Predictions Incorporating Surface Tension Effects

Following the analysis, OSS decided to build a fixed-tube, development unit designed to measure the base accuracy of the gauge itself. No pickup mechanism was incorporated into the unit. Two rigid tubes that were soldered to the metal hubs in the inner vessel replaced the mechanism. The capacitance gauge was rigidly attached to one of these tubes by soldering one of the plates to the tube. This provided not only a structural joint but also an electrical connection. A wire was soldered to the other plate and routed out the other tube to complete the electrical circuit.

A series of test was performed on the unit to quantify the capacitance gauge accuracy. During the test, the dewar was filled with liquid air and placed on a tilt stand with the capacitance gauge hanging vertical. The dewar was slowly rotated from upright to upside down and then back to upright. The gauge readings were recorded every 15°. Twenty percent of the liquid air was then drained from the dewar and the orientation test repeated. Cryogen levels of 60%, 40%, 20% and 0% were also tested. The results of these tests are summarized in Figure 5.2-23 and Table 5.2-2. The error bars associated with each curve in Figure 5.2-23 show the allowable error for the gauging system. These results verify that the gauge design meets the NIOSH gauging accuracy requirements. Note: during the test, the capacitance units were measured in counts. These are the units the backpack electronics unit records and then relates to quantity of liquid air. The quantity of liquid air varies inversely proportional with capacitance count.

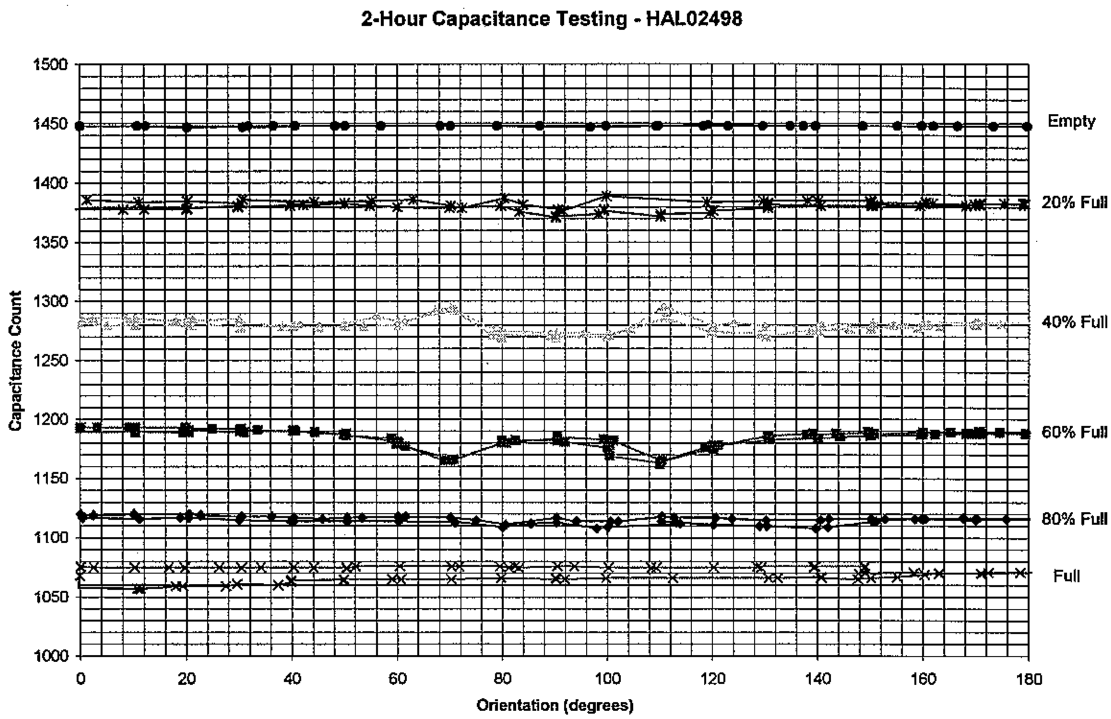


Figure 5.2-23: Capacitance Gauge Test Results

Table 5.2-2: Measured Capacitance Gauge Accuracy

Fill Level	Average Count	Max Error		Min Error	
100%	1067	9	2%	-10	-3%
80%	1114	6	2%	-6	-2%
60%	1178	15	4%	-16	-4%
40%	1283	13	3%	-14	-4%
20%	1380	9	2%	-9	-2%
0%	1448	1	0%	-1	0%

5.2.4 Outer Vessel and Harness Development

The prototype backpack developed during Phase I utilized an aluminum outer vessel that was machined from a large block using a CNC mill. The vessel was expensive to manufacture, was relatively heavy, and was prone to corrosion. The use of aluminum on the outer vessel also forced us to use aluminum for the tubes running between the inner and outer vessels. We were forced to use aluminum tubes because no reliable method was found to seal other tube materials (such as 304 SS) to the aluminum outer vessel. As discussed in Section 5.2.7, this significantly increased the heat leak to the inner vessel.

As a result of these limitations, OSS reviewed various materials from which to make the outer vessel during Phase II. The primary candidates considered included 300 series stainless steels, nickel based super alloys such as Inconel 718, and titanium. Titanium was eventually selected as the material of choice because it has excellent strength to weight and stiffness to weight ratios, excellent corrosion resistance, and it can be inexpensively formed using super plastic forming (SPF).

SPF uses high temperatures and relatively low pressures to press a titanium sheet onto a male mold. It is analogous to thermoforming of plastics. This process allows complex three dimensional shapes to be formed from an inexpensive plaster mold.

Titanium to stainless steel transition bushings were also located early during Phase II. These bushings are formed by explosively bonding a plate of stainless steel to a plate of titanium. The bushings provide a method for sealing the tubes coming from the inner vessel. The titanium side of the bushing is welded to the outer vessel. The tubes running from the inner vessel pass through the bushings and are welded to the bushing's outer stainless surface; the dewar tubing was changed from aluminum to stainless steel during Phase II to minimize heat leak. This approach provided a vacuum tight seal on the tubes that could withstand cryogenic temperatures.

A detailed design of the outer vessel shape used in Phase I was developed for titanium vessel halves fabricated using SPF. When the design was completed, OSS subcontracted the production of several vessel halves. These vessel halves were used to build up breadboard units to test the outer vessel design. A picture of this outer vessel design is presented in Figure 5.2-24.

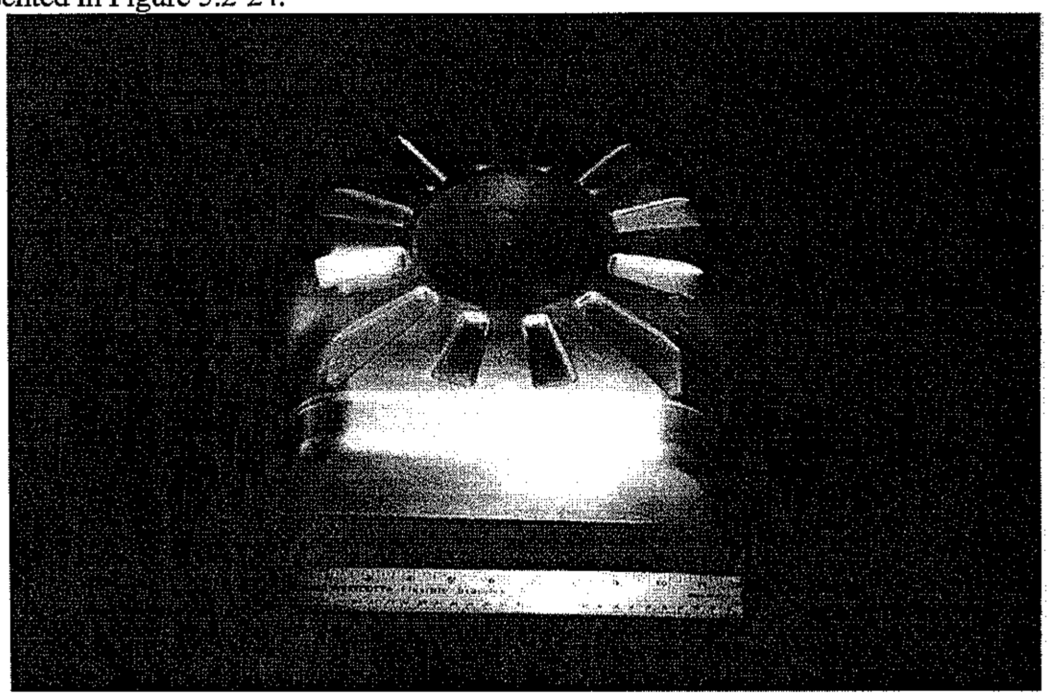


Figure 5.2-24: Initial Phase II Outer Vessel Design

Initial problems were encountered with welding the vessels. The welds were found to be brittle and tended to crack. The problem with the welds was due to hydrogen embrittlement of the metal. A by product of the SPF process is scale build up on the outer surfaces of the titanium. We determined this must be removed by grit blasting, then the titanium must be chemically etched to remove 0.001" to 0.002" of material from all surfaces. This process removes any material that may have absorbed too much hydrogen, which embrittles the titanium. A secondary benefit of etching is it provides a smooth surface that is aesthetically pleasing, is easy to clean, and exhibits minimal outgassing. No additional titanium welding problems were encountered after these procedures were instituted.

The outer vessel had to be redesigned once the new inner vessel shape was adopted. The outer vessel not only needed a different shape, it had to be stronger. The new inner vessel was self-supporting. It no longer required the suspension system and outer vessel to help carry the internal pressure loads. Consequently, the new outer vessel needed to be stronger to carry the vacuum loads. A picture of the new outer vessel design is presented in Figures 5.2-25. This picture shows a single outer vessel half. A flange has been welded to this half as part of a prototype backpack. The final version of the backpack would not have this flange.

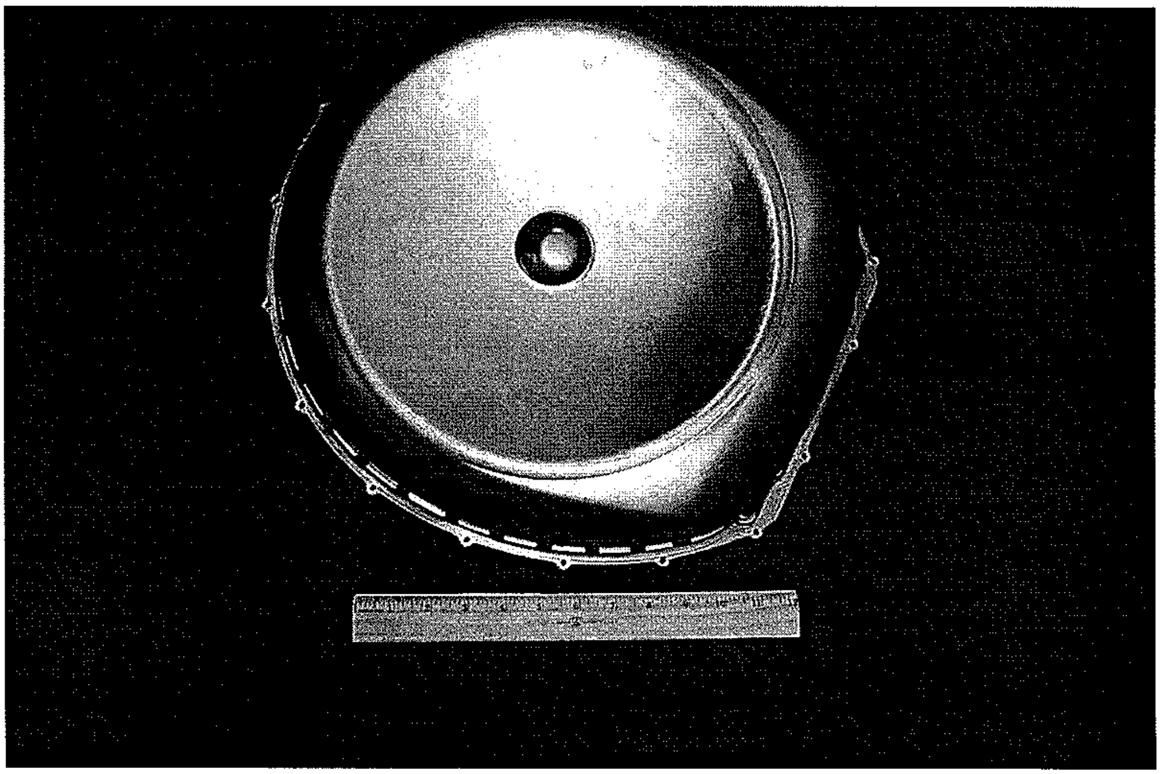


Figure 5.2-25: New Outer Vessel Design

The new outer vessel design used a thicker titanium shell and inward dished heads to carry the vacuum loads. A protruding bump in the middle of the dish was necessary for clearance between the inner and outer vessels. This bump was also used to position the tension suspension system.

Other features were added to this new outer vessel design. The lower half of the outer vessel profile was made somewhat oblong to make room for tube runs and penetrations through the outer vessel. This oblong section deviated from the traditional shapes generally considered for pressure vessels.

During dewar assembly, a completed inner vessel assembly was installed in an outer vessel half, the second outer vessel half placed on top, and the two halves were welded together at the perimeter. The new outer vessel used the same type of weld joint as the previous outer vessel; two radiused flanges butted up against one another and edge welded. When welded, the flanges melt back and provide the filler material to form a shallow uniform bead around the perimeter of the vessel. This joint provides accurate assembly, as it is part of the titanium shell created during super plastic forming. It also allows for fast, low tolerance trimming of the titanium shells from the formed part. Burst tests on outer vessels with this type of joint showed no failure in the welds.

Five titanium brackets were welded to the assembled dewar. Four of the brackets were identical and were welded to the bottom of the outer vessel, two on each half. These brackets interfaced with the bottom box. The fifth bracket was welded on the top of the outer vessel and interfaced with the backpack harness. The harness consists of two shoulder straps and a waist belt. The shoulder straps are attached to the top bracket on the dewar and the waist belt is attached to the bottom box structure. OSS tested several variations of the harness design to ensure the final design was comfortable and easy to don and doff. A picture of the harness installed on a prototype backpack is presented in Figure 5.2-26.

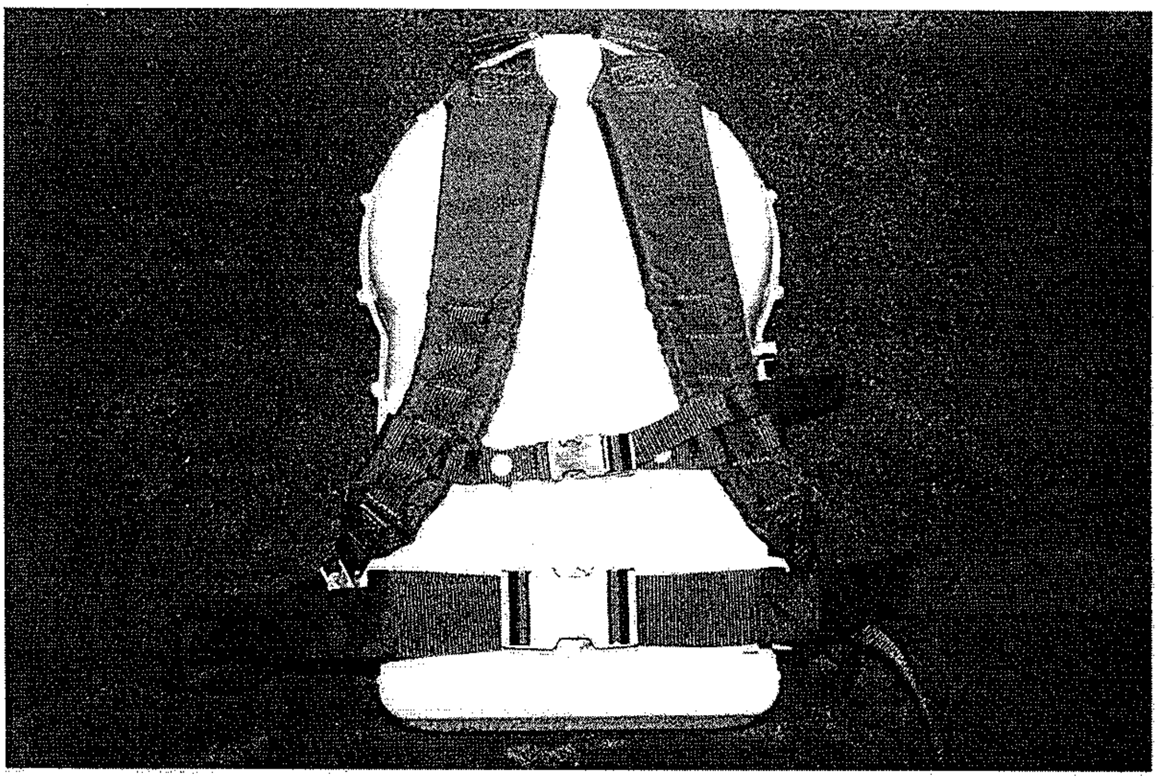


Figure 5.2-26: Backpack Harness

A custom built titanium pump out port was the final item welded to the dewar. The port was designed and built by OSS. It is a slightly larger version of the one used during Phase I. The port was machined from titanium and welded on the side, near the bottom, of one of the outer vessel halves.

During the redesign of the outer vessel, OSS also developed a series of fixtures to drill holes in the outer vessel for the transition bushings, weld the transition bushings in place, weld the bottom four brackets in place, and weld the two outer vessel halves together. These fixtures aided assembly and ensured the interfaces with the bottom box conformed to the interface drawing jointly developed by Scott and OSS.

During testing of the system, two problems with the new outer vessel design were identified:

- Permanent deformation during DOT external pressure test, and
- Outward buckling of the outer vessel when the vacuum space is pressurized.

When the new two-hour dewar under went DOT testing, the oblong portions on the bottom of the outer vessel deformed during the external pressure test. Small areas in this region buckled inward approximately 1/16" during the test. These areas did not pop back out when the external pressure was removed; if the vacuum space was pressurized back to atmospheric pressure, the areas would pop back out. Because the outer vessel showed permanent deformation, the vessel failed the test. Fortunately, this phenomenon presented no indication of a failure in the inner vessel or suspension system and so does not pose a safety problem.

Two possible options for resolving this problem have been identified: 1) stiffen the outer vessel or 2) modify the DOT requirement. It may be possible to add ridges in the outer vessel near the areas that buckled to stiffen the regions and prevent buckling. Welding in separate gusset plates inside the vessel would also stiffen the areas. However, this option requires additional welding and material and will therefore increase the assembly costs and the backpack weight. It may also be possible to modify the DOT requirement to allow for this condition. As previously stated, the phenomenon does not pose a safety hazard and so should not prevent the dewar from being DOT certified. Unfortunately these options have not been aggressively pursued due to budget constraints and this remains one of the open issues in the dewar design.

The second problem uncovered during testing concerned the pump out plug and was more serious. The pump out plug is a cylindrical disk that fits into a port on the side of the outer vessel. Through the use of a valve operator, the plug can be removed to evacuate the annulus space between the inner and outer vessels. Once the space has been adequately evacuated, the plug is reinstalled.

The plug also acts as a pressure relief device. If the backpack annulus space is ever pressurized due to a failure in the inner vessel or tubing, the plug will be pushed out to relieve pressure before the outer vessel ruptures.

A custom titanium plug and port were developed for the AWPS outer vessel based upon the design of commercially available components. The plug relies on a double o-ring seal between the outer diameter of the plug and the inner diameter of the port to seal the dewar vacuum.

During testing of one of the prototype two-hour dewars, the pump out plug was inadvertently held in place. A failure occurred in one of the tube braze joints inside the vacuum space. As a result, the vacuum space pressurized which caused one of the outer vessel halves to buckle outward. The pressure in the outer vessel was quickly vented and the outer vessel snapped back into place.

This failure raised a concern that the pump out plug may not blow at sufficiently low pressures to prevent the outer vessel from buckling outward. The first step taken to resolve this issue was to conduct several tests to quantify the buckling pressure of the outer vessel and the blow out pressure of the pump out plug. One of the flanged prototype outer vessels previously developed was slowly pressurized several times until it buckled. The outer vessel pressure was recorded using a PC based data acquisition system. A graph of one of these tests is presented in Figure 5.2-27.

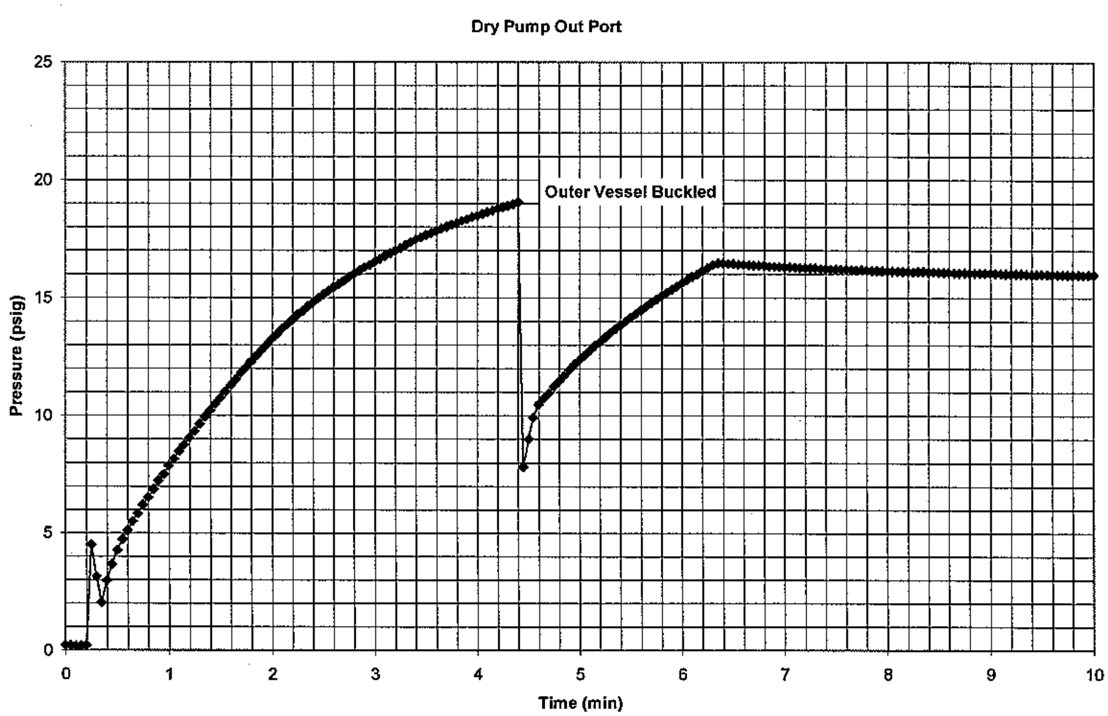


Figure 5.2-27: Outer Vessel Buckling Pressure

The outer vessel buckled when the pressure dropped suddenly. The sudden drop in pressure was due to the sudden increase in volume as the outer vessel buckled outward. As indicated in Figure 5.2-27, the buckling pressure occurred near 18 psig. This buckling pressure was fairly repeatable and set the requirement for the pump out plug.

Following the buckling tests, tests were performed to identify the pump out plug's blow out pressure. A test fixture was built to allow the back side of the plug to be pressurized. The pressure was ramped up at various rates and the blow out pressure recorded. Some of the test results are presented in Figure 5.2-28.

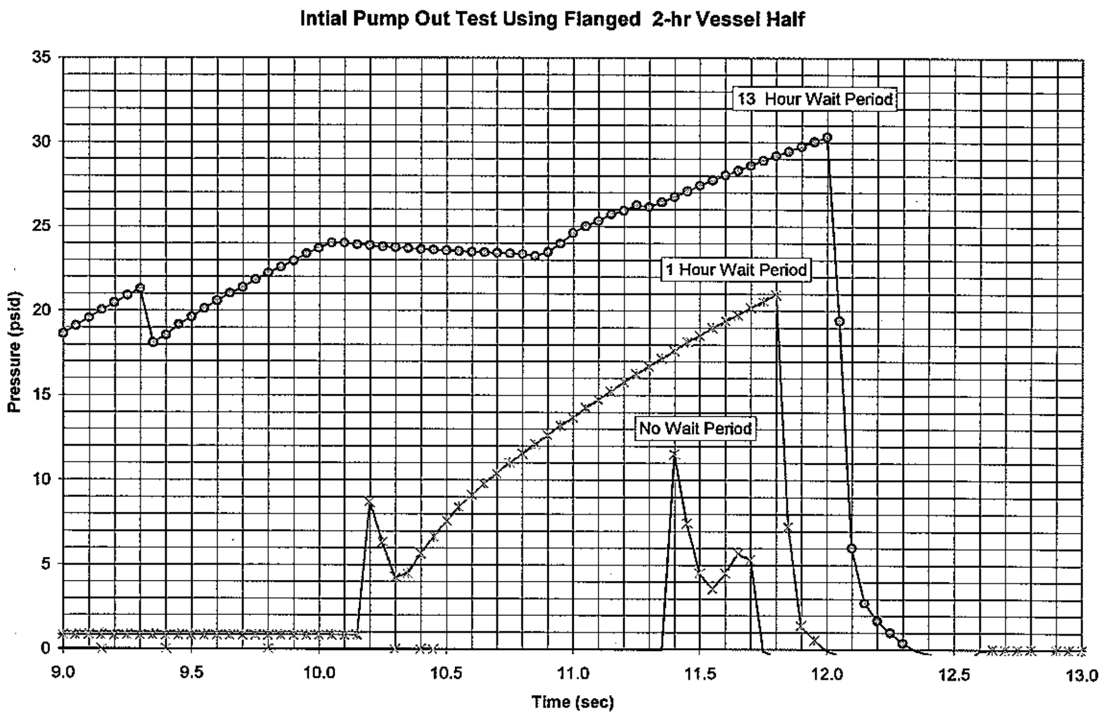


Figure 5.2-28: Pump Out Plug Blow Out Pressures

As indicated in the graph, the plug will pop out at a pressure between near 10 psig immediately after it is installed in the pump out port. If the plug is allowed to sit in the port, the grease around the o-ring will be pushed away and the blow out pressure increase significantly. Testing indicated the blow pressure can almost triple over time and well exceed the outer vessel's buckling pressure.

Again, two options for solving this problem were pursued. OSS first looked at stiffening the outer vessel to increase the buckling pressure. Initially, we thought that adding ridges across the dished head would stiffen the outer vessel and not only increase the buckling pressure but also prevent the oblong portions of the outer vessel from buckling inward during the DOT external pressure test.

The primary concern with this approach was the feel of the pack on the user's back. We believed that any ridges or gusset plates may feel uncomfortable. To resolve this issue, OSS performed several tests to assess the impact of adding stiffening structure to the outer vessel had on comfort. During these tests, ridges and gusset plates were added to a prototype backpack. Several users donned the backpack, performed a series of standard motions, and then commented on the feel of the backpack. The test was repeated without the stiffening features. Each test subject commented that the stiffening features tended to dig into their back when they reached forward and were extremely uncomfortable.

It was therefore decided to pursue our second option, reducing the operating pressure of the outer vessel's pressure relief device. A variety of approaches were tested. These included:

- removing one of the two plug o-rings,
- using a larger pump out plug,
- using an off-the-shelf vacuum relief device, and
- using a burst disk.

Both the blow out (relief) pressure and the leak rate of the first three options were measured. A summary of the test results are presented in Table 5.2-3. Unfortunately, none of these options proved acceptable. Removing one of the plug's o-rings greatly reduced the blow out pressure. However, it also increased the leak rate across the plug to an unacceptable level. A larger pump out plug also demonstrated a lower blow out pressure, but not low enough. The vacuum relief device tested is a commercially available product that is similar to a spring loaded relief valve. The device provided a suitably low relief pressure but allowed too great a leak rate, was heavy, and very expensive.

Table 5.2-3: Outer Vessel Relief Device Test Results

Component	Relief Pressure psig	Leak Rate (x10-9)
SV3-084-5W5 - Pumpout/Relief Port (Initial)	7.02	34
SV3-084-5W5 - Pumpout/Relief Port (Repeat)	7	34
PR3-084-5W2 - Relief Valve (Initial)	1.24	220
PR3-084-5W2 - Relief Valve (Repeat)	1.65	220
SV8-088-5W2 - Large Pump Out Plug (Initial)	8	0.2
SV8-088-5W2 - Large Pump Out Plug (Repeat)	15	0.2
Data Recorded in Log Book #4, Pages 051		
Large Pump Out Plug w/ both O-Rings (Initial)	8	0.2
Large Pump Out Plug w/ both O-Rings (Steady State)	15	4.2
Large Pump Out Plug w/ bottom O-Ring (Initial)	0.48	3
Large Pump Out Plug w/ bottom O-Ring (Steady State)		60
Large Pump Out Plug w/ side O-Ring (Initial)	6.5	0.2
Large Pump Out Plug w/ side O-Ring (Steady State)	11.2	36

The use of a burst disk was also considered. Unfortunately, no burst disk could be found that provided a low enough burst pressure, maintained the 14.7 pressure differential across the outer vessel, and operated over the full temperature range expected.

Another option was then considered. Using previous data taken on the large (1" diameter) plug, we developed a model to predict the blow out pressure and helium leak rate for a given pump out plug design. Using this model, we predicted that increasing the depth of the O-ring grove on the side of the plug from .091" to .11" would reduce the blow out pressure from 15 psid to 8.8 psid and only change the leak rate from 4.2 x 10^{-9} cc/sec to 4.3 x 10^{-9} cc/sec.

We modified one of the plugs and tested its performance. The results of the blow out tests are presented in Figure 1. As indicated in the graph, the blow out pressure ranges from 5.7 psid to 8.8 psid depending on the pressurization rate and on the amount of time the plug has been installed in the port. The outer vessel buckles at approximately 20 psid and so this blow out pressure provides a factor of safety of approximately 2.5.

The helium leak rate for the modified plug was initially measured to be 1.8 x 10^{-9} cc/sec, an acceptable rate. However, this leakage is lower than the leakage of the initial plug. This result was unexpected. The test was repeated to verify the leakage had increased to approximately 4.5 x 10^{-9} cc/sec, very close to the predicted leak rate. This concept was very promising. Unfortunately, we ran into difficulties in integrating the concept onto the outer vessel. DOT requirements prevent penetration with welds from being added on or nearby curved surfaces. Consequently, we could no find a suitable place on the outer vessel to locate the large pump out port.

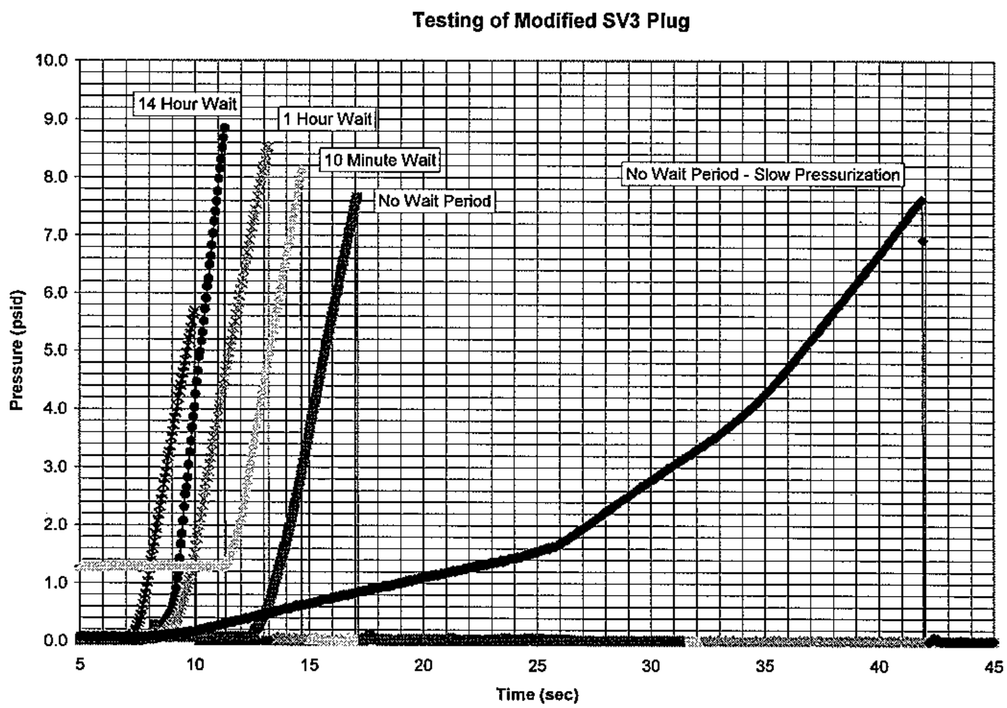


Figure 5.2-29: Test Results with Modified Large Pump Out Plug

Since no suitable relief device could be located, OSS developed a new relief device concept. The concept built upon one of the configurations tested, the current plug design with a single o-ring. This configuration provided an adequate blowout pressure but possessed too great a leak rate. In the new concept, a thin aluminum foil disk is epoxied over the top of the pump out port after the plug is installed. The metal disk will significantly reduce the leak rate through the pump out port. The top of the pump out plug is also modified to include a sharp point in its center. This point will rupture the foil disk in the event the outer vessel is pressurized. Consequently, the foil disk should not increase the plug's blow out pressure.

The small space between the foil and the plug would be filled with vacuum grease. Unfortunately, budget and schedule constraints on the AWPS project prevented the concept from being detailed, built, and tested.

5.2.5 Suspension System Development

During the early stages of Phase II, work focused on optimizing the design of the cone suspension system to reduce the heat transfer, weight, and costs. The initial cones were laid up by hand on a fixture. The process was relatively time consuming and costly. Consequently, OSS considered using other manufacturing techniques and other materials, such as thermal forming a material pre-pregnated with epoxy, and injection molding using a glass filled plastic.

Before any decisions were made on materials and fabrication techniques, the new inner vessel was baselined. The concept of a tension suspension system was developed shortly after we realized the need for stiffening rings on the outer edges of the inner vessel.

The tension suspension system had the potential to be lighter weight and easier to manufacture, and to reduce heat transfer to the inner vessel. Several variations of a tension suspension system were evaluated, including stamping a single continuous part that incorporated the tension ring for the inner vessel into the part. We settled on a system using titanium spokes swaged to eyelets that were riveted to the tension ring. The other end of the spokes were captured in a central hub made of Lytex, a tough, compression molded composite; the design is presented in Figures 5.2-30a and 5.2-30b.

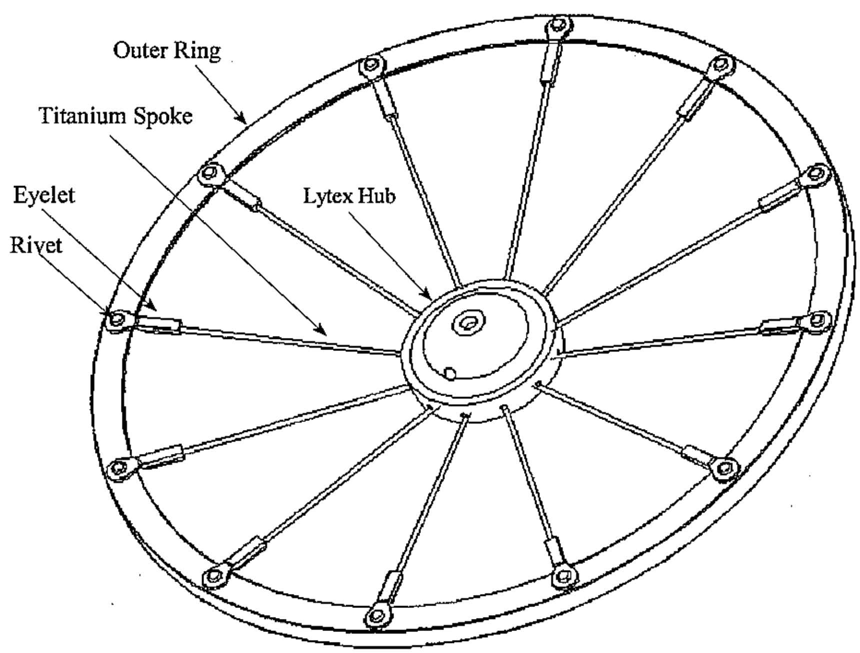


Figure 5.2-30a: Sketch of Spoke Tension Suspension System

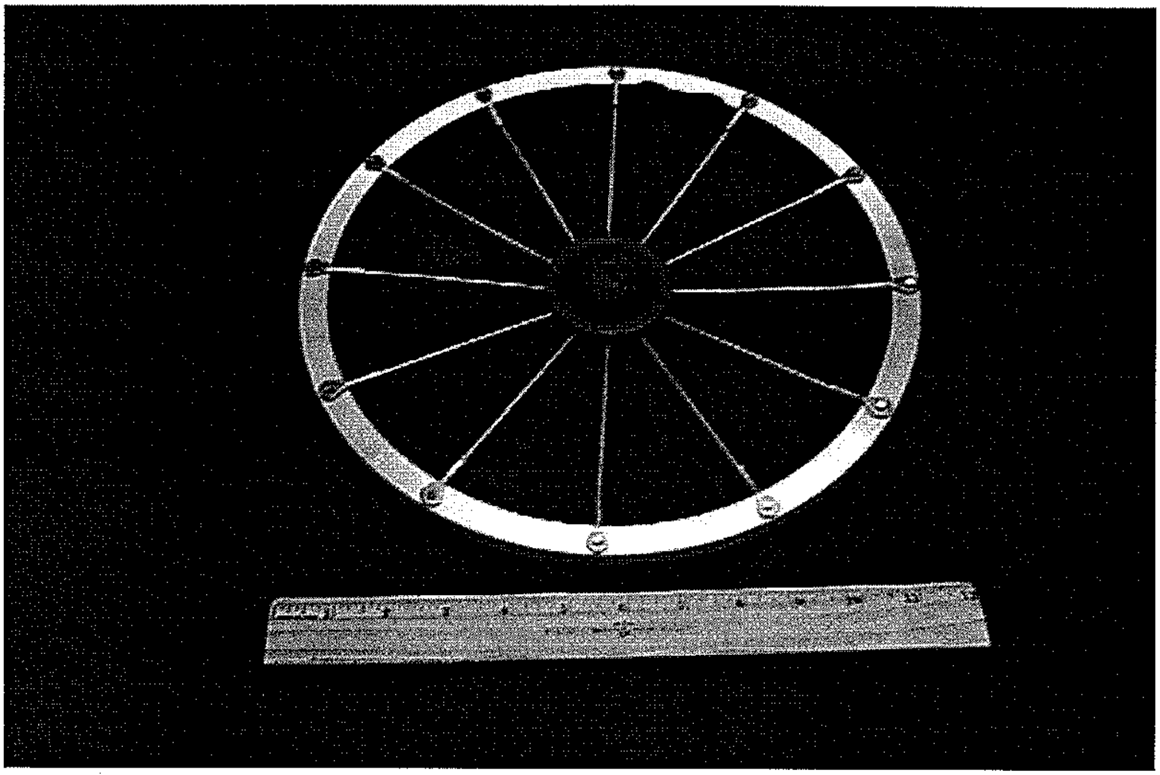


Figure 5.2-30b: Spoke Tension Suspension System Hardware

Of high importance in our selection criteria for the suspension system was the ability to manufacture parts quickly. While stamping may have been a better choice in the long run, the lead times, risk, tool costs, and engineering effort to design the stamped part and work with a stamper were severe disadvantages. The titanium spoke system turned out to have a very high part count, and be difficult to manufacture due to necessarily tight tolerances. The processes of swaging and riveting did not lend themselves to holding tight tolerances.

While developing the detailed design for the spoke system, OSS performed a series of pull tests on spokes and spoke/eyelet swaged connections. The pull tests were to ensure the suspension system would possess adequate strength. The outer vessel had been stiffened to carry the vacuum load. However, it was expected that the suspension system would still carry some load. Based upon preliminary analysis and the pull tests we estimated each spoke assembly needed a minimum of 12 spokes to distribute and carry the anticipated loads.

The detailed design of the system was completed and we subcontracted the fabrication of several molded Lytex hubs. After receiving the hubs, the suspension system design was built and tested in a prototype dewar. No obvious problems were encountered. The design was then incorporated into the 6 dewars to be used for NIOSH certification.

A similar system was being developed and tested for the one-hour dewar at this time. The suspension system for this unit was thoroughly inspected after repeated system testing. Inspection revealed cracks in the base of the Lytex hubs due to excessive hoop stress in the part. An aluminum backing ring was added to the design to carry the hoop stress. Since then, no further Lytex hub failures occurred. We feared the two-hour design would experience the same failure.

During the disassembly of one of the two-hour NIOSH dewars, the suspension system was thoroughly inspected and cracks were indeed found at the base of the Lytex hub. The design was modified to accommodate an aluminum backing ring, as was done in the one-hour dewar design. A sketch of the design with the aluminum backing ring is presented in Figure 5.2-31a. Figure 5.2-31b shows a picture of the Lytex hub with a backing ring resting on top of it. Initial testing of the new design installed in a fixed-tube dewar built to test the capacitance gauge and shortened vaporizer indicated the backing ring prevented damage to the Lytex hubs.

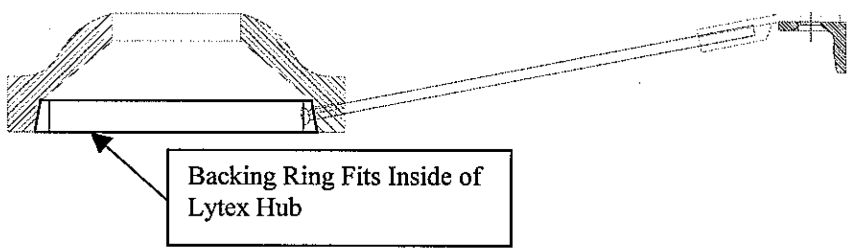


Figure 5.2-31a: Sketch of Suspension System Aluminum Backing Ring

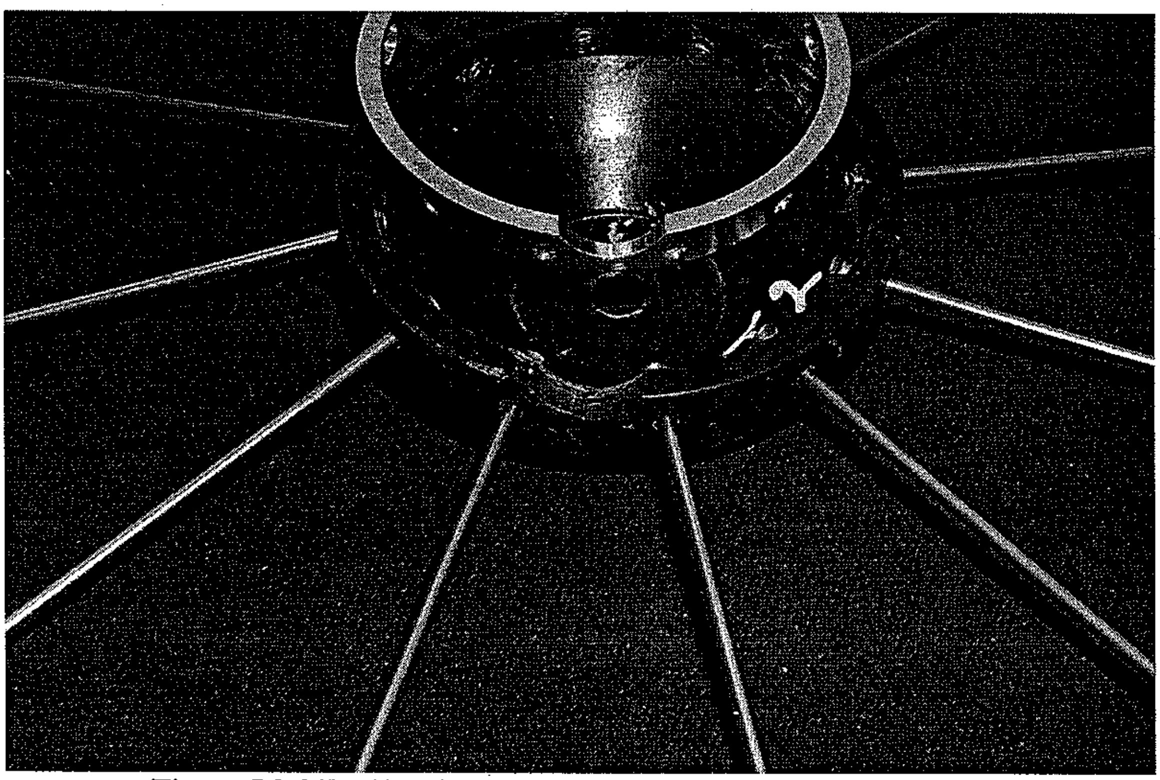


Figure 5.2-31b: Aluminum Backing Ring and Suspension System

During the fabrication of the prototype suspension system, OSS also designed a fixture and developed assembly procedures to allow the system to be more easily assembled. The fixture and assembly procedures allowed the eyelets to be swaged onto the spokes at the proper position, within +/- 0.005". This ensured the spokes were all of the same length and therefore the loads were evenly distributed among all 12 spokes. However, if the backpack is ever to be certified and units mass produced, the use of a stamped component should be examined again.

5.2.6 Vaporizer and Tubing Development

A variety of tubes run from the inner vessel to the outer vessel inside the dewar's vacuum space. These tubes allow the dewar to be filled with liquid air, allow ullage gas to be vented during a fill and during storage, allow liquid air to be withdrawn from the inner vessel during operation, and allow the inner vessel to be drained. The heat exchanger responsible for vaporizing and warming the air supplied to the user, and cooling the LCG water is also housed in the dewar vacuum space.

The layout of the internal tubing evolved significantly from Phase I to Phase II. The tubes used in the Phase I dewar were aluminum. It was hoped aluminum tubes could be used to reduce weight. Unfortunately, the aluminum tubes sharply increased heat leak into the dewar and reduced the dewar's storage time, a critical parameter for a commercial backpack. As a result, the tubing material was changed from aluminum to stainless steel.

The material change not only reduced heat leak into the dewar, it also allowed commercially available, titanium to stainless steel bushings to be used to seal the tubes as they exited the outer vessel. The titanium side of the bushing was welded to one of the outer vessel halves, the inner vessel and tubes installed and routed through the bushings, and the outer surface of the tubes welded to the stainless steel side of the bushings. This method provided a leak tight seal that could withstand the expected temperature extremes.

Other methods of sealing the tubes exiting the outer vessel, such as metal compression fittings, were considered. These techniques would have been less expensive than the transition bushings but either lead to tube configurations that were difficult to manufacture or impossible to install.

Once the agreement between Scott and OSS had been signed, both companies worked to finalize the location of the tube outlets on the outer vessel. Scott developed a source control drawing that specified the location of the tubes and other interfaces that effect the bottom box design. The drawing was based upon the most current dewar design. OSS reviewed and agreed to the drawing, thereby freezing the external dewar interfaces and allowing Scott to begin designing the components and manifolds that would interface with the dewar.

The internal tube layout changed three times during Phase II, even though the external tube position were fixed based upon the interface source control drawing. The initial change was driven by pressure control testing and by the results of a new FMEA. A series of pressure control tests were conducted early during Phase II using a 1-hour development unit. During this testing, a phenomenon similar to geysering was observed. Liquid air would be withdrawn from the inner vessel when the user inhaled. The liquid air would enter the vaporizer and quickly boil. This created a pressure spike that forced some of the air, now in gas phase, back into the inner vessel. The pressure in the inner vessel would increase as a result. The pressure would increase with each breath until it reached the relief valve setting. The relief valve would then begin to vent air to maintain the inner vessel pressure at its maximum allowable value. This venting wasted gas, reduced the backpacks rated duration, and tended to increase the oxygen percentage of the liquid air in the dewar.

The geyersing problem was solved by installing a check valve in the liquid withdrawal line just outside of the inner vessel. The check valve allows liquid air to be withdrawn from the inner vessel when the user inhales but prevents any gas or cryogen from flowing back into the inner vessel. A separate line was also added between the check valve and the inner vessel to allow the dewar to be filled with liquid air. The line is also used to drain the dewar and to provide a second flow path for breathing air in the event the check valve fails closed.

The second change in the tube layout occurred when the new inner and outer vessel shapes were adopted. The tubes had to be modified to accommodate the new vessel shapes. During this redesign, metal bellows included in the previous design were eliminated. Metal bellows were originally soldered to each tube, near the outer vessel penetration, to provide some flexibility during assembly and to accommodate thermal expansion and contraction of the system. However, after assembling and testing numerous breadboards and prototype backpacks, we determined the bellows were not needed and only increased the tubing cost and the chances of a leak occurring.

Both previous tube layouts were developed under the constraint that the check valve be placed as close to the inner vessel interface as possible. The intention was to ensure little or no liquid air boiled before it passed through the check valve. As a result, the check valve was located within the dished section of the inner vessel. The resulting tube layouts were difficult to bend and install. Each tube was unique and the system was expensive to fabricate and assemble.

This tube configuration was used in the 6 NIOSH dewars. During the redesign effort following testing of these dewar, the tube layout was changes. The check valve was moved farther from the inner vessel interface, over to the side of the vessel. The tube layouts were then simplified. Many of the new tubes were identical to one another, required no compound bends, and utilized standard bend radius. The time to fabricate and assemble the tubing was almost cut in half with the new tube layout.

The general design of the vaporizer did not change significantly during Phase II. The Phase I KSU testing indicated the initial vaporizer design performed adequately. The vaporizer only needed to be optimized to reduce its weight and production costs, and to ensure the vaporizer would not be damaged in the event the water froze.

The vaporizer is responsible for vaporizing and warming the air supplied to the user, and cooling the LCG water. It is a parallel-flow, tube-in-tube heat exchanger that is wrapped around the dewar inner vessel. Water flows through the inner tube and the liquid air flows between the inner and outer tubes. A brass tube is wrapped around the inner tube at a pitch of 1" and forms a spiral flow passage between the inner and outer tubes. This technique increases the surface area and film coefficient for heat transfer from the air to the heat exchanger walls. A small plastic tube also runs through the inner tube. This tube will collapse in the event the water freezes and will prevent damage to the inner tube. The vaporizer layout is presented in Figures 5.2-32a and 5.2-32b.

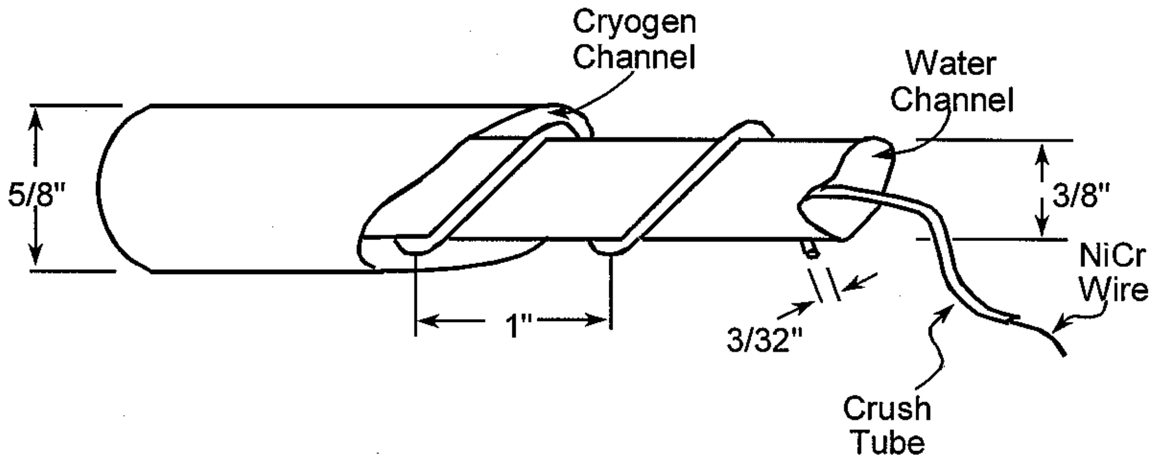


Figure 5.2-32a: Cut Away of Initial Vaporizer Configuration

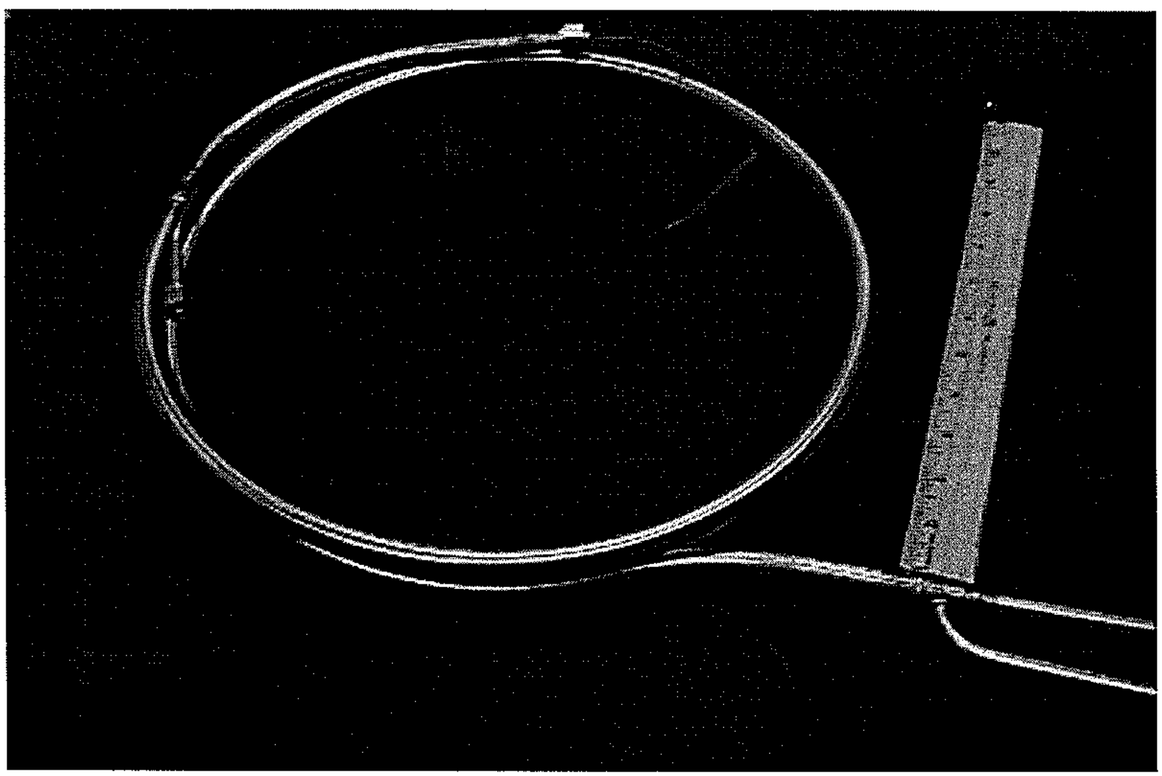


Figure 5.2-32b: Initial Vaporizer Layout

In the initial backpack developed in Phase I, the vaporizer tubes were aluminum. The material was changed to stainless steel in Phase II to allow the vaporizer to be readily integrated into the new outer vessel design.

One of the primary development tasks for the vaporizer was to lower the production costs. One option that was considered was the use of a fluted tube. A fluted tube would accomplish the same result as that of a straight tube wrapped with brass tubing. Such tubes are used by Turbo-Tec in similar tube-in-tube heat exchangers.

The fluted tubes are made using an automated process and are inexpensive. However, the tubes add significant weight. The tubes also tend to crack in the event the water in the vaporizer freezes due to either a LCG pump failure or a blockage in the water flow passage. In the baseline vaporizer design, the plastic tube running through the center of the water flow passage deforms if the water in the vaporizer freezes, thereby preventing damage to the heat exchange; testing during Phase I and II showed that without the plastic crush tube the inner vaporizer tube would split in the event of a freeze up. However, despite the use of a plastic crush tube, fluted tubes tended to crack if the water froze. It was assumed that water became trapped inside the tube flutes during the freeze process. As this water froze, it would expand and split the flutes. This phenomenon was observed during failure testing of several prototype vaporizers that used fluted tubes. Consequently, the possibility of using fluted tubes was dismissed.

Despite not using fluted tubes, we were able to significantly reduce the production cost of the vaporizers. Through repeated vaporizer assemblies we perfected the assembly procedures. We also built several custom fixtures to wrap the brass tubing around the inner tube and to coil the vaporizer. As a result, we were able to cut the production labor costs approximately in half.

During Phase II, the thermal performance of the vaporizer also became an issue. We initially performed a series of tests to characterize the vaporizer performance and to identify the conditions under which the vaporizer might freeze. One of the prototype packs was used in the testing. These results are presented in Table 5.2-4. The results indicate that freezing of the vaporizer is highly dependent on water flow rate and inlet water temperature. Based upon this testing and preliminary models predicting inlet water temperatures for various operating conditions, we did not expect freezing to be a problem.

Table 5.2-4: Initial Vaporizer Freeze Up Testing

Test	Flow Rate Gas (SLPM)		Water (GPM)	Water Temperature (deg F) Inlet	Outlet	Delta T	Outlet Gas T (deg F)	Freeze
4_2_1	STD	40	0.4	80	74	6	67.6	no
	Hard	80	0.4	80	66.8	13.2	67.5	no
	Max.	100	0.4	80	63	17	67.5	no
	STD	40	0.4	75	68.7	6.3	67	no
	Hard	80	0.4	75	62.5	12.5	66.5	no
	Max.	100	0.4	75	57.8	17.2	66	no
	STD	40	0.4	69.2	63	6.2	67	no
	Hard	80	0.4	68.5	55.5	13	66.5	no
	Max.	100	0.4	68.7	51.5	17.2	65.1	no
4_2_2	STD	40	0.4	64	57.5	6.5	67	no
	Hard	80	0.4	64	52.1	11.9	65.5	no
	Max.	100	0.4	63.2	45.4	17.8	65.5	no
	STD	40	0.4	59	52.8	6.2	65.7	no
	Hard	80	0.4	59.2	46.7	12.5	65	no
	Max.	100	0.4	59.8	41.2	18.6	64	no
	STD	40	0.4	56	50	6	65.7	no
	Hard	80	0.4	56	44.3	11.7	65	no
	Max.	100	0.4	55.7	37.8	17.9	64	no
4_2_3	STD	40	0.4	51	45	6	74	yes
4_4_2	STD	40	0.5	59.6	55	4.6	70	no
		40	0.39	54.8	48.5	6.3	69.6	yes
4_4_3	STD	40	0.5	59.7	55.5	4.2	70	no
		40	0.45	59.9	55	4.9	68.8	no
		40	0.39	59	53.5	5.5	68	no
		40	0.35	59.2	53	6.2	67.5	no
		40	0.3	59.4	52.2	7.2	67.4	yes
4_4_4	Hard	80	0.5	59.5	49.5	10	70	no
		80	0.45	59.7	49	10.7	68	no
		80	0.4	59.8	47.7	12.1	68.8	no
		80	0.35	60	46.5	13.5	68.7	no
		80	0.3	59	43	16	68.8	no
		80	0.31	60	44.7	15.3	68.8	no
		80	0.245	58.8	39	19.8	68.8	yes
4_4_5	Max.	100	0.5	59.6	46	13.6	70	no
		100	0.45	59.7	45	14.7	68	no
		100	0.4	59.9	44	15.9	66	no
		100	0.35	60	41.5	18.5	65	no

Unfortunately, several times during the human testing at OSS and the IUOE demonstrations, the water in the vaporizer froze. Initially, this failure was attributed to a pinch off in the LCG which restricted the water flow and caused the vaporizer to freeze. However, extensive review of test conditions and results indicated that the freeze was not necessarily due to a reduction in the water flow rate.

The freezing was found to occur when the user was working at low to moderate rates and the pack had a good vacuum. The problem was initially thought to be caused by heat transfer from the water inlet tube (the tube that runs from the outer vessel to the vaporizer inlet) to the inner vessel. During human testing with one of the prototype backpacks, the LCG and pack reached a steady state condition when removing between 400 W to 500 W of heat from the test subject. The test subject was wearing a fully encapsulated suit and walked on a treadmill at 3 mph. The test subject's breaths per minute was monitored and their average breathing rate was estimated to be slightly less than the standard NIOSH rate (24 breaths/min @ 1.6L = 40 SLPM). A breathing model developed by OSS indicates that the user is at a metabolic rate between 580 W and 620 W when breathing at a rate of 40 SLPM. At this breathing rate, heat exchanger calculations predict that the LCG should provide approximately 300W cooling, assuming a heat exchanger efficiency of 90%. However, the test data indicated that the LCG load was providing much more than 300 W of cooling.

This additional cooling of between 100 W and 150 W was thought to be provided by heat transfer from the water tube to the inner vessel. As a result, we conducted a test in which a prototype dewar was filled with liquid air and water was circulated through the vaporizer. Sensors in the water loop measured the inlet and outlet water temperatures and the water flow rate. Contrary to our predictions, the results indicated that heat transfer from the vaporizer was much less than 100 W.

We were in the process of reviewing this and previous test data to resolve the freezing issue when the decision was made to shorten the vaporizer from 62" to 40". The decision was based upon the need to reduce the backpack weight. The new vaporizer layout reduces the backpack weight by almost ½ pound.

The performance of the new vaporizer was estimated based upon testing of 62" long vaporizer. The vaporizer was covered with thermocouples (every 4") and wrapped in insulative foam. Water was circulated in the inner tube at approximately 1/2 gallons per minute and liquid nitrogen (LN_2) through the annulus space at various flow rates. The temperature distribution was measured for the various LN_2 flow rates. This data, in addition to estimates on film coefficients, led to the performance estimates listed below.

At NIOSH flow rate:	
Outlet Gas Temperature:	0 °F
Heat transfer to Water:	313 W
Heat Exchanger Efficiency:	92%
At NFPA flow rate:	
Outlet Gas Temperature:	-65 °F
Heat transfer to Water:	710 W
Heat Exchanger Efficiency:	83%

The performance predictions indicated that the decrease in vaporizer performance was not unreasonable and so a prototype short vaporizer was developed and incorporated into the fixed tube dewar built to test the capacitance gauge accuracy. The unit was tested to quantify the vaporizer performance. During the tests, the proposed shortened vaporizer installed in the fixed tube dewar was tested this past month. In the test, the dewar was filled with liquid air. Water from a 70 °F water bath was circulated through the vaporizer at a rate of 0.4 gpm. The backpack was connected to a breathing machine and run through the following breathing profile.

Breathing Rate (SLPM)	Breathing Duration (Minutes)
40 (NIOSH rate)	20
80	20
100 (NFPA rate)	40

The vaporizer's thermal performance is presented in Figure 5.2-33. The figure indicates a definite decrease in vaporizer efficiency. The outlet gas temperature at the maximum breathing rate reaches equilibrium at approximately –67 °F. The longer vaporizer typically produced equilibrium temperatures only slightly below the outlet water temperature. Figure 5.2-34 compares the performance of both the long and short vaporizers. As indicated in the figure, the heat transfer provided by the two different size vaporizers doesn't vary except at the at the maximum breathing rate. At the maximum breathing rate the decrease in efficiency is approximately 80 W, less than a 15 % drop in performance. The reduction in weight and the production costs provided by the shorter vaporizer far outweigh vaporizer 's small drop in performance.

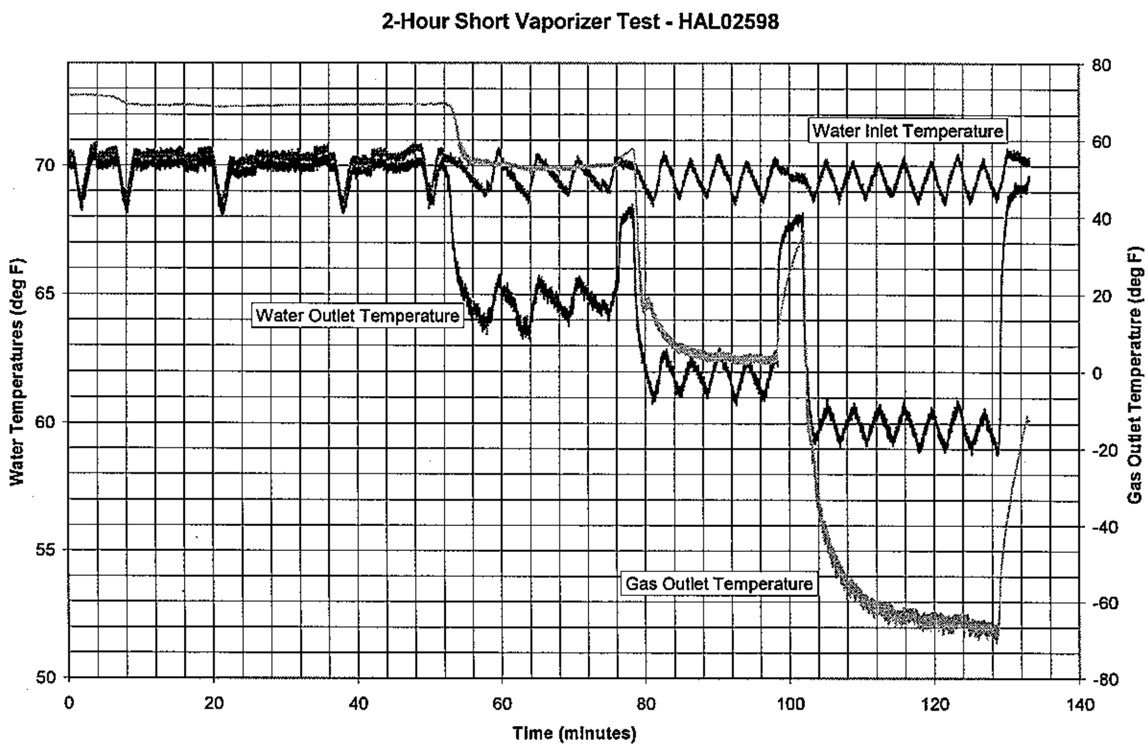


Figure 5.2-33: Short Vaporizer Test Results

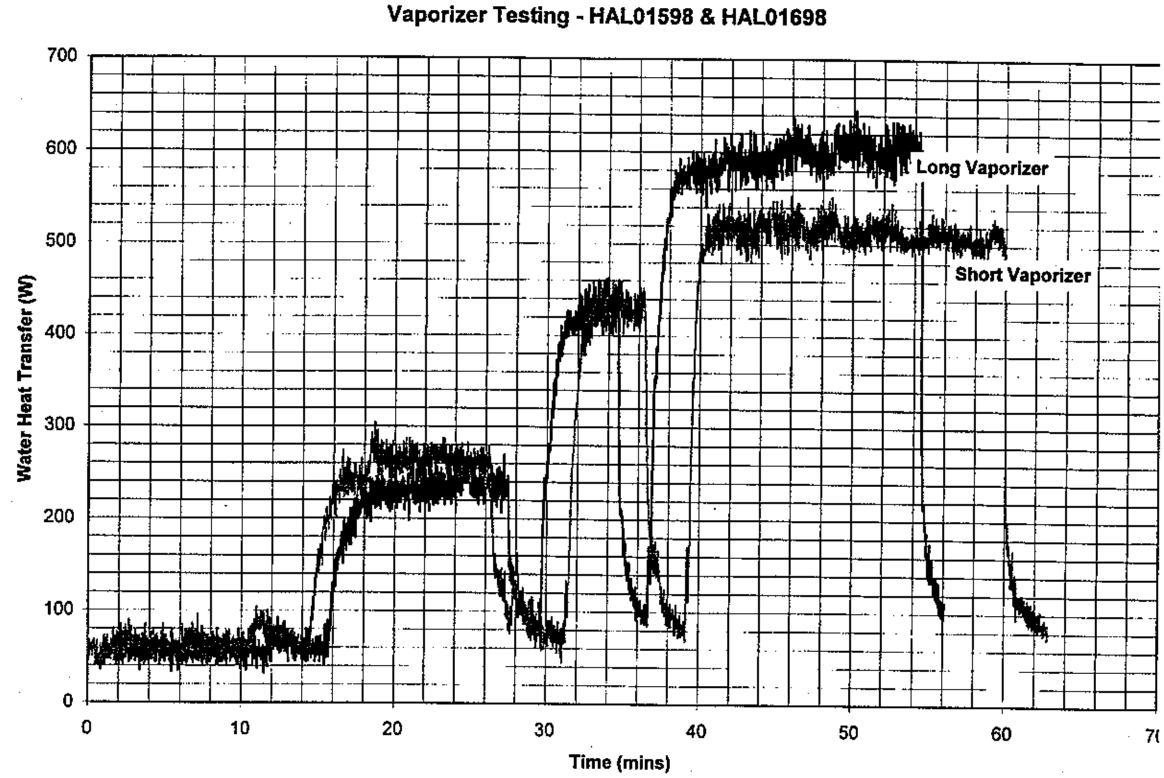


Figure 5.2-34: Comparison of Short and Long Vaporizer Performance

5.2.7 Dewar Insulation

The dewar is insulated to reduce heat transfer (heat leak) into the inner vessel. The boil off rate increases as the heat leak increases while the storage time (the amount of time the dewar can sit on the shelf between filling and use and still provide the rated duration of air) decreases. If the heat leak is severe enough, the dewar may vent during use. This venting will reduce the amount of air available to the user. We have also observed that excessive venting, over time, changes the oxygen percentage of the liquid air. The liquid nitrogen in the mixture tends to boil at a faster rate than the liquid oxygen. Consequently, the liquid air becomes oxygen rich while the ullage gas becomes nitrogen rich. This phenomenon could impact NIOSH certification because NIOSH levies tight constraints on the composition of the breathing gas, specifically on the oxygen percentage.

As a minimum, the backpack must provide a storage life long enough to allow the unit to be filled with liquid air, the full backpack transported to the work site, and the worker to suit up. These tasks could take from 1 to 3 hours. Following this delay, the system should be capable of providing the full two hour rated duration.

In applications where worker response time is critical, such as for fire fighter of emergency HazMat clean up teams, a longer storage time is desired. For these applications, informal surveys indicate that users would like to fill units with liquid air at the beginning of a 6 to 8 hour shift. Any time during the shift, the unit should be ready to use and be capable of providing the full rated duration. At the end of the shift, the units would either be topped off or emptied and refilled.

The dewar insulation consists of alternating layers of 0.0003" thick aluminum foil from Alfoils and a ceramic paper scrim, Cryotherm 243. A picture of this insulation applied to the inner vessel is presented in Figure 5.2-35. The design of this Multi-Layer Insulation (MIL) was optimized over the course of the AWPS development. Early during Phase II, OSS developed simple math models to predict the heat transfer into the dewar. These models not only included the insulation, but also other sources of heat leak such as conduction through the suspension system and the tubing. The models were used to assess the impacts of various design changes in the vacuum/MLI configuration, the suspension system design, and the tubing selection. A comparison of the results of these early models are shown in Figure 5.2-36. As indicated in the figure, the largest source of heat transfer, when the backpack annulus space was evacuated, was from the aluminum tubing. Consequently, we changed the tubing material to stainless steel.

Figure 5.2-35: Multi Layer Insulation Applied to Inner Vessel

Option	Configuration			Heat Leak (W)			
	Vacuum	Suspension System	Tubes	Vacuum	Cones	Tubes	Total
1	No MLI, Coated Surfaces	Cones with Vespel Spacer	Aluminum Tubes	0.45	0.32	4.620	5.39
2	No MLI, Coated Surfaces	Cones with Ultem Spacer	Thin Aluminum Tubes	0.45	0.15	2.376	2.98
3	No MLI, Coated Surfaces	Cones with Ultem Spacer	Stainless Steel Tubes	0.45	0.15	0.265	0.87
4	No MLI, Coated Surfaces	Cones with Ultem Spacer	Thin Stainless Steel Tubes	0.45	0.15	0.136	0.74
5	0.084" MLI, Coated Surfaces	Cones with Ultem Spacer	Thin Stainless Steel Tubes	0.86	0.15	0.136	1.15
6	0.112" MLI, Coated Surfaces	Cones with Ultem Spacer	Thin Stainless Steel Tubes	0.65	0.15	0.136	0.94
7	0.169" MLI, Coated Surfaces	Cones with Ultem Spacer	Thin Stainless Steel Tubes	0.43	0.15	0.136	0.72
8	0.112" MLI, Coated Surfaces	New Cones with No Spacer	Thin Stainless Steel Tubes	0.65	0.09	0.136	0.87
9	0.169" MLI, Coated Surfaces	New Cones with No Spacer	Thin Stainless Steel Tubes	0.43	0.09	0.136	0.66
10	0.169" MLI With No Vacuum, Coated Surfaces	New Cones with No Spacer	Thin Stainless Steel Tubes	5.96	0.09	0.136	6.19

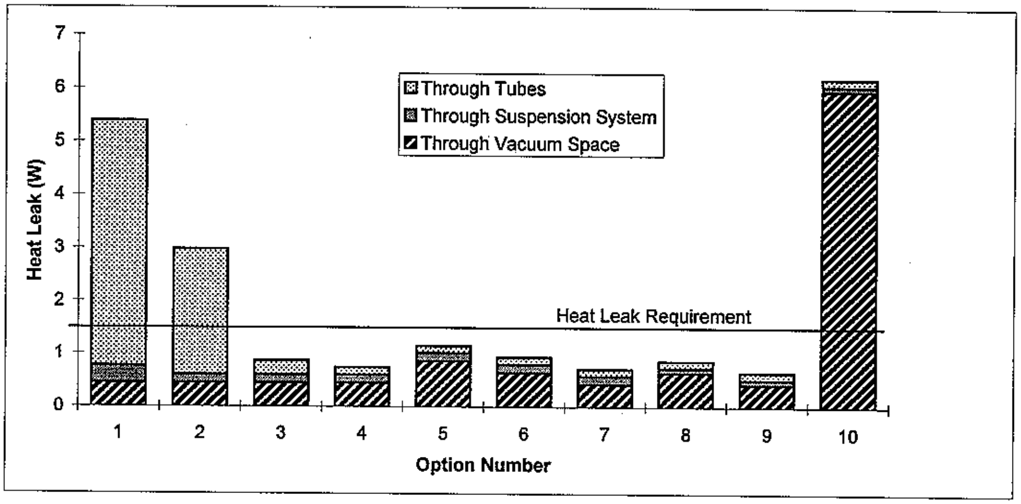


Figure 5.2-36: Initial Dewar Heat Leak Analysis Results

This early analysis indicated the importance of maintaining an appropriate vacuum, better than 1 x 10^{-3} torr, to reduce heat leak. In fact, much of the our work on the insulation during Phase II focused on maintaining a good vacuum for an extended period of time. Through repeated testing of prototype backpacks built during Phase II, we observed that the dewar vacuum would slowly degrade over a several week period. As a result, the boil off rate would increase significantly and frost would collect on the outside of the outer vessel when the pack was filled with liquid air. We added a series of getters, 10 Combination getters and 3 Supergetters, produced by SAES Getters to help maintain the dewar vacuum. Unfortunately, this solution did not completely solve the problem; the vacuum continued to degrade despite the addition of the getters.

We then underwent a methodical study to identify the cause of the vacuum degradation. The possible causes included off gassing of materials in the vacuum space and permeation of gasses through the LCP inner vessel. We first tested several LCP samples and determined that permeation through the LCP was very small. We then quantified the off gassing of a variety of material samples and found that the LCP and Crest epoxy used to glue the two inner vessel halves together do off gas in a vacuum. We coated several samples with metalized films to determine if such coatings would be effective at sealing the materials. Test results showed that sputtered titanium effectively sealed the LCP but could not seal the epoxy surface. Unfortunately, the titanium coating was expensive and there were concerns that the coating would crack due to thermal and pressure cycling.

During this time, we carefully monitored the vacuum in a variety of prototype backpacks and discovered that the rate of rise in the vacuum was approximately 3 x 10^{-3} torr/day. This proved to be true whether the dewar was a few weeks old or over a year old. Pressures as high as 200 microns (2 x 10-1 torr) were measured in the dewars with no sign of the pressure rise slowing or leveling off. A graph of some of these results is presented in Figure 5.2-37.

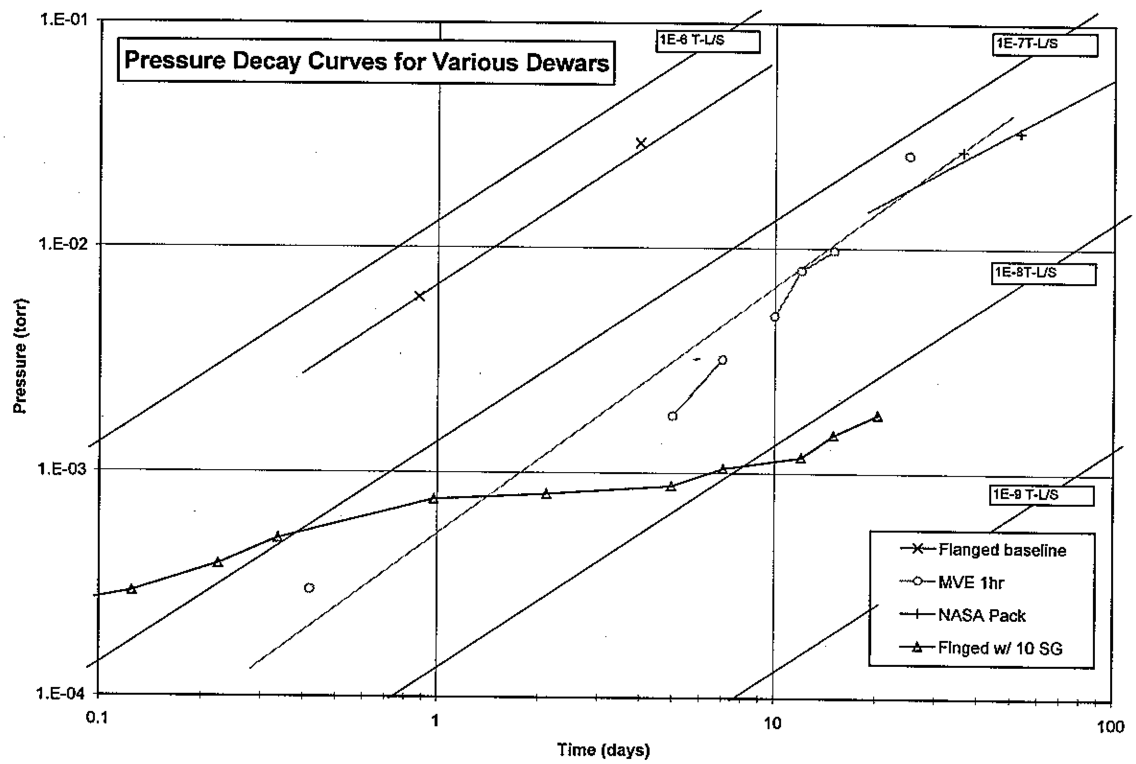


Figure 5.2-37: Pressure Decay Curves for Various Dewars

This seemed to indicate that permeation was the cause of the vacuum degradation, (outgassing would generally begin to level off). Residual Gas Analysis indicated that most of the contamination in the dewar was Argon. The theory is that air is slowly leaking across the pump out plug and possibly across the inner vessel. Since the getters cannot absorb Argon, it builds up over time, thus causing the vacuum to degrade. The proposed solution is to attach a molecular sieve packet to the outside of the inner vessel. When the dewar is filled with liquid air, the molecular sieve will get cold and absorb the Argon and other residual gasses in the vacuum space. This will cause the vacuum to drop to an acceptable level during storage and operation of the backpack. This recommendation has yet to be implemented due to lack of funds.

Initial dewars were equipped a molecular sieve. However, after reviewing the early assembly and handling procedures, we believe the molecular sieve was contaminated and out gassed rather than absorbing residual gasses. The new proposed assembly and handling procedures have been updated to ensure this does not happen in the future.

5.3 Bottom Box Development

The bottom box is responsible for supplying air to the user, maintaining internal dewar pressure during operation and storage, and circulating water through the vaporizer and LCG. The bottom box also provides a means of filling and draining the dewar. During Phase II, OSS developed and tested preliminary bottom box designs. These designs were turned over to Scott once the agreement between the two companies was signed. Scott was to optimize the design to reduce weight and manufacturing costs, and to ensure the bottom box would meet all of the regulatory requirements.

The bottom box consists of the following six primary subsystems:

- Ambient Heat Exchanger
- Pressure Control System Components
- Additional Valves
- Pump
- Batteries and Electronics
- Structure

Pictures of prototype bottom box buildups are presented in Figures 5.3-1 and 5.3-2. This section provides an overview of these subsystems and describes the work performed on the bottom box by OSS during Phase II. The work performed by Scott is presented later in Section 5.7.

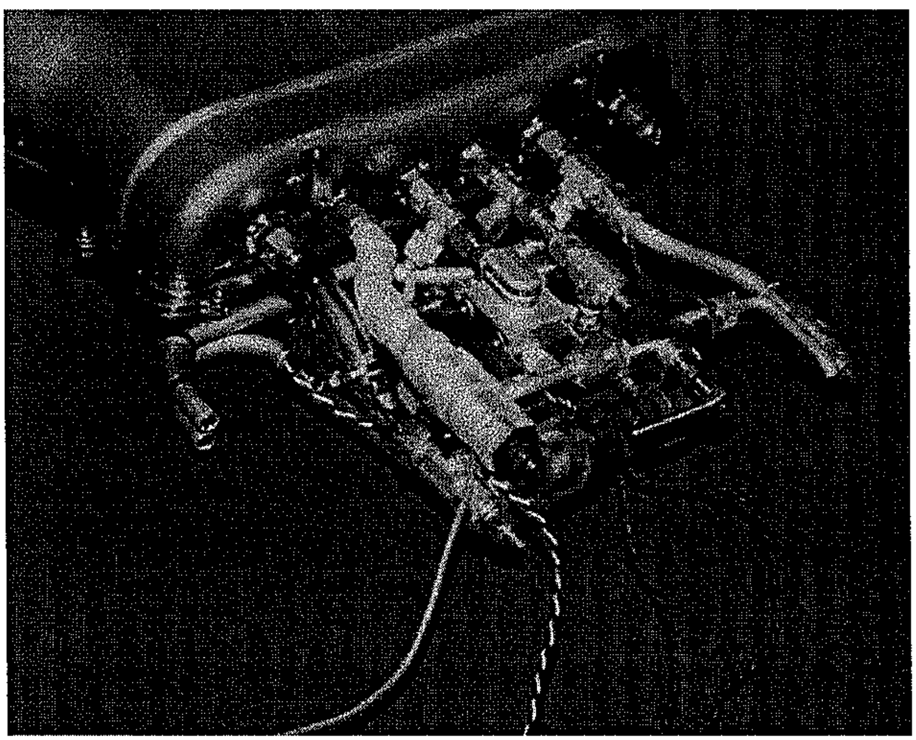


Figure 5.3-1: Prototype Bottom Box Assembly

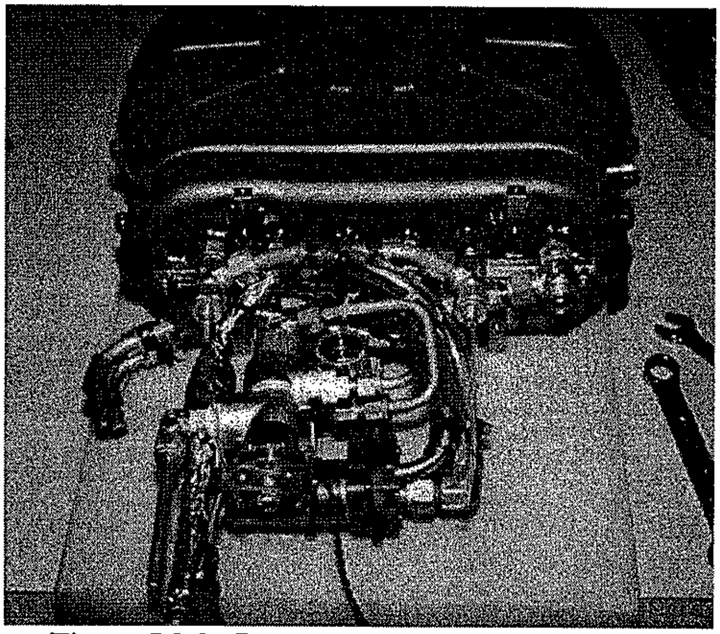


Figure 5.3-2: Prototype Bottom Box Assembly

5.3.1 Ambient Heat Exchanger

The Ambient Heat Exchanger (AHX) is a critical component in the liquid air backpack. It connects to the vaporizer outlet and is responsible for ensuring air delivered to the user is at an acceptable temperature. In the event the vaporizer ceases to function properly, the AHX relies on heat transfer from the environment to vaporize and warm air supplied to the user by the dewar.

The AHX must be capable of vaporizing and warming air flowing at the maximum expected flow rate. The focus of the design effort was therefore to obtain sufficient heat transfer from the heat exchanger while minimizing the its flow resistance, weight, and cost.

At the beginning of Phase II, OSS began testing a variety of AHX concepts ranging from coiled tubing to stamped plates with flow passages. During this time, we located the only supplier of aluminum plate heat exchangers in North America, Al Goods. Al Goods heat exchangers are used in the walls of essentially every household refrigerator and freezer. The heat exchangers are lightweight, thin plates with flow channels formed into them. They provide much better ambient heat transfer than the concepts we had previously tested and can be easily tailored to provide different flow patterns and shapes. The plates can also be bent to conform to a desired shape.

Al Goods heat exchangers are fabricated by silk-screening the desired flow pattern onto an aluminum plate. Another aluminum plate is pressed onto the first one. The two plates are pressure welded to one another except where the screen dye was laid down. The flow passages are then formed by pressurizing the channels, essentially inflating them.

OSS first obtained sample heat exchangers developed by Al Goods for another project and tested them. During the tests, the heat exchangers were connected to a low pressure dewar of liquid nitrogen. The flow of nitrogen through the heat exchanger was controlled by a valve located downstream of the unit. Two temperature sensors and a flow meter were included in the setup to measure inlet and outlet temperatures and nitrogen flow rate. A picture of this setup is provided in Figure 5.3-3.

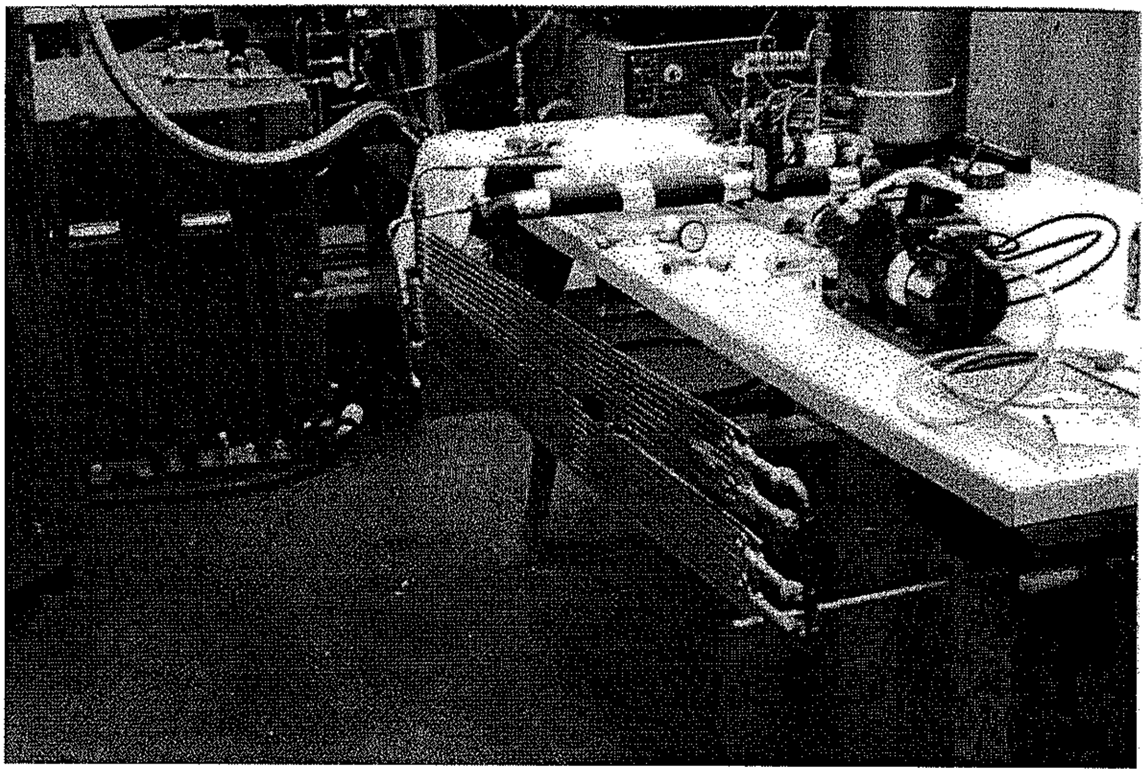


Figure 5.3-3: Testing of Al Goods Heat Exchanger

The plate heat exchangers performed exceptionally well. Unfortunately, frost collected on the heat exchanger when it was tested in a humid environment. Frost is an excellent insulator. Consequently, the portions of the heat exchanger covered by frost did not provide good heat transfer. It is understandable therefore that during testing, the area covered in frost increased and the frost line progressed down the length of the heat exchanger. This phenomenon is shown in Figure 5.3-4 occurring on a plate heat exchanger prototype we had developed prior to locating Al Goods.

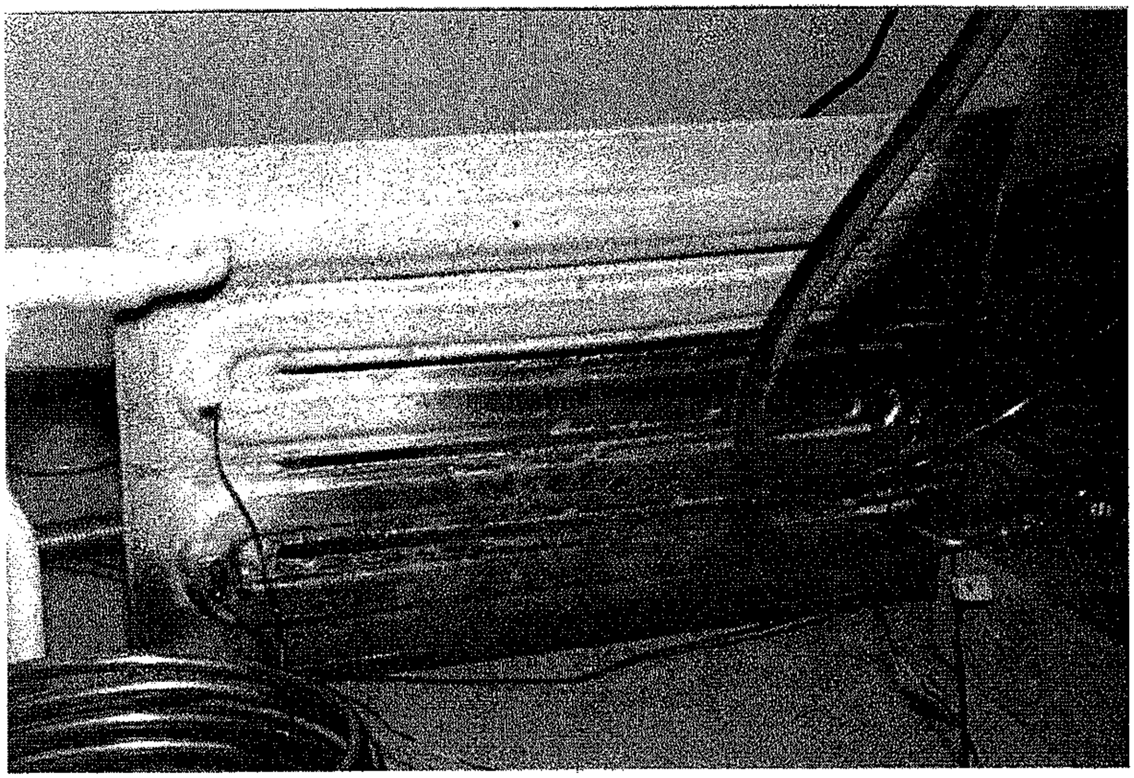


Figure 5.3-4: Frosting of the Ambient Heat Exchanger Prototype

The results for the initial testing of the Al Goods AHX are presented in Figure 5.3-5. For small to moderate flow rates, the heat exchanger reached an equilibrium, no additional frost collected on the heat exchanger, and the outlet gas temperature stabilized at an acceptable value. For large flow rates however, frost would continue to collect on the heat exchanger and eventually the outlet gas temperature would begin to drop. Various options, such as using a fan to blow off the frost and to provide some forced convection, were considered. However, due to safety concerns and potential failure modes, it was decided the AHX would only employ passive elements.

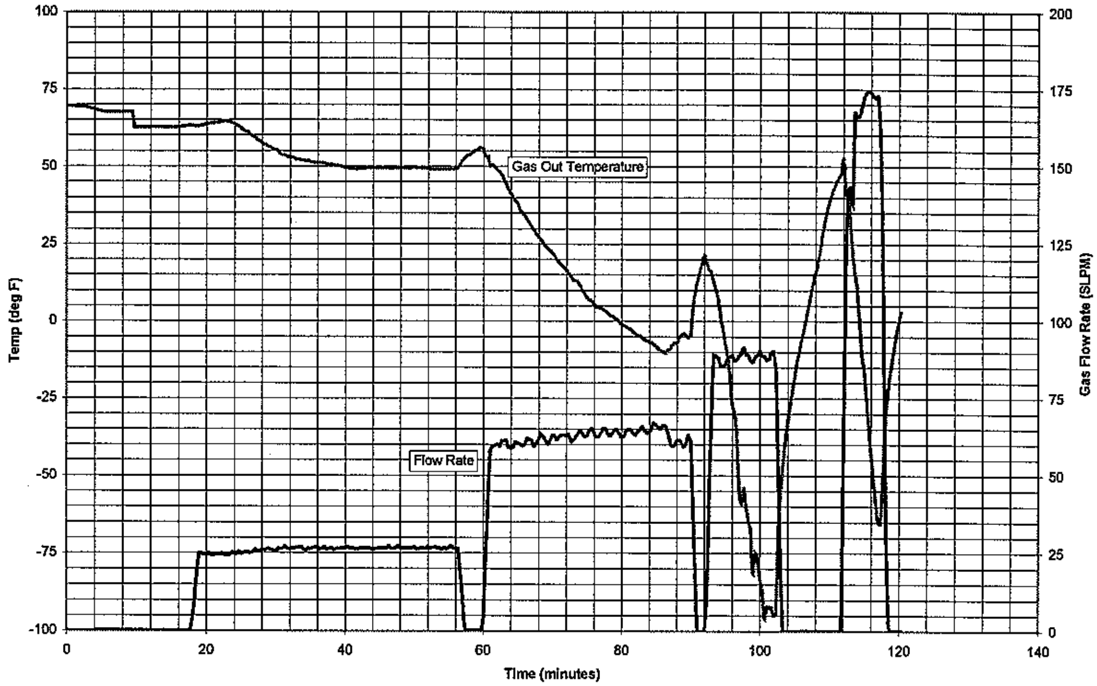


Figure 5.3-5: Plate Heat Exchanger Test Results

Based upon this testing and upon a packaging study to determine the length of heat exchanger that could be placed in the bottom box, OSS ordered a custom heat exchanger from Al Goods that was 76" long and 9.75" high with a series of flow passages running down and then back up the heat exchanger. The heat exchanger was made from 0.020" thick sheets of aluminum 1001. A sketch of the design is presented in Figure 5.3-5.

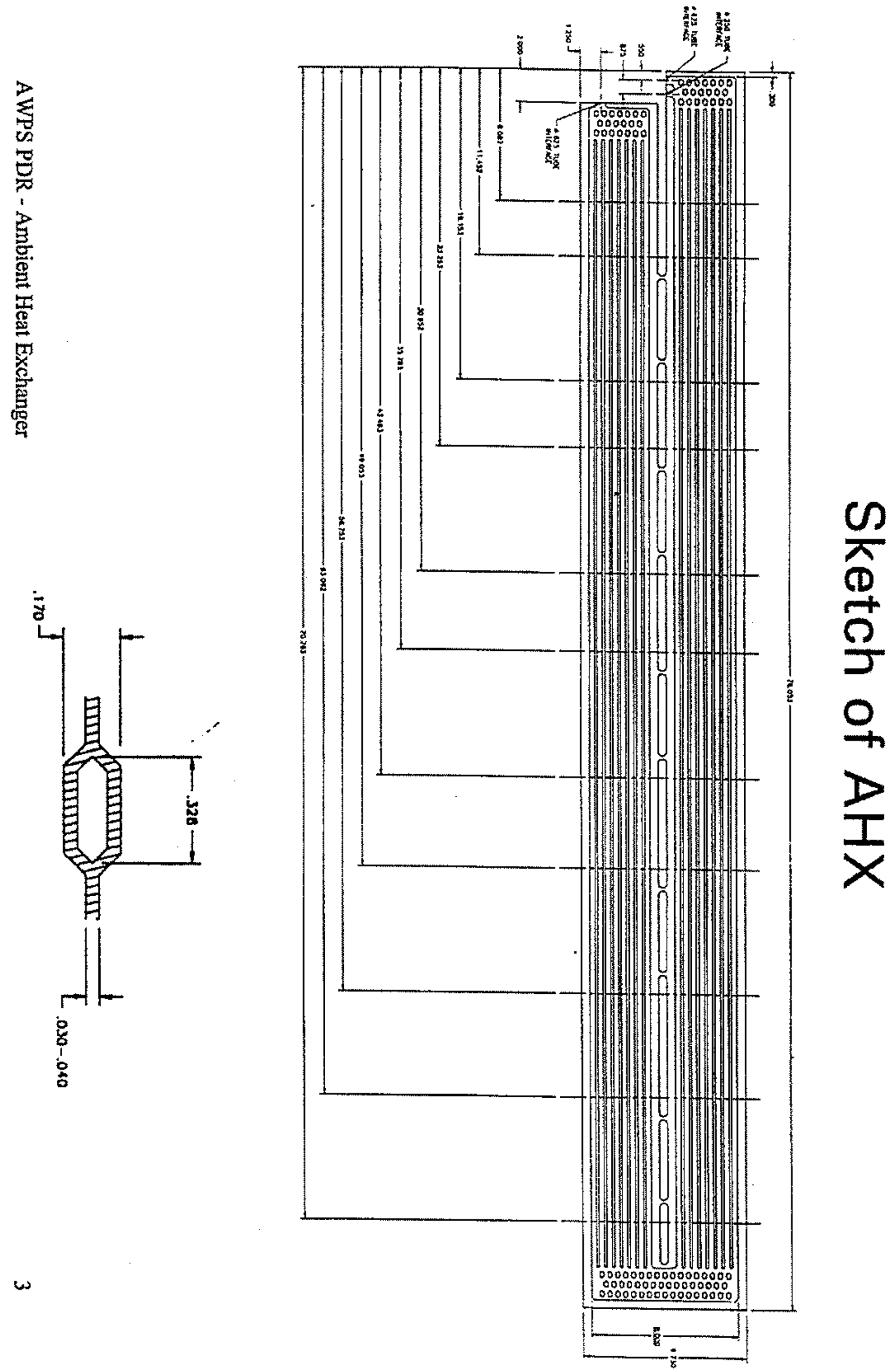


Figure 5.3-6: AHX Design

OSS received the custom heat exchanger and performed preliminary testing on the units. The custom design provided sufficient heat transfer. At the standard NIOSH breathing rate the heat exchanger provided an outlet air temperature close to the ambient air temperature, and less than a quarter of the AHX frosted up.

Following the initial testing, we coiled one heat exchanger into an oval shape. The AHX was designed to fit around the rest of the components in the bottom box, with the exception of the box structure. A fixture was built to help bend the heat exchanger. The AHX wrapped around the fixture approximately three times, with a gap of approximately 1/2" between each layer. This layout provided ample room to package the remaining bottom box components inside the AHX. A sketch and pictures of the coiled heat exchanger are presented in Figures 5.3-7a through 5.3-7c.

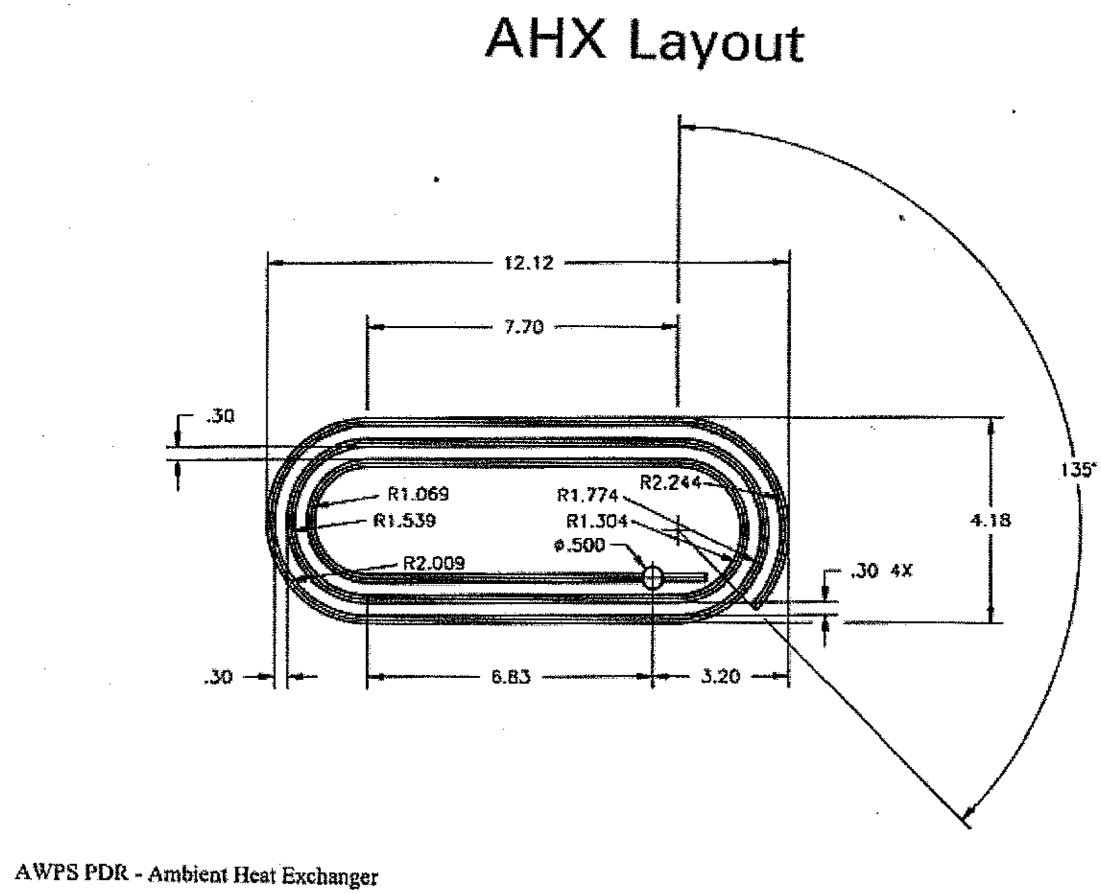


Figure 5.3-7a: Sketch of Coiled Ambient Heat Exchanger

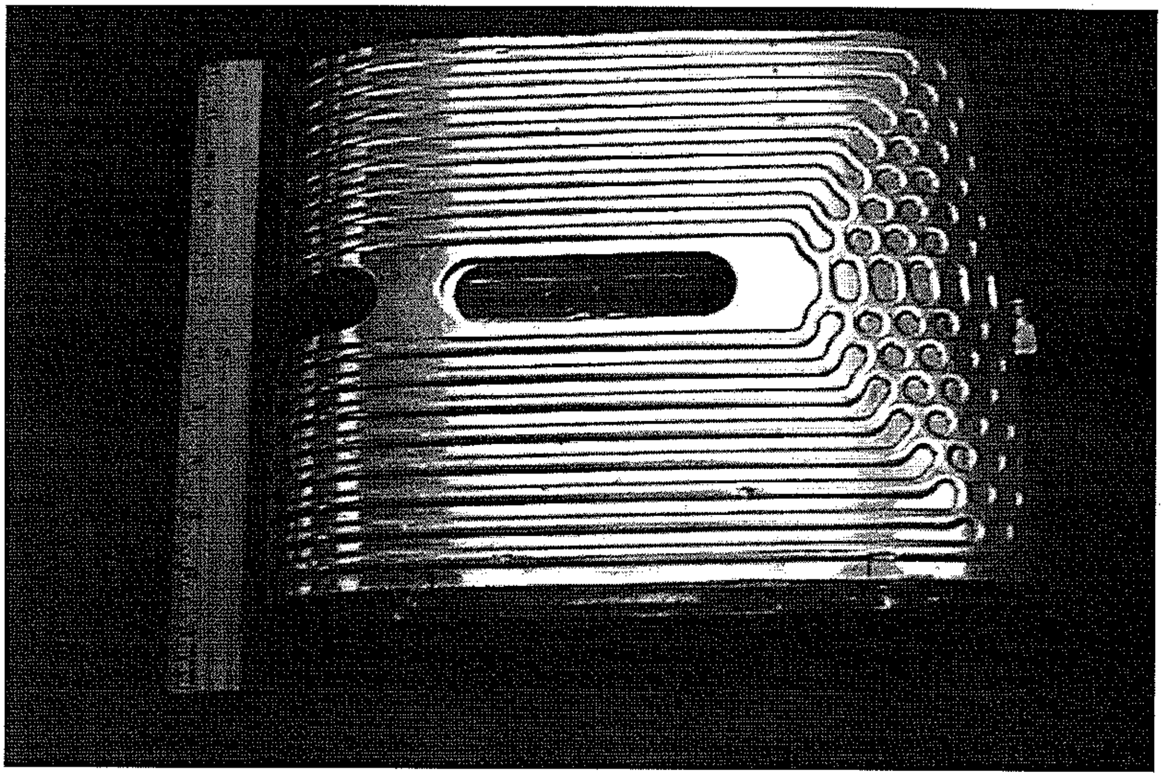


Figure 5.3-7b: Coiled Ambient Heat Exchanger – Side View

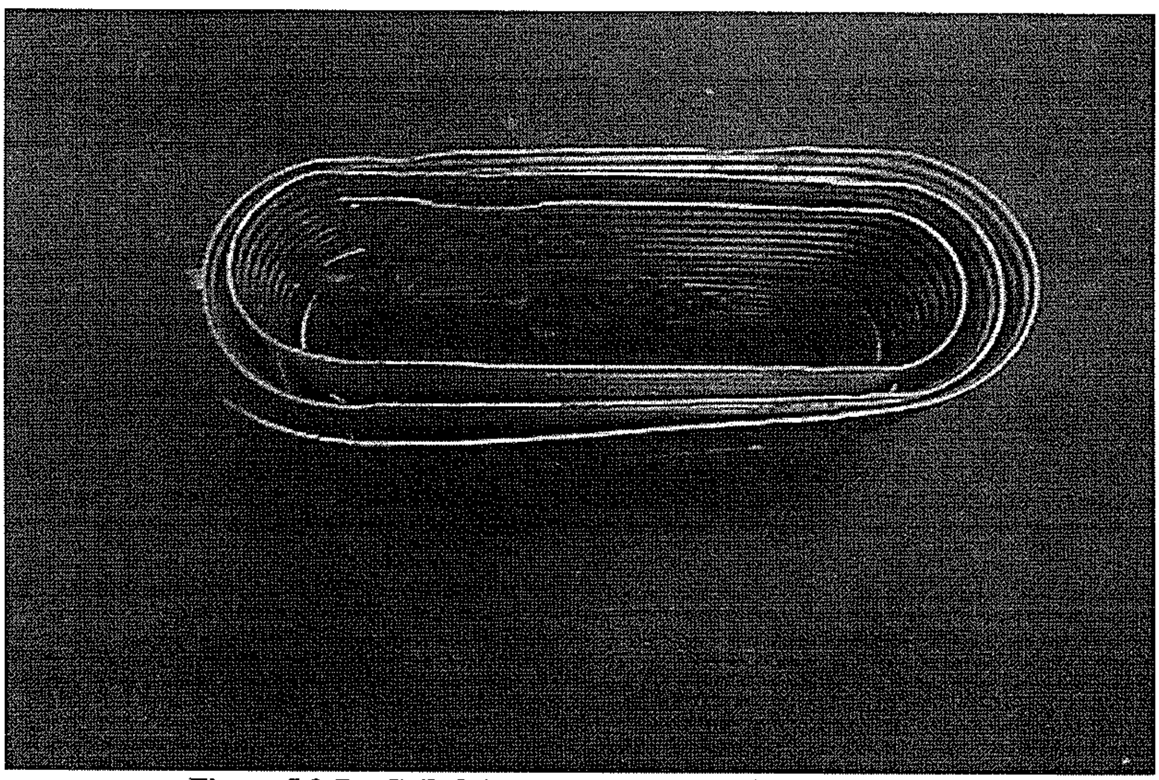


Figure 5.3-7c: Coiled Ambient Heat Exchanger – Top View

Once coiled, the AHX was integrated with the dewar. A perforated external cover, which acted as part of the bottom box structure, was placed around the AHX to protect it. The cover was perforated to allow air to flow into the bottom box and over the AHX. The addition of the dewar and cover reduced the AHX's natural convective heat transfer. However, the units still maintained the outlet air temperature at sufficiently high values, above 40 °F, for the expected breathing rates when the ambient temperature was above 50 °F.

In 1996, we took one of the prototype backpacks to Scott's New York facility to test its performance. As part of the testing, we evaluated the AHX performance in cold (-25 °F) and hot (125 °F) environments. Prior to testing, all water was drained from the vaporizer. During the tests, the backpack was filled with liquid air and placed in an environment chamber that had been set to the desired temperature. The backpack was then connected to a breathing machine located outside of the chamber and the breathing machine run at the standard NIOSH rate until the backpack was empty. Throughout the test, the mask temperature and the AHX inlet and outlet temperatures were recorded.

The backpack was first tested at room temperature, then in a hot environment, and finally in a cold environment. These results are presented n Figure 5.3-8 through 5.3-10. The results indicate that even at temperature extremes the ambient heat exchanger can provide acceptable breathing gas temperatures.

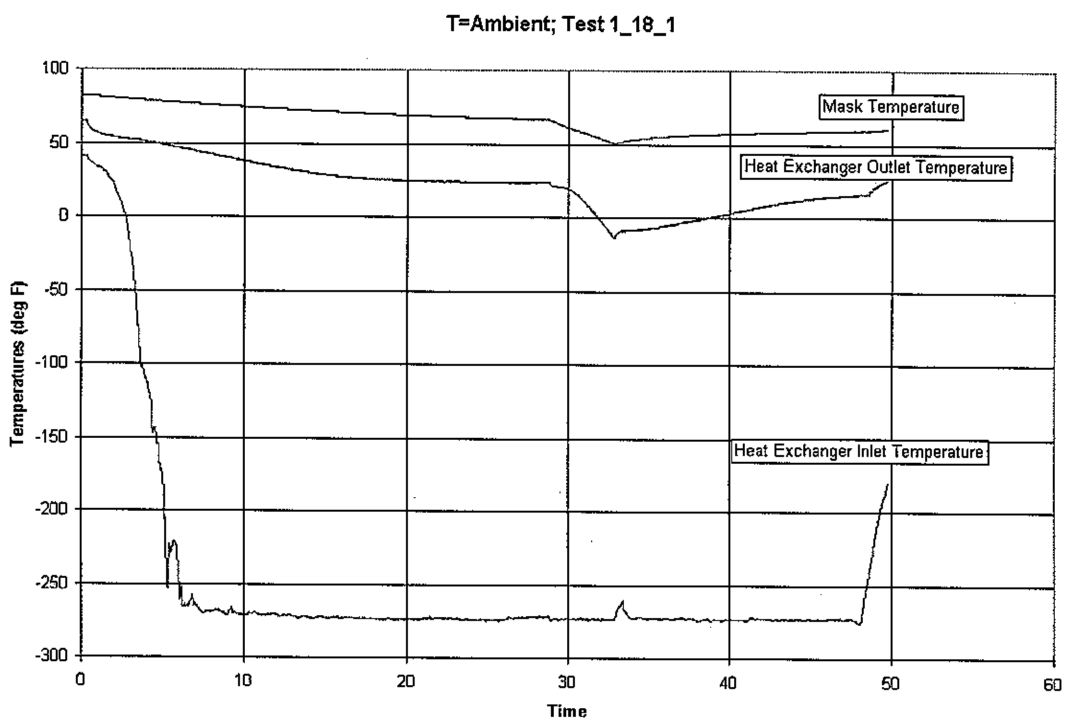


Figure 5.3-8: AHX Test Results at Room Temperature

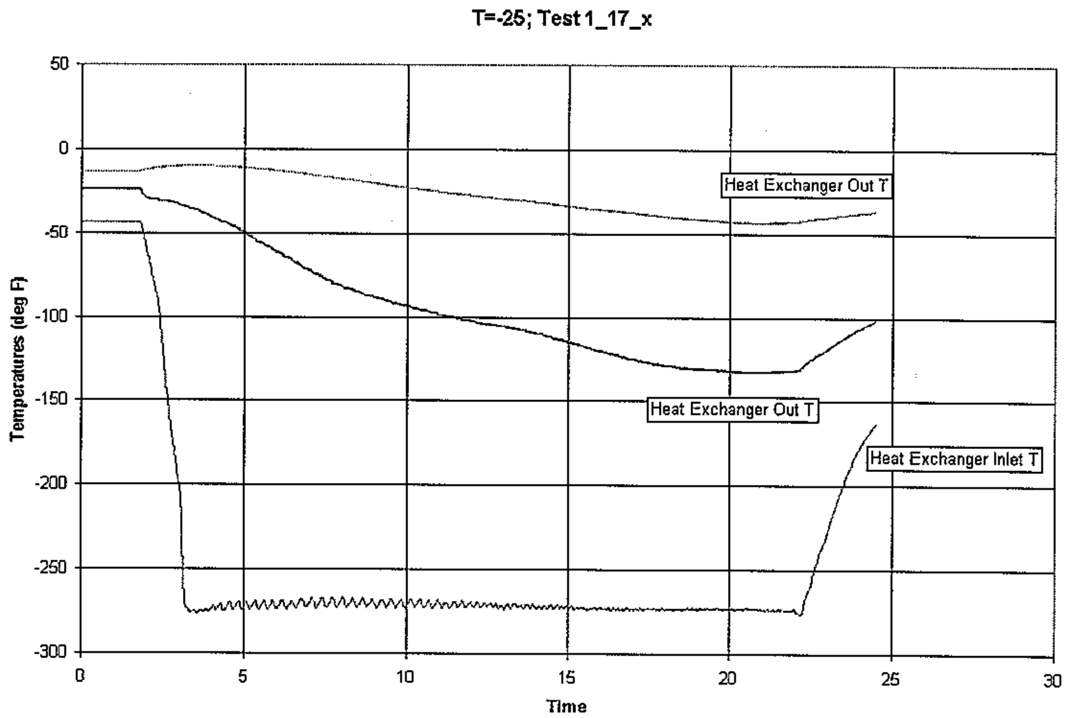


Figure 5.3-9: AHX Test Results at –25 °F Ambient Temperature

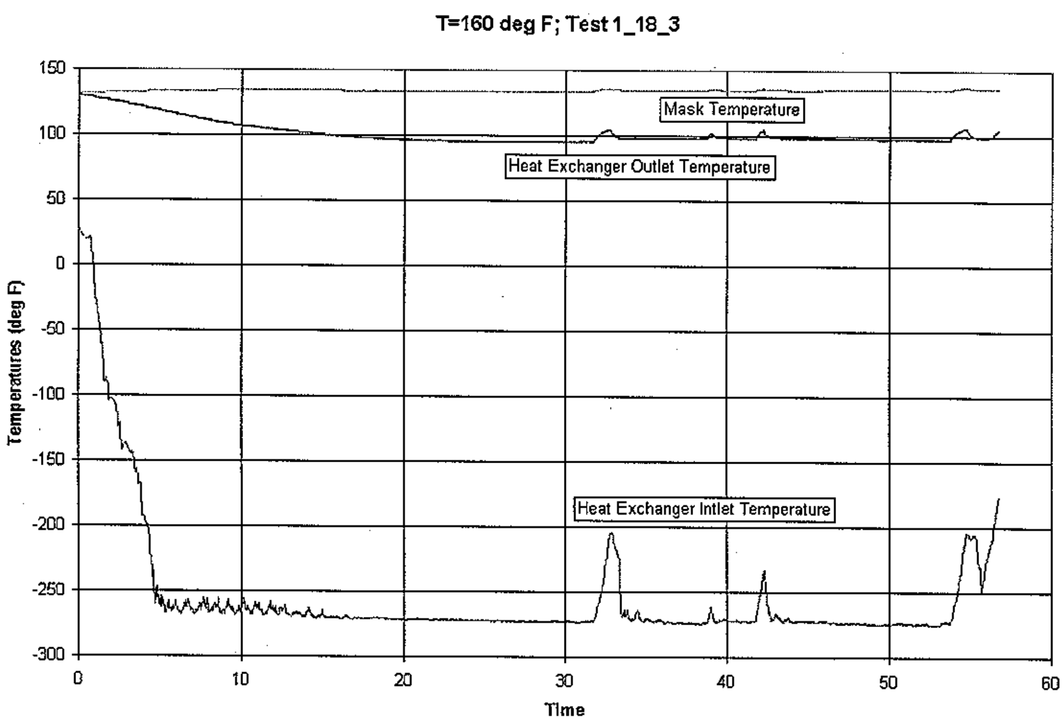


Figure 5.3-10: AHX Test Results at 160 °F Ambient Temperature

This design was handed over to Scott in 1998 when they assumed responsibility for the bottom box design. It was expected that Scott would resolve the primary remaining design issue, that of coating of the AHX to prevent corrosion.

5.3.2 Pressure Control System Components

The pressure control components are responsible for maintaining the inner vessel pressure between 35 and 40 psig during storage and operation. The primary components are a Pressure Closing Valve (PCV), three relief valves (RVs), and three check valves (CVs). These components are shown on the schematic in Figure 5.3-11. The specific layout for much of the pressure control system components and detailed catalog information is presented in Appendix C.

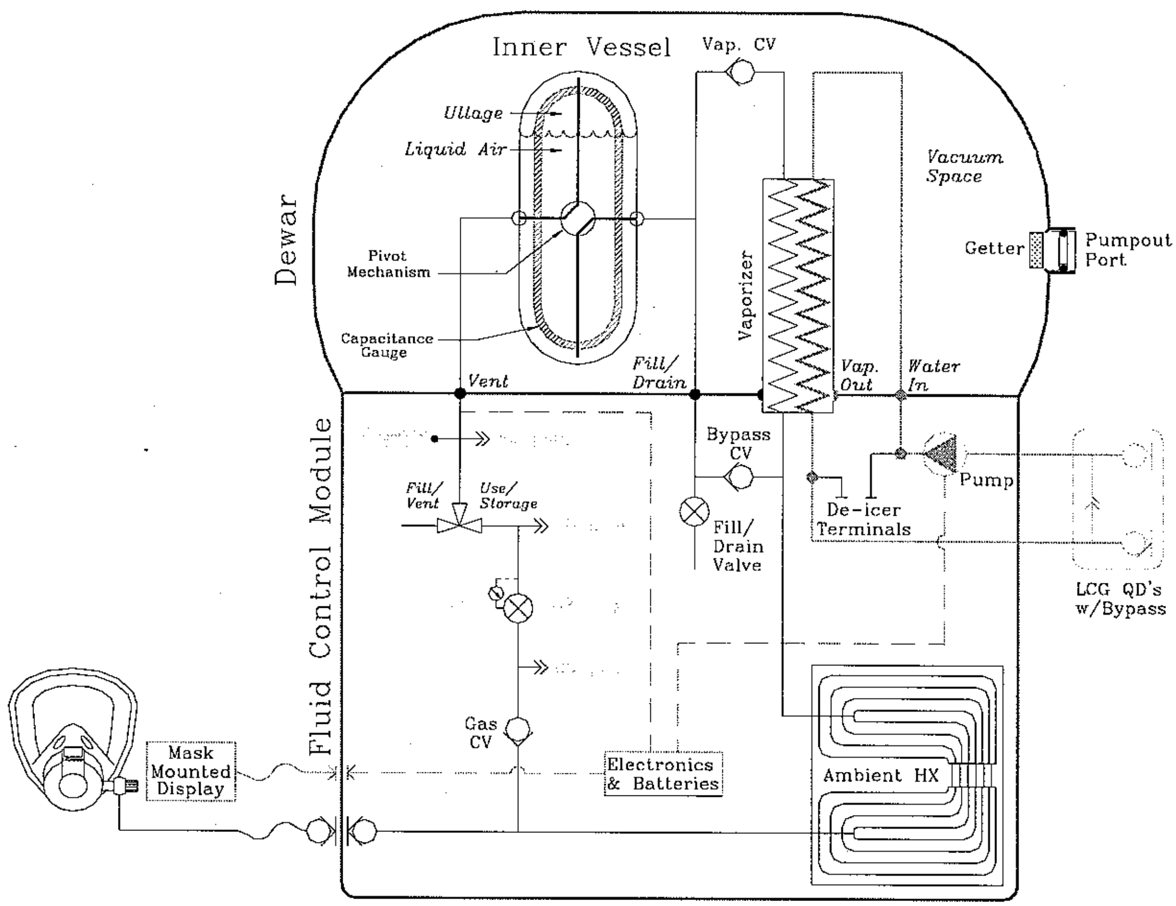


Figure 5.3-11: Phase II Backpack Schematic

The PCV acts a supply regulator for the inner vessel. During operation as the user inhales, a slug of liquid air is pulled through the check valve inside the dewar into the vaporizer where it quickly boils. This creates a slight pressure increase in the vaporizer and AHX. The internal CV prevents this pressurized fluid from flowing back into the inner vessel. We found that without this check valve, the internal dewar pressure would slowly increase with each breath until the pressure reached the relief valve pressure at which point the RV would begin to vent at a rate higher than to be expected.

If the inner vessel pressure drops below the PCV set point, the valve will open and allow the slightly higher pressure air in the vaporizer and AHX to pressurize the inner vessel. A check valve is placed between the AHX and the PCV to prevent gas being drawn from the inner vessel ullage when the PCV is open and the user inhales. This check valve was added during Phase II to improve the performance of the pressure control system. The lack of this valve may have been the cause of the low dewar pressure during the first twenty minutes of use experienced in the KSU evaluations. This phenomenon was not observed in the Phase II system testing.

Both of these CVs use a metal-to-metal seat. When properly cleaned, both of the valves work well. However, if they become dirty both tend to fail open. Once during breadboard, testing the internal check valve failed close. It was suspected that a piece of debris was lodged in the CV housing; following the test, the CV was freed up by repeatedly pressurizing the backside of the valve with gaseous air. When the internal CV failed close, the by-pass check valve was forced open and the backpack was able to provide breathing to the user.

The by-pass check valve was added to the schematic during Phase II for such a failure. During an updated FMEA performed during Phase II, the internal CV was identified as a single point failure that could block the flow of air to the user. As a result, a second tube and the by-pass CV was added to provide a redundant flow path for the breathing air. The cracking pressure of the by-pass CV is slightly higher than the internal CV cracking pressure to ensure that during nominal operations the by-pass valve remains closed.

The internal CV failure previously mentioned was identified by a small drop in dewar pressure, a drop in vaporizer performance, and frosting of the AHX. The failure highlighted the need to properly clean the system during assembly and to filter the liquid air being used to fill the dewar. One option that was considered to prevent this specific failure from occurring again was to install a screen filter directly upstream of the internal CV. This is a standard option offered by LEE, the maker of the internal check valve. However, breadboard testing indicated that the flow resistance across the screen was too great to provide adequate flow to the demand regulator. Addition of the screen caused the mask pressure to drop negative, an unacceptable condition.

The relief valves are present to prevent the dewar from over pressurizing during storage. When the dewar has been filled, the inner vessel pressure will increase as some of the liquid air boils due to heat leak into the system. Once the internal pressure reaches 40 psig the primary relief valve will begin to vent to maintain the dewar pressure. A second 40 psig relief valve is added to the system as a redundant pressure relief mechanism. The third relief valve is set at 80 psig and prevents the pressure in the vaporizer and AHX from exceeding their operating pressure.

The schematic shown in Figure 5.3-11, was developed by testing a variety of breadboard configurations early in Phase II. The schematic is slightly different than the one developed in Phase I. The bypass and PCV check valves were added for reasons previously discussed.

The burst disk used in Phase I was also replaced by a relief valve. This decision was made in order to reduce the number of different components. Furthermore, the burst disk was bulky and its rupture pressure changed considerably with temperature. This change with temperature raised concern that the disk would burst at too low of a pressure when at elevated temperatures or, more importantly, at too high a pressure when at cold temperatures.

The metering valve included in the Phase I system was deleted during Phase II. The valve was removed for several reasons. A failed open metering valve could cause the vaporizer to freeze and could tax the AHX such that the air temperature to the user would drop to unacceptably low values. Furthermore, the metering valve vents air, and therefore reduces the backpack's duration. Based upon these issues and on the fact testing indicated a system without a metering valve still provided an adequate amount of cooling, the metering valve was removed.

Additional efforts components in Phase II focused on identifying reliable components and on packaging the components in a cost effective, compact unit. The components that demonstrated the lowest reliability were the low pressure (40 psig) relief valves. Often these valves would begin to vent cold gas and frost would collect on the valve, preventing it from reseating at the proper pressure. The higher pressure relief valves were not plagued with the same failure. The spring on the higher pressure valve is substantially stronger and is able to consistently reseat the valve even if a small amount of frost has formed.

Three potential vendors for the low pressure relief valves were located, Essex, Circle Seal, and Macro Technology. The designs of the Circle Seal and Macro Technology valves are similar and much more compact than the Essex design. Unfortunately, these valves are also more prone to failure. The seal in these valves is much more exposed to the ambient air than it is in the Essex design. As a result, the seal seats are more likely to collect frost and prevent the valve from resealing. The poppet is the Circle Seal and Macro Technology valves can also be easily damaged if not handled properly.

Essex also produced the PCV we used. Essex is the only vendor found to offer a compact, light weight, pressure closing valve. The PCV proved to be very reliable during component and system testing.

It was expected that Scott would build upon our initial designs and valve selections to develop an optimal pressure control system that was more reliable. It was hoped that the pressure control system weight could be reduced by adding manifolds and potentially housing the valve packing directly in the manifold, thereby eliminating the need for a separate valve body. Unfortunately, Scott was not able to complete this work, see Section 5.7.

5.3.3 Additional Valves

Two manual valves and a check valve are used to fill and drain the dewar. The vent tube exiting the dewar is connected to the common port of a stainless steel 3-way valve produced by Hoke. In one position, the valve connects the vent tube to the ambient environment.

This position is used to fill the vessel. It allows gas in the ullage space to vent from the inner vessel as the vessel is being filled with liquid air through the fill tube. In the other position, the valve connects the vent tube with the pressure control system components. This position is used during storage and operation.

The body of the 3-way valve is machined down to remove extra material and reduce the weight of the valve. The handle of the valve is also removed. The valve has to be actuated using a simple tool developed to interface with the valve stem. This approach not only reduces the valve weight, it also prevents the valve from accidentally being actuated when the backpack is in use. The valve only needs to be actuated immediately prior to and following a fill.

The other valve is a light weight, aluminum toggle valve connected to the fill/drain tube running from the dewar and produced by Macro Technologies. This valve is used to drain the inner vessel. A compact, aluminum check valve produced by Circle Seal is also connected to this tube and is used to fill the inner vessel. The check is connected to the recharge station and allows liquid air to flow into the dewar but not out of it. The end of the check valve is capped after the dewar has been filled. This is done to prevent debris from getting up inside the valve and to prevent liquid air from draining out of the dewar in the event of a leak in the check valve.

A separate fill/drain valve and check valve were used because these components proved to be the most reliable, lightest weight combination to allow the system to be filled and drained. We considered eliminating the check valve and filling through the drain valve. Unfortunately, this valve did not provide sufficient flow and the valve tended to freeze open. This made it difficult to close after a fill. We also considered eliminating the fill/drain valve and use a custom tool to actuate the check valve and allow the liquid air to flow back through the valve. Given the project constraints we opted to use a separate off-the-shelf valve.

The final valve in the system is a plastic ball valve used to shut off from the backpack to the regulator and mask. The regulator has a shut off switch to stop the flow of air when the system is not in use. The plastic on/off valve acts as a back up in case the regulator leaks.

Various valves and configurations were evaluated for these applications. The intent was to utilize off-the-shelf hardware where possible to prove the functionality of the system. As previously mentioned, custom valves and packaging were to be developed by Scott.

5.3.4 Pump

The pump is connected to the water inlet tube via a short Tygon tube. The pump circulates water through the vaporizer and the LCG between a rate between 0.4 and 0.5 gpm. A variety of pumps developed by companies such as Tuthill and Greylor, were considered for this application. However, none met the performance requirements within the given the weight, power and volume constraints. As a result, OSS developed a custom pump for the backpack.

OSS developed a positive displacement pump that uses a custom wound Pittman motor. The pump head uses two off-the-shelf spur gears and is housed in a machined plastic case. The case lid is bolted down and an elastomer gasket is used to seal the interface. A spring-energized seal is used to seal against the motor shaft.

The design is compact with an envelop of 3.5" x 1.2" x 1.3" and weighs only 0.4 pounds. A picture of the pump is provided in Figure 5.3-12. The pump is extremely efficient. It is able to flow between 0.4 and 0.5 gpm against a head pressure of 6 to 8 psi for less than 6 W (1 amp at 6 volts). Various performance curves for this pump were generated during development testing and are presented in Figures 5.3-13 through 5.3-15. In these figure, the current pump design is referred to as Pump 2 – 6V.

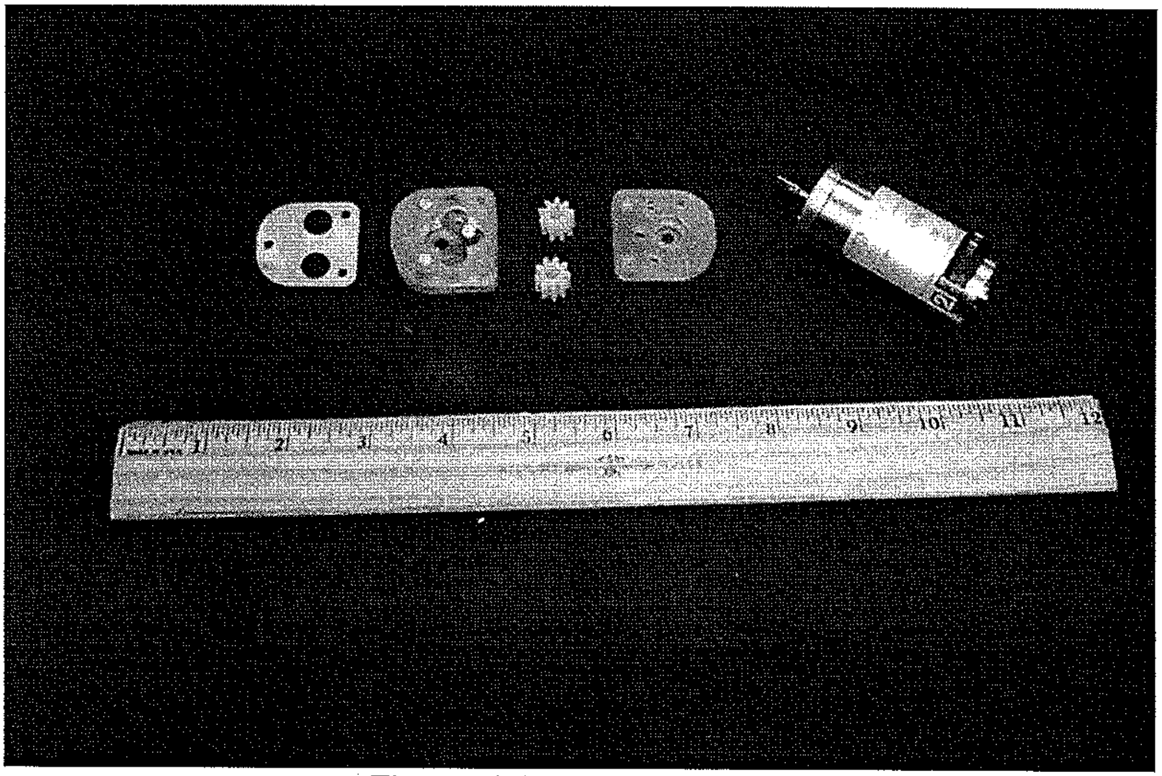


Figure 5.3-12: Backpack Pump

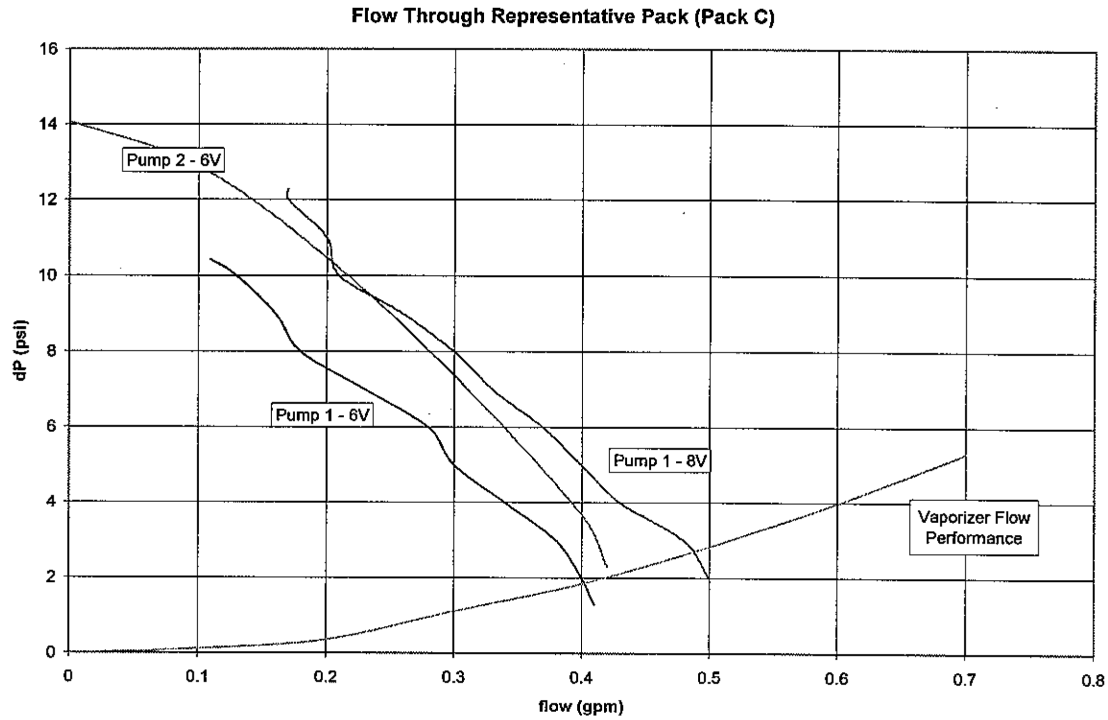


Figure 5.3-13: Pump Performance – Flow vs Head Pressure

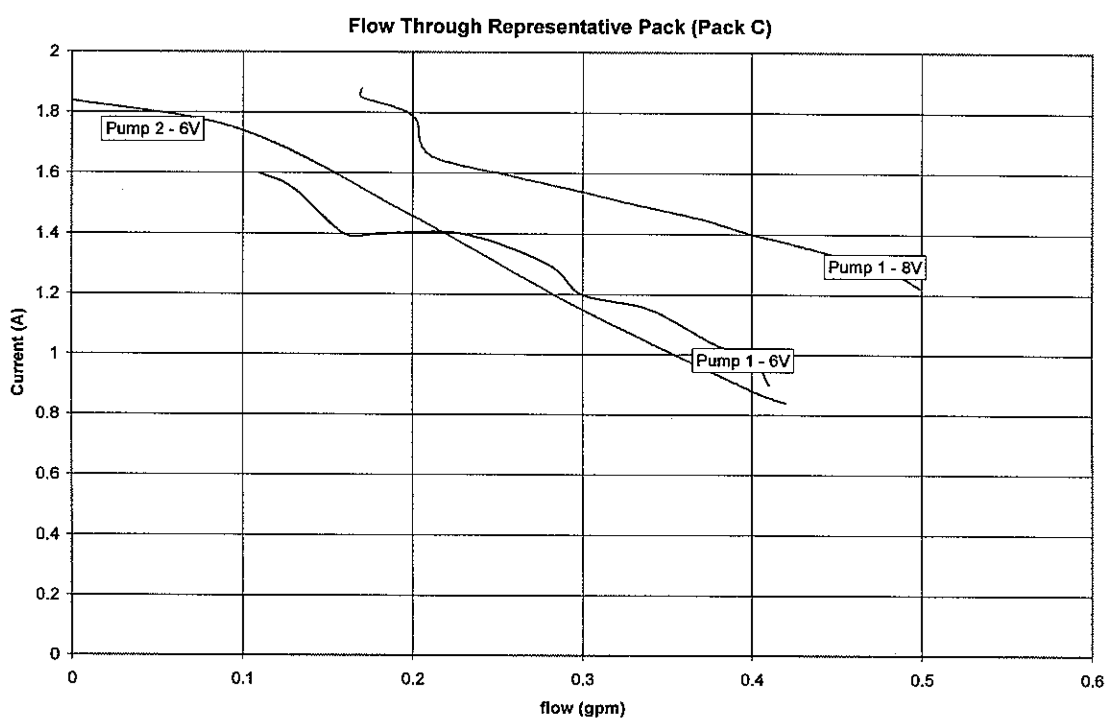


Figure 5.3-14: Pump Performance – Flow vs Current

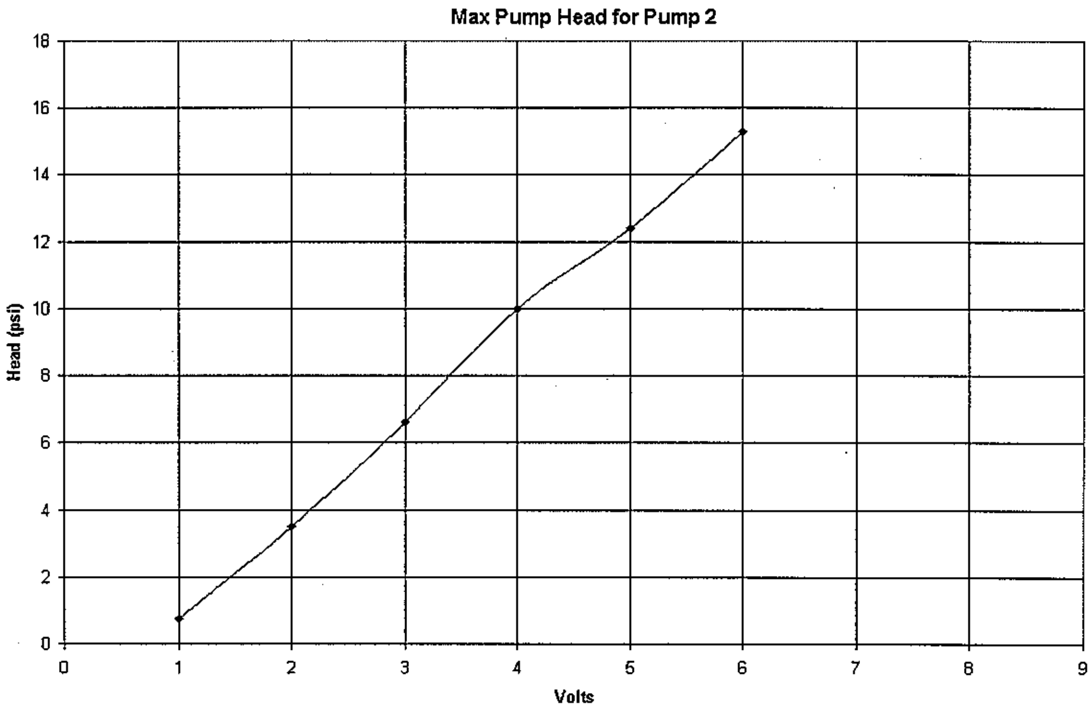


Figure 5.3-15: Pump Performance – Volts vs Head Pressure

The only drawback with this design is that the shaft seal may need to be replaced on a regular basis. However, not enough testing of the pump was completed to clearly resolve this issue before the design was relinquished to Scott.

5.3.5 Electronics and Batteries

A block diagram of the backpack electronics is provided in Figure 5.3-16. The backpack electronics are responsible for:

- Monitoring the capacitance gauge,
- Identify and alerting the user of any failures,
- Driving the gauge display,
- Controlling the audible level alarm,
- Monitoring the battery charge, and
- Monitoring and controlling the LCG pump.

OSS developed an integrated microcontroller based circuit to execute these functions. The circuit is powered by a +12V power supply of battery. The microcontroller allows complete flexibility in the electronic design. Changes to the electronic logic and gauge display operation can easily be changed by modifying the microcontroller software. In our current design, approximately 30% of the programming space and 10% of the RAM on the microcontroller chip have been used. More detailed information on the specific design of the electronics system is presented in Appendix D.

Electronics Block Diagram

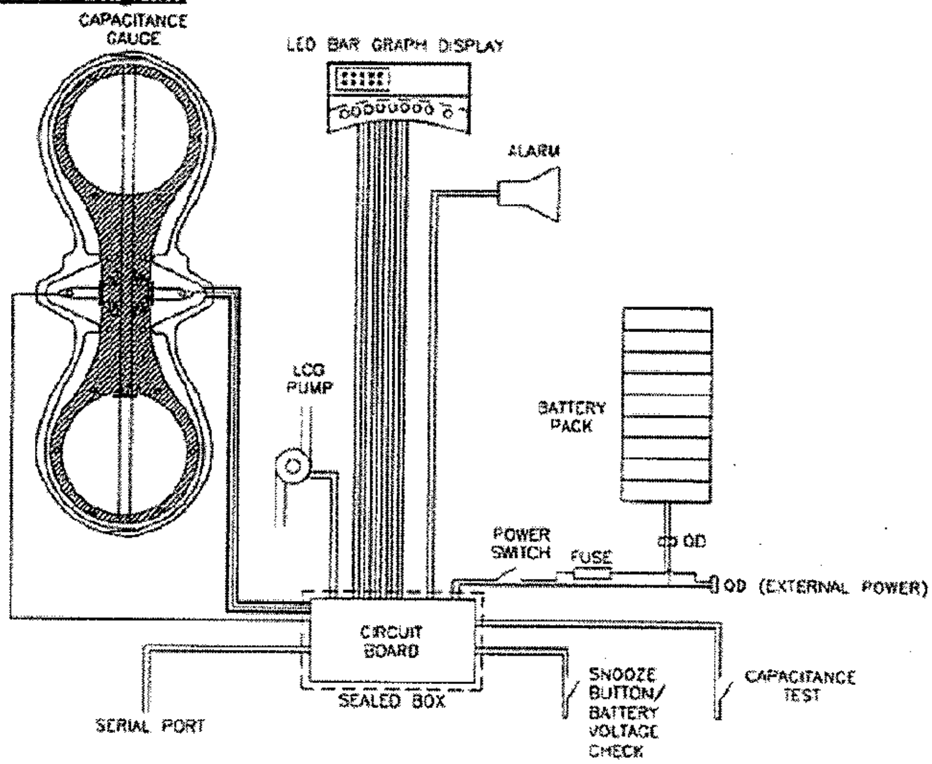


Figure 5.3-16: Electronics Block Diagram

This system has been built and successfully demonstrated in numerous tests. The design and microcontroller software were handed over to Scott when the agreement was signed. Scott focused on ensuring the electronics package was explosion proof.

During operations, the electronics package is powered by a nickel metal hydride (NiMH) battery pack developed by Harding Energy. The battery pack is made up of nine A-cells linked in series.

The battery pack is designed to provide a nominal of approximately 7 W of power at 12 volts for two hours. A voltage regulator in the electronics package provides a steady voltage for the microcontroller, the pump, and the gauge display. The microcontroller monitors the battery performance to ensure the voltage is not drained low enough to damage the battery cells. The microcontroller will first cut off the LCG pump to conserve power once the battery voltage reaches the first set point of 10 V. If the voltage drops below 8 V the battery pack is shut down completely.

Initially, we considered using more proven nice batteries. However, after doing extensive research and reviewing test data provided by the vendor we concluded that a NiMH battery pack could meet our requirements, was safe, had a higher capacity than NiCd batteries, can be quickly charged, and has no memory effect.

5.3.6 Bottom Box Structure

The bottom box components are protected by an exterior cover and interior structure. The cover protects the components from being hit while the both interior structure and cover help to absorb the impact if the backpack is dropped. The cover also provides attachment points for the backpack harness.

The cover consists of a solid aluminum plate 0.06" thick that is rolled along the sides to conform to the one half of the dewar bottom. The plate fits around the back of the backpack between the pack and the user's lower back. It is bolted to two of the brackets welded to the bottom of the dewar. The plate has a series of holes drilled in it through which the harness belt is attached. The front of the cover consists of a perforated aluminum plate, 51% open and 0.06" thick. The front plate is open to allow air to flow into the bottom box and past the ambient heat exchanger in the event of a vaporizer failure.

The front plate is bolted to the remaining two mounting brackets on the bottom of the dewar. Like the back plate, this front plate is rolled along the sides to conform to the bottom of the dewar. The two plates overlap each other along each side of the bottom box and are bolted together at this point. Nut plates are attached to one of the covers to simplify assembly of the structure.

The internal structure that helps support the bottom box consists of an upper bracket, a lower bracket, four tension rods, and eight spacer brackets. A simplified sketch of the structure is provided in Figure 5.3-17. The upper bracket is bolted to the four mounting brackets welded to the bottom of the dewar. Four spacer brackets are then bolted to the upper bracket. Three nylon bumpers are screwed into each spacer bracket. These bumpers fit between the AHX coils and hold the heat exchanger in place. Four tension rods are bolted to the upper bracket. The lower bracket is identical to the upper bracket and is bolted to the bottom of the tension rods. The lower bracket is also equipped with four spacer brackets that help to hold the AHX in place. Pictures of the lower bracket are presented in Figures 5.3-18 and 5.3-19. As shown in the figures, an additional plate is bolted to the lower bracket to hold the electronics On/Off switch and a bulkhead electrical connector that can be used to recharge the battery.

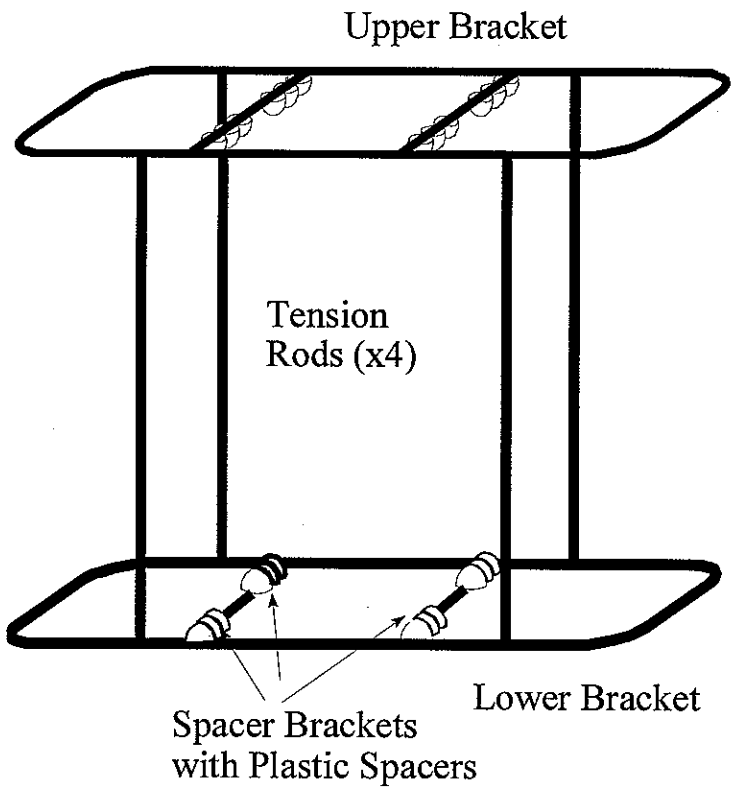


Figure 5.3-17: Simplified Sketch of Bottom Box Structure

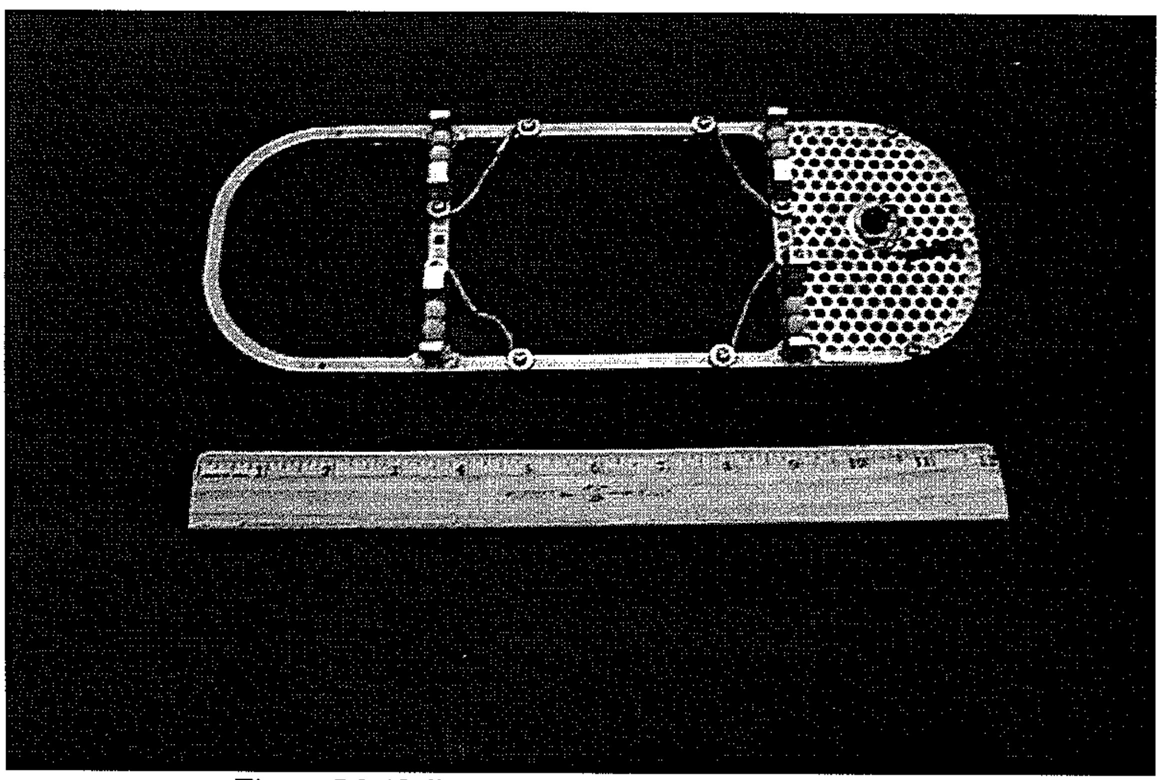


Figure 5.3-18: Bottom Box Structure Lower Bracket

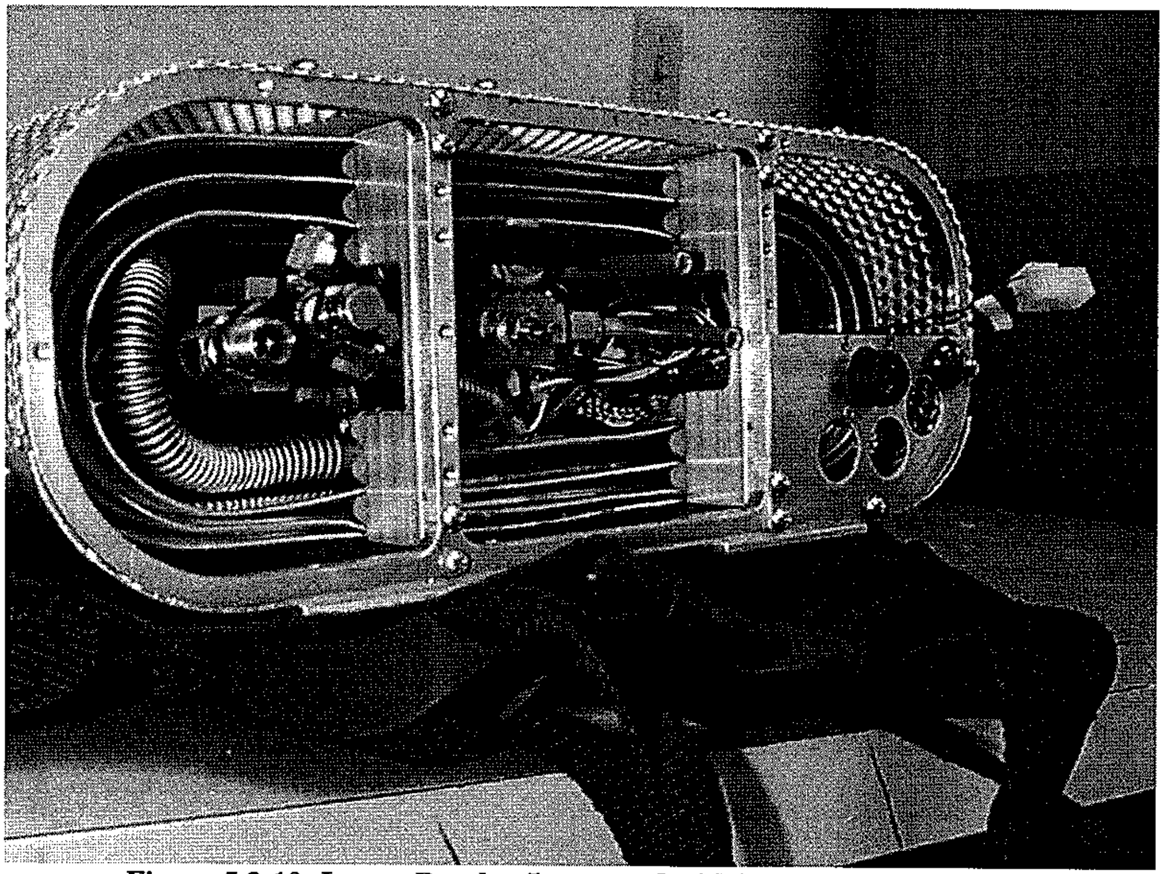


Figure 5.3-19: Lower Bracket Integrated with Bottom Box Structure

During Phase II, a variety of configurations for the bottom box structure, such as honeycomb and composite structures, were considered. The selected approach was considered the optimal solution given the cost, schedule, and weight constraints of the program.

During the testing and demonstrations performed during Phase II, this design worked well. However, we did not expose the backpack to the full range of loads that could be experienced during field operations, in large part, because these loads are not well defined and no such testing in required by NIOSH. As a result, Scott worked to optimize and strengthen the bottom box structure and ensure it could withstand a reasonable amount of anticipated wear and tear.

5.4 Mass Budget

Weight is one of the largest concerns for the two-hour backpack. NIOSH requires standard self contained breathing apparatus to weight less than 35 pounds. However, the SCBA can weigh up to 40 pounds, when full, if the apparatus contributes materially to the user's comfort, e.g. by providing cooling to the user. Since the backpack must contain approximately 14 pounds of liquid air to provide a 2-hour NIOSH duration, the dry backpack weight cannot exceed approximately 26 pounds. The initial backpack built during Phase I exceeded this limit by slightly more than 5 pounds.

As a result, considerable effort was focused on reducing the backpack weight. The titanium outer vessel/LCP inner vessel configuration was chosen because it offered the lightest overall design and the inner vessel redesign was undertaken to increase the inner vessel's rated pressure without increasing its weight.

Figure 5.4-1 charts the actual and design weights tracked throughout the project and Table 5.4-1 shows where some of the largest weight savings have occurred. As indicated in Figure 5.4-1, the current backpacks that have been built, i.e. the actual weights presented in the figure, still exceed the weight requirement by nearly 1 pound. However, the design weight is significantly less than the actual. This difference is due to design changes that have been made but that have not been incorporated into a complete backpack and the new system tested.

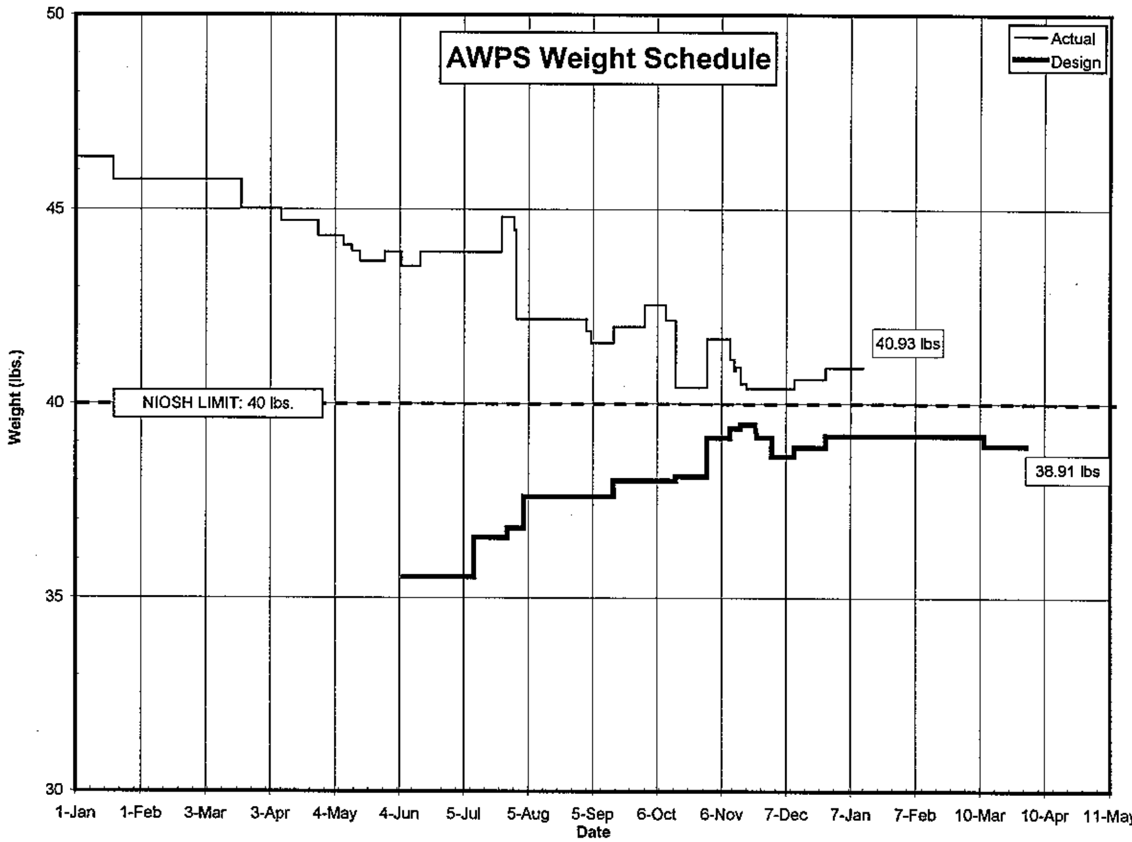


Figure 5.4-1: Mass Tracking Chart

Table 5.4-1: List of Major Mass Savings

Backpack Modifications Implemented	
Backpack Modification	**Weight Savings (lbs)**
Switch to Current Outer and Inner Vessel Designs	1.60
Optimize Harness	0.50
Weight Relieve Bottom Box Valves	0.60
Trim and Reduce Length of Ambient Heat Exchanger	0.80
Reduce Vaporizer Wall Thickness	0.26
Switch from Cone to Spoke Suspension System	0.50
Sum	4.26

A summary of these modifications are presented in Table 5.4-2. Because these changes have not been actually implemented, there are potential errors with the weight estimates. However, based upon our extensive experience with these systems, we feel the potential errors are well within the current 1 pound margin between the weight requirements and the projected design weight and therefore, the backpack will meet the weight requirement. Figure 5.4-2 provides a breakdown for the final backpack design.

Table 5.4-2: Design Changes to Meet 40 Pound Requirement

Proposed Backpack Modifications	
Backpack Modification	**Weight Savings (lbs)**
Shorten Vaporizer	0.27
Build Optimized Motor and Pump Head	0.19
Manifold and Lighten Bottom Box Valves	0.57
Lighten Bottom Box Structure	0.22
Reduce OV Thickness from 0.060" to 0.055"	0.34
Optimize Electronics and Electronic Housing	0.42
Sum	2.01

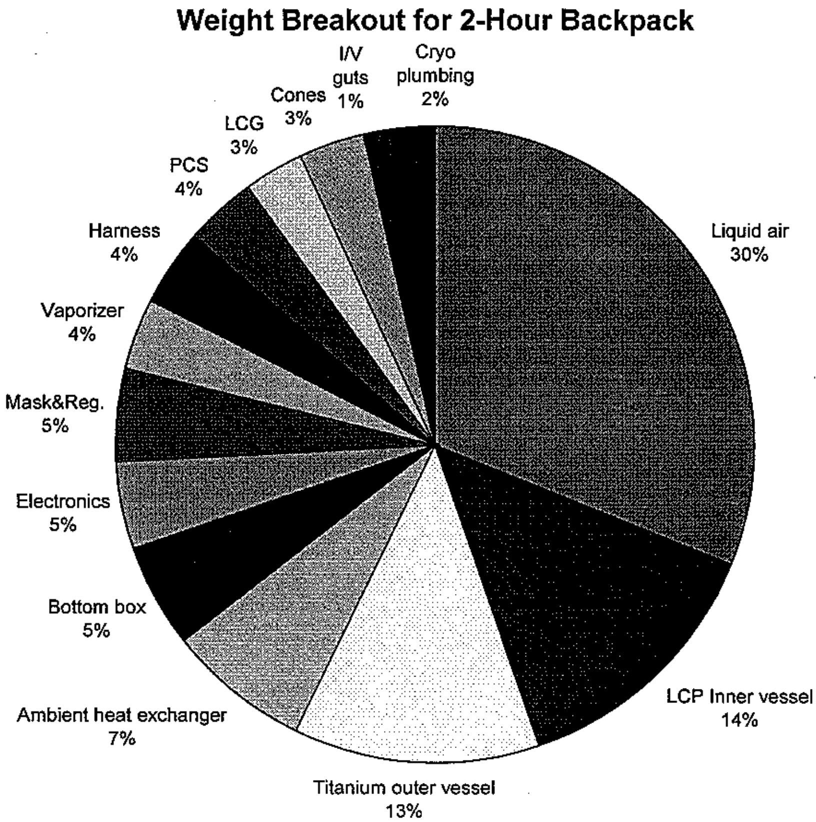


Figure 5.4-2: Weight Breakdown of Proposed Final Design

5.5 Human Testing at OSS

Prior to the second IUOE demonstration in the summer of 1997, OSS performed a series manned tests to evaluate various LCG designs and configurations. These tests were divided into three phases. During the first phase, the performance of four different LCG designs was evaluated. A new optimized LCG design was developed based upon this evaluation and tested during the second phase. During the final phase of testing, the new LCG was tested with the remaining AWPS ensemble. The details of this testing and the specific conclusions reached are presented in Appendix E.

5.6 IUOE Demonstrations

5.6.1 Initial IUOE Evaluation

In late 1995, the AWPS was chosen to be evaluated at the new International Environmental Technology Training Center on the grounds of the U.S. Mining Academy in Beaver, West Virginia. The mission of the IUOE and the Technology Training Center is to evaluate new technology that is planned for use by the Department of Energy.

The general objective of the IUOE Technology Evaluation was to gain user input and field experience to augment the development of the AWPS. Specifically the IUOE wanted to:

- provide user feedback on comfort, operation, encumbrance, and ease of use for input into the final stages of the design of the AWPS,
- surface any design problems with the system's ruggedness and robustness in a realistic environment,
- demonstrate the potential of the system for increasing user work times and decreasing recovery times for tasks which simulate actual decontamination activities, and
- shake down and help evaluate the new IUOE test facilities.

The intent of this IUOE Technology Evaluation Program was to test units that were as close to the future certified units as possible. Two AWPS prototypes, with one hour duration, along with liquid cooling garments, splash suits, and a recharge station were taken to the IUOE's International Environmental Technology Training Center for evaluation in September, 1996.

Using the IUOE's standard protocol for given tasks, the AWPS was integrated into the protocol in place of the standard compressed air SCBA typically used. The IUOEs protocols are similar to those typically used to qualify personnel for specific tasks. In this case, the protocols used field experienced personnel to assess the capabilities of a new technology.

Prior to the evaluation, the IUOE operators were given instruction on filling the AWPS backpacks; the backpacks were filled using the recharge station mated with the IUOE's standard SCBA cascade/fill system. The IUOE operators were also given instructions on donning the LCGs, donning the splash suits, and donning the backpacks. Using the AWPS backpack and splash suit was not much different from using standard SCBAs and protective suits the operators were familiar with. The operators were also familiar with the Scott facemask, which further facilitated their training. However, donning and interfacing with the LCG represented new tasks and required the most instruction.

As soon as the system was donned the users began to understand the benefits of the full body cooling supplied by the system. The operation of the system could be monitored using the mask mounted display system.

The evaluations took place from Wednesday September 18th, through Saturday September 21st. In all, twelve complete tests were conducted using each of the two AWPS packs. The tests covered seven of the IUOE Test Protocols. The protocols used in order were: Vertical Confined Space Entry, Water Pail Carry, Horizontal Confined Space Entry, Worker Decontamination, Wheel Barrel Push, Heavy Equipment Operation, and Heavy Equipment Decontamination. User comments were captured on standard forms and analyzed.

The most valuable result of the evaluation was feedback from the actual users on all aspects of the system. Comments on overall comfort of the garments and the backpack were important to creating a final product that is more acceptable to the end user. How the system operates, and how the user interfaces with the system was also important to the end user. Because the AWPS is a new technology, and has slightly different interfaces than a standard SCBA, any encumbrances found by the user were regarded as important information.

Another important aspect of the evaluation process was to determine if the AWPS was ready for the "real world". The protocols completed during the evaluations were an excellent milestone in the determination of the systems ruggedness and ability to withstand normal field use. This was the area that OSS was most interested in gathering data. The equipment must be capable of handling the rigors of every day use. The equipment did not fail to supply the user air during any of the testing. Other components of the system will be optimized to better suit the environment.

The AWPS was also successful at demonstrating its capability to reduce the onset of heat stress, decrease the recovery times normally required of workers in these situations, and increase the work times of the worker. As stated above, workers were checked for pulse, respiration, blood pressure, and oxygen saturation in the blood, before the test, immediately after the test, and approximately twenty minutes following the test. The test subjects showed little to no signs of heat stress, and pulse rates recovered quickly after doffing the respirator.

The evaluations also sought to determine how well the evaluation process worked both for the IUOE and for OSS. OSS felt that this was an outstanding opportunity to evaluate the AWPS technology in a field environment. When the equipment did experience symptomatic problems, the OSS personnel on site were allowed to diagnose the problems so that the equipment could be properly optimized at a later date. Because of this type of cooperation throughout the evaluation process, we were able to improve the AWPS design.

The backpacks never failed to supply the user air throughout the testing in any environment and in any orientation. During several of the tests the packs electronics turned the pump off when it sensed what it thought was a problem in the system. The reason was a constricted water line in the LCG that was created by the body harness worn for Confined Space Entry work. This was discovered during the first Vertical Confined Space Entry test. The water circulating pump shutdown approximately fifteen minutes into the test protocol. Because the user was still receiving breathing air the protocol was completed, and the user remarked that he remained cool throughout the exercise. The remaining three tests involving Confined Space Entry proved to highlight the same problem with the system.

While performing some of the other tests the pump appeared to be laboring while the worker performed certain tasks that in some way were constricting the flow of water. This information is invaluable for improving the design to make it more rugged for field use. Information on user comfort, and any encumbrance of the system was also gathered during these same tasks. All comments on the backpack itself were complimentary in the way it fit, how it felt, and it's weight.

The AWPS one-hour system extended no further from the user's back than five inches. This allowed the subjects to enter the confined space tube without removing the backpack. Ascending the catwalk on the vertical tower was also made easier by this low profile.

Comments on the LCGs were also complimentary. The water hose interfaces between the backpack and the LCG were said to be annoying, and could be an encumbrance because of the way they were looped out of the splash suit. The splash suits obtained many comments on the fit and feel, the lack of visibility of the hood, and the ambient noise created by the moving of the material.

Other user related information that came from the testing was the ability of the worker to "recover" after a protocol was performed. Pulse rate, breathing rate, blood pressure, and oxygen saturation measurements were taken prior to each test, immediately after each test, and five minutes after each test to determine the worker's recovery rate. After each test the test subject/worker was able to recover and be prepared for another test within twenty minutes. With current systems, this recovery period can last as long as an hour.

The primary application of this technology is to the worker in the Decontamination and Decommissioning of the many DOE sites. The IUOE field testing verified that the AWPS relieves the worker of the symptoms of heat stress and allows the worker to be more efficient and concentrate more on the task at hand. One of the heavy equipment operators at the IUOE technology evaluations while wearing the AWPS on a backhoe actually said "because I was not worried about getting hot and stressed in the suit, I was able to concentrate better on operating the equipment and doing my job".

5.6.2 Second IUOE Evaluation

In the summer of 1997, the DOE requested a second evaluation of the AWPS by the IUOE. The evaluation was conducted at the William C Waggoner Training Center for the Southern Nevada Operating Engineers JATC. This second evaluation allowed the IUOE to provide feedback on the latest AWPS design. Two AWPS prototypes, each with a two hour duration, along with liquid cooling garments, splash suits, and a recharge station were taken to the IUOE's training center in Nevada for evaluation in October, 1997.

The cooling garments used in this evaluation were significantly different than other cooling systems currently available, and were an improvement over the LCG design used in the first evaluation. At the time of the evaluation the LCG design was patent pending. Since then, OSS has been awarded a patent on the concept and design.

The LCG uses a series of heat sealed "patches" placed over the major muscle groups that are interconnected with tubing and integrated into a form fitting garment. The large surface area of the patches allows for maximum heat transfer using warmer water than typically used in ice powered cooling systems. The warmer water minimizes the possibility of vaso-constriction, and reduces the probability of water freezing in the vaporizer. All of these features combine to form a cooling garment that is easily used, easily maintained, and highly efficient. The cooling garment could also be used without the backpack whenever a heat sink is available such as on heavy equipment, or when using supplied air umbilicals.

The evaluations took place from Monday October 6th, through Thursday October 9th. Four test subjects each performed six different activities typical of field operations using the AWPS. The protocols used in order were: Water Pail Carry, Horizontal Confined Space

Entry, Wheel Barrel Push, Worker Decontamination, Heavy Equipment Decontamination, and Heavy Equipment Operation. Vertical confined space entry was not conducted. Control runs using Level D, and Level B suits with a traditional SCBA were planned but not conducted due to time constraints. User comments and physiological measurements were captured on standard forms and analyzed.

This evaluation provided the first successful large scale demonstration of the new 2-hour backpack design, production run LCGs, and a new splash suit that incorporated a caribiner pass-through, a front zipper, and secure glove rings. The system provided positive pressure air to the users at all times and reliably cooled the user. We were able to eliminate all but one of the LCG pinch off points.

As in the previous evaluation, the IUOE operators were given instruction on filling the AWPS backpacks, donning the LCGs, donning the splash suits, and donning the backpacks. IUOE personnel were able to fill the backpacks with minimal training but several comments were made that recharge station design was immature and that the fill process took too long and used too much consumables. These comments were understandable because we had not spent a considerable amount of time on the recharge station.

During the testing, we collected a variety of useful comments and observations, which are summarized below. These comments and observations were used to update the AWPS design. Unfortunately not all of the modifications could be implemented due to budget and schedule constraints.

- Everyone liked the cooling provided by the LCG.
- The glove design was well liked and proved to be a good feature of the new outer suit.
- The backpack was perceived as too complicated.
- The "hood" on outer garment was too restrictive (visibility). This was in part due to the caribiner pass-through. It restricted head motion in a horizontal confined space such that the user couldn't look up/forward.
- The cut of outer garment and garment fabric was too restrictive. The users like current PVC suits with the backpack outside and windbreaker style hoods. Keeping the backpack inside suit is too restrictive of suit type. Our conclusion was that there is not one technical solution for all scenarios.
- Despite training, users still wear the backpack on shoulders not waist. The backpack is intended to be worn like hiking backpack, where the majority of the weight is carried on the hips. Other users commented that the harness make backpack ride too low on back, making it more difficult to maneuver.
- Any backpack worn while on heavy equipment is too thick. Even when operator could manipulate machine, the backpack restricted the user's mobility and visibility, potentially making the operation unsafe.
- The backpack was too big for 24" confined space entry. There is very little that can be done to correct this problem. It maybe that a 1-hour pack or a backpack sized for a 90 minute duration be used for confined spaces. We proved during the first demonstration that the 1-hour pack would fit in the 24" confined space entry.

- Users commented that the recharge process takes too long. One suggestion to reduce the fill time and simplify the process is to add cryogen Quick Disconnect (QD) on backpack fill line.
- The two piece suit makes decontamination much harder, if not impossible.
- The need for a scape air source was raised.
- The booties were annoying and sometimes painful primarily due to poor fits. The general consensus was the users would prefer no booties, and would like to wear regular size boots and simply tape their cuffs to the boots. We also observed that our boot cuffs too low and thus provided a crevice that was hard to decontaminate.
- The comment was made that "air suddenly became uncomfortably warm" after approximately 10 minutes of exertion. Consistent comments were made that air was too warm. We have recorded these comments before when testing a cooling system by itself. However, when the user tests a standard SCBA (one with no cooling) after using the AWPS, they comment that the AWPS provided much more comfortable work conditions.
- The suggestion was made that a ratchet or push & turn feature be added to the regulator's purge valve to eliminate accidental purging of the regulator.

5.7 Scott Aviation Participation in AWPS Development

As of July 5, 1995 Scot Health and Safety Products expressed an interest in manufacturing and marketing OSS' liquid air backpack as a commercial product. They agreed in principle to participate in the development and production of the bottom box, mask and regulator, and the recharge station. They would also obtain NIOSH certification for the system and provide all documentation required by NIOSH, including user manuals. Two of these manuals are among the three originally to be developed and delivered for the AWPS contract. Scott would assume responsibility for completing the design and manufacturing the recharge station. All of this work, including producing six backpacks for use in NIOSH certification in support of the AWPS contract, would be done at no cost to either OSS or the DOE.

Early in Phase II, Scott developed a low pressure regulator that operated with a source pressure of 40 pisg. This was a significant improvement over the Interspiro regulator used in Phase I, which required a source pressure of 60 psig. This new regulator allowed the dewar pressure to be reduced to 40 psig. The regulator interfaced with one of Scott's existing masks.

Scott's early participation in the program also involved evaluation and testing of OSS hardware. They uncovered several limitations in the prototype designs during these tests.

Throughout 1996, OSS prepared for Scott's active involvement with the development of AWPS hardware. OSS held a major technical review for their benefit in June and another coordination meeting in August. At the August meeting, both parties decided that to control the configuration of the system OSS would build two identical backpacks, one to remain at OSS and one to be located at Scott's facility in Buffalo, New York. Any changes made to the design would be implemented in both backpacks. In 1997, OSS built two configuration control units that reflected what was thought to be the final dewar design.

From the initial meeting in 1995, OSS and Scott worked to develop a business between the two companies. Scott worked only at a low level of effort prior to the signing of the agreement on February 10, 1997. After the signing, Scott began work on the bottom box in earnest. Over the next year Scott began to make progress on the design of the bottom box.

However, in 1998 Scott became increasingly concerned about the backpack production costs, its weight, and the slippage in schedule as a result of the design modifications. As a result, the agreement between OSS and Scott was terminated in October of 1998. Several months after the termination of the agreement, OSS sent representatives to Scott to review the progress Scott had made and to collect the OSS hardware that Scott had in its possession. The following paragraphs provide an overview of Scott's work.

Following the signing of the agreement, Scott used the configuration control pack in their possession to test a variety of pressure control configurations and components. It was hoped that the size, weight, and costs of previously assembled prototype systems could all be reduced with custom components and manifolds that could be easily mass produced using Scott's manufacturing facilities. Scott also worked on the design of a custom low pressure relief valve that would be more robust and reliable than the ones tested by OSS. The valve worked well in initial testing.

In parallel, Scott worked on a new pump and an integrated LCG QD/bypass connector. They developed and injection molded pump head based upon the design OSS had originally developed. Scott also had a new custom Pittman motor developed for the pump, and began to look at different motor shaft seals. The new pump design was intended to be more rugged, cost less to mass produce, and be explosion proof; NFPA requirements dictate the pump and batteries must be explosion proof. The leading concept for making the pump and batteries explosion proof entailed encasing them in a sealed injection molded housing.

Using the concept of a ganged quick disconnect that incorporated a bypass valve, Scott developed a light weight, compact LCG QD/bypass connector. The purpose of the by-pass was to allow pump to continue to circulate water through the vaporizer in the event the LCG was either pinched off or disconnected from the backpack, and thus help prevent the vaporizer from freezing. The unit was shown to DOE and IOUE representatives at the second IUOE demonstration and worked well in testing. However, the design needed to be modified to reduce the production costs.

Scott worked on three other primary bottom box components, the ambient heat exchanger, the bottom box structure, and the electronics. After reviewing OSS test data and performing preliminary testing of their own, Scott ordered a slightly different plate heat exchanger from Al Goods. The new heat exchanger was slightly longer and had slightly different interfaces than the design developed by OSS. Scott also tested different coating for the heat exchanger. Since the heat exchanger is made from 3000 series aluminum, it is very susceptible to corrosion. As a result, the heat exchanger needs to be coated to pass the

NIOSH corrosion test and to ensure it will not develop corrosion leaks over time. However, there was a concern that a coating might reduce the heat exchanger's effectiveness. Unfortunately, no conclusive results on coatings were obtained before Scott halted work.

Scott built and tested several bottom box structures. The initial designs were similar to the prototypes developed by OSS. They were much stronger than the ones built by OSS but also much heavier. Scott performed a series of drop tests on the structures. A backpack mockup was attached to each structure and the unit dropped from shoulder height onto a concrete floor. As a result of these tests, stiffening features were added to the structure.

Scott also contacted vendors capable of inexpensively mass producing the structure. Such techniques as stamping and deep drawing were considered. The most cost effective technique identified used formed sheet metal parts that were riveted together to create the bottom box structure. Scott was able to produce a rugged, cost effective structure design. However, the design exceeded the structure's weight budget and needed to be further optimized to reduce the weight without sacrificing strength, if possible.

OSS and Scott both spent time developing the interface specifications between the dewar and the bottom box and developing new electronics for the backpack. Early in 1998, position of tube penetrations in the outer vessel and the bottom box mounting brackets were finalized. This allowed Scott to develop an interface control drawing that clearly specified the mechanical interfaces between the subsystems being developed by each company. OSS also worked on the performance specifications and the verification and validation testing required on the dewar and the complete backpack. Drafts of these documents and procedures were developed and reviewed by both companies.

In addition to the bottom box components, Scott assumed the responsibility for developing a commercial version of the recharge station. Scott developed and tested a prototype recharge station. The station was similar in external appearance to a recharge station developed by OSS for NASA, see Figure 5.5-1. Little details on the Scott's design was obtained when the agreement was terminated.

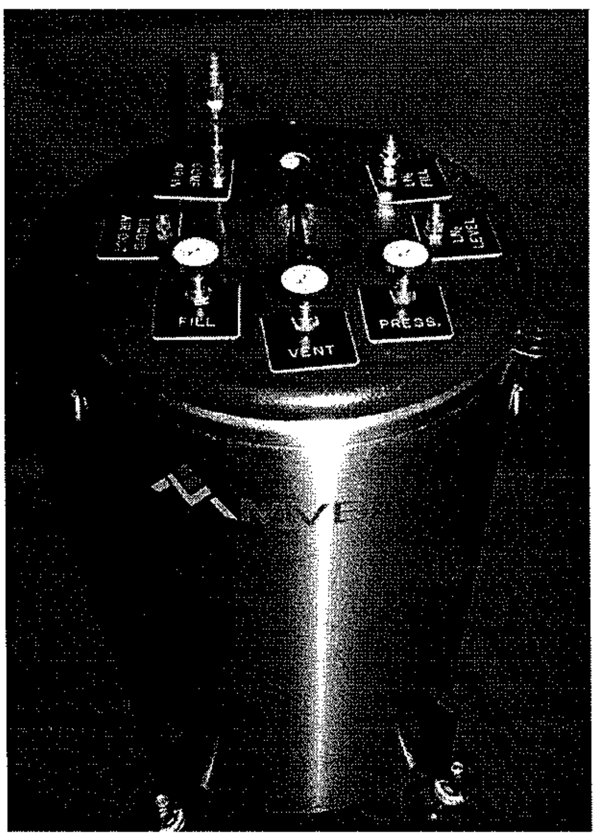


Figure 5.7-1: OSS Recharge Station for NASA

6.0 Conclusions and Outstanding Issues

During this seven year effort, OSS successfully developed and tested a prototype Advanced Worker Protection System that provides breathing air, body cooling, and Level B protection to the user. We clearly demonstrated through repeated testing that a system providing cooling can significantly increase worker productivity by extending the time they can function in a protective garment. Tests demonstrated that subjects using the AWPS can operate up to 2 1/2 times longer than when using a gas-based SCBA that does not provide cooling. This increases end-to-end task efficiency by at least a factor of 5 because not only can the user operate longer when suited, the time to recover from a suited operation is greatly reduced.

Tests also showed that workers could more clearly focus on the task at hand when they received cooling. One of the heavy equipment operators at the first IUOE technology evaluations while wearing an AWPS prototype on a backhoe said "Because I was not worried about getting hot and stressed in the suit, I was able to concentrate better on operating the equipment and doing my job."

Another graphic demonstration of the effectiveness of the cooling provided by the AWPS occurred at a DOE demonstration in Nevada in 1997. During the demonstration two workers performed standard clean up tasks outside in the hot summer sun. One of the workers wore a standard SCBA with a splash suit while the other worker wore a prototype AWPS. After a short period of time, between 15 and 30 minutes, the workers stopped. The worker using the AWPS felt comfortable while the other worker was sweating profusely and had to doff his suit. This user's shirt was soaked with sweat while the other's clothes were dry and cool to the touch. The worker wearing the AWPS remained in the ensemble during the following briefing on the AWPS technology and was finally forced to exit the suit only when his breathing supply was exhausted.

During additional testing, we were also able to demonstrate the AWPS' ability to function in real world conditions. During testing, users performed a wide variety of cleanup tasks such as manually shoveling dirt, crawling inside pipes, climbing tank ladders, and operating heavy equipment. The AWPS worked effectively to provide both breathing air and cooling. During these tests, we discovered that the 2 hour duration backpack is too large to allow entry through a 24" diameter opening. Note: the 1-hour duration backpack was tested in a similar test and is thin enough to allow entry in this small of an opening.

We also learned during testing that any backpack worn while operating heavy equipment interferes with the user's movement and thus limits their field of view. One option for workers who will be operating heavy equipment is to remove the backpack when they mount the equipment and then stow it nearby. This approach would allow the user to receive breathing gas and cooling from the backpack and still maintain their mobility. Slightly longer umbilicals could be added to the pack if needed.

During the project, work focused on the development of garments and the liquid air backpack. While OSS made great strides in both of these areas, the garment designs are much more mature than the design of the backpack. In fact we are near to the point of being able to offer outer garments and liquid cooling garments as catalog items that offer considerable benefits over current protective equipment. The benefits of these two garments are listed below:

LCG Benefits:

- Full body cooling with greater heat transfer surface area than available tube based suits.
- Uses cool, not cold, water to provide cooling thereby reducing the chance of vasoconstriction.
- Patches concentrate cooling upon major muscle groups.
- Low cost due to the use of heat sealed, plastic flow patches that minimizes the labor hours required to assemble the garment.
- Machine washable.

Outer Protective Garment (Level B Suit) Benefits:

- Self donning and doffing.
- Easily replaceable gloves. This allows the gloves to be replaced when they wear out rather than throwing the suit away, thereby extending the suit life and reducing secondary waste associated with site clean up.
- Form fitting with backpack and harness internal to the suit. This helps with suit decontamination because there are few areas where waste can be trapped.

Human testing at OSS and IUOE evaluations provided critical feedback that was used to guide the garment designs. Based upon this data, we were able to significantly improve upon the initial designs. For example, various pinch points that could block the flow of water in the initial LCG design were identified during the IUOE evaluations and the design was modified to eliminate them.

The liquid air backpack proved much more difficult to develop than the garments. The biggest technical challenges for the backpack proved to be weight and reliability. NIOSH requires the backpack to weigh no more than 40 pounds when full. The backpack must carry approximately 14 pounds of liquid air to provide the desired 2 hour NIOSH duration. As a result, the empty backpack has to weigh less than 26 pounds.

To meet this weight requirement, we developed a light weight pressure vessel injection molded out of Liquid Crystal Polymer (LCP). One of the biggest accomplishments of the project was to obtain, after extensive testing, a DOT exemption for this plastic cryogenic pressure vessel.

During the development of the backpack we built and tested seven different prototypes. The backpack design evolved throughout this process and we discovered that the pack reliability and robustness was a much larger issue that initially thought. As the design matured, we began to test the units more extensively. The units generally performed well initially. However, after repeated testing the pack performance began to degrade. Components began to wear and cause subsystems to fail. The primary problems were centered around the pickup mechanism inside the LCP vessel. The mechanism tended to become sticky and not rotate freely, and the capacitance gauge signal would drift and eventually drop out. We performed extensive life cycle testing of the following components to determine the sources of these problems:

- Bellows in the pickup mechanism liquid and gas inlet tubes
- Capacitance gauge dynamic electrical connection
- Pickup mechanism pivot seals and bearings
- Pickup mechanism and kicker weight

Based upon these tests we upgraded component designs and performed limited subsystem testing of the new designs. During this time, several other technical issues were identified. Due to limited funding these technical issues were not completely resolved. A discussion of all of the outstanding AWPS issues is presented in Table 6-1. A suggested plan to resolve each item is also presented in the table.

Table 6-1: Outstanding Issues and Suggested Resolutions

Issue	Suggested Resolution
Incomplete System Testing – We have completed upgrading the design of the pickup mechanism and have extensively tested the subcomponents. However, we have not incorporated the new design into a backpack and thoroughly tested it. This must be done before the design can be considered complete. The two primary characteristics that must be tested include liquid withdrawal and capacitance gauge accuracy in all orientations.	Build up several second generation liquid air backpacks that incorporate all of the new design features and thoroughly test it first in the lab and then in the field.
Vaporizer Performance - During manned testing, the vaporizer froze several times. We have shortened the vaporizer in the latest design to help prevent freezing and to reduce the weight of the backpack. However, this new design must still be integrated in a pack and thoroughly human tested.	Implement new shorter vaporizer in second generation backpacks and thoroughly test vaporizer performance.
Outer Vessel Pump Out Plug - The pump out plug on the outer vessel prevents the vessel from over pressurizing in the event the inner vessel develops a leak into the vacuum space. The plug also provides a means to evacuate the annulus space between the inner and outer vessels. During testing of our prototype backpacks we discovered this plug would become set in the plug housing; the pressure required to force the plug out increased over time and eventually exceeded the safe allowable pressure inside the outer vessel. We have developed a concept to resolve this issue but we have not thoroughly tested the concept.	Build several test articles and thoroughly test them prior to integrating the design into the backpack. Should include testing at various hot and cold environmental conditions.

Vacuum Performance – The integrity of the backpack's vacuum insulation is critical to providing storage life of the liquid air. We have currently identified a 1 to 3 hour storage life for the AWPS backpack.	Review operational scenarios to ensure that a 1 to 3 hour storage life is indeed needed and acceptable then implement the getters and molecular sieves outlined in Section 5.2.7 in the second generation dewars. Perform periodic vacuum and residual gas measurements.
Backpack Ruggedness – NIOSH levies very few requirements on the ruggedness of the backpack. However, current SCBAs can withstand the harsh treatment (being dropped on the floor, rolling down stairs, etc) expected in the field and still function properly.	Perform additional field testing to try to quantify worst case loads. Test current prototypes to destruction to quantify the results of various loads (i.e. drop a full backpack on concrete and observes what happens).
Weight – The latest weight budget indicates that the pack is still slightly over the 40 pound limit required by NIOSH.	Implement the suggestions highlighted in Section 5.4.
Outer Vessel Buckling on the External Pressure Test - The outer vessel does not pass the DOT external pressure test. Small areas in the outer vessel buckle inward 1/16" during the test. This is no indication of a failure in the inner vessel or in the suspension system. If the vacuum space is repressurized, the outer vessel returns to its original shape.	Investigate the use of a waiver for this requirement. Due to the low pressure nature of this pressure system, the outer vessel is not capable of the same pressure loads as a high pressure bottle. Obtaining a waiver on this requirement would in no way compromise the safety of the system.
Bottom Box Design – The bottom box design is not complete. We developed and tested several prototype designs before turning this responsibility over to Scott. Scott developed and tested several concepts for the bottom box structure and custom manifolds but the design was not completed. The difficulty in completing the bottom box design is the competing set of requirements. The bottom box must meet the specified weight budget but must also be rugged and inexpensive to manufacture.	Locate a new company specializing in this type of packaging and valve design. Work with them to develop appropriate solutions to these problems.
Pump Seal Reliability – After extensive testing, several of the pump shaft seals have begun to leak. We must perform testing to quantify their life and either develop a simple method for replacing the seal and/or extending the seal life.	Test multiple units to quantify pump seal life and either develop a simple method for replacing the seal, extend the seal life, or add a redundant seal to the design.
Explosion Proof Electronics – The electronics in the bottom box must be explosion proof to meet requirements. These components include the pump, the battery pack, and the capacitance gauge electronics module. Scott began to resolve this issue but not complete the work.	Locate a new company specializing in this area to assist with certification of this aspect of the design.

Despite these outstanding technical issues, we developed improved outer protective and liquid cooling garments and proved the usefulness of the AWPS. Should the suggestions made in Table 6-1 be implemented, we feel that the resulting backpack design could be

NIOSH certified. For NIOSH certification, the updated design must be completely documented, quality controlled units musts be built and tested, a data package must be compiled, and a minimum of four backpacks must be submitted, along with the data package, to NIOSH. This process is lengthy and costly. Costs could be minimized by working with a company familiar with the NIOSH certification process. During the course of the AWPS project, we have become familiar with the process but have never submitted a product to NIOSH. NIOSH has also never reviewed a product like the AWPS. They are not familiar with the procedures and practices associated with handling cryogens. As a result, the certification process may be more lengthy and complicated than usual.

7.0 Recommendations

OSS has compiled a list of recommendations that build upon the work accomplished on the AWPS project. We feel the DOE should reassess the current needs for Personal Protective Equipment (PPE) and develop an agency-wide approach to breathing/cooling systems with the realization that a single system may not be suitable for every application.

As part of this effort, the cost model developed during Phase I should be updated to determine the life cycle cost savings that the AWPS can provide given the current PPE needs. The cost model should also be augmented to include other potential cooling and breathing systems, such as an ice-based cooling system combined with a standard SCBA, and other unique applications. The use of semi-portable breathing/cooling systems, such as a briefcase version of the backpack or a cart based compressed gas system combined with thermoelectric cooling, should also be considered; such a system could be particularly useful when operating heavy equipment. This analysis will help the DOE focus their funding on the technologies that will provide the largest payoffs and will indicate whether additional funding for the AWPS is warranted.

The DOE should also review the technologies developed on this project and determine where else they may be applied to solve other DOE problems. The specific technologies that may prove useful to the DOE are listed in Table 7-1. We hope that some of this seven year effort will be carried forward to provide benefits to the DOE.

Table 7-1: Useful AWPS Technologies

Technology	Key Features
Advanced Liquid Cooling Garments	• Provides full body cooling • Low cost • Machine washable • Uses cool, not cold, water to provide effective cooling
Advanced Outer Protective Garments	• Provides Level B protection • Self donning and doffing • Reusable • Easily replaceable gloves • Provides caribiner pass through • Good visibility • Form fitting and integrated with breathing/ccoling backpack
Plastic Pressure Vessels	• Light weight • Can be molded to unique shapes • Good chemical compatibility • Extremely low permeability (compared to other plastics)
Freeze Protected Heat Exchangers	• Will not be damaged in the event a fluid in the heat exchanger freezes • Provides a means of melting the fluid if a freeze up does occur • Efficient heat transfer
Multi-Orientation Liquid Storage/Supply and Gauging Systems	• Can supply liquid regardless of tank orientation • Can vent gas regardless of tank orientation • Can gauge contents regardless of tank orientation
Compact Pump	• Efficient • Compact • Light weight • Self priming • Low cost
Super Plastically Formed Titanium Vessels/ Structures	• Allows complex shapes to be formed out of sheet titanium • New components can be quickly produced • Process is relatively inexpensive
Liquid Air Recharge Station	• Provides easy, cost effective way to produce liquid air using readily available consumables (liquid nitrogen and compressed air)

8.0 List of Acronyms

AAPD	Advanced All Position Dewar
AHX	Ambient Heat Exchanger
ASTM	American Society of Test and Measurement
AWPS	Advanced Worker Protection System
CIL	Critical Items List
CV	Check Valve
D&D	Decommission and Decontamination
DOE	Department of Energy
DOT	Department of Transportation
EVA	Extra Vehicular Activity
FEA	Finite Element Analysis
FMEA	Failure Mode and Effects Analysis
GPM	Gallons per Minute
HazMat	Hazardous Materials
IDLH	Immediately Dangerous to Life and Health
IUOE	International Union of Operating Engineers
KSC	Kennedy Space Center
KSU	Kansas State University
LCC	Life Cycle Costs
LCG	Liquid Cooling Garment
LCP	Liquid Crystal Polymer
LED	Light Emitting Diode
MLI	Multi-Layer Insulation
MVE	Minnesota Valley Engineering
NBPLSS	Neutral Buoyancy PLSS
NFPA	National Firefighter Protection Agency
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride
NIOSH	National Institute of Occupational Safety and Health
NSTS	National Space Transportation System
OSHA	Occupational Safety and Health Administration
OSS	Oceaneering Space Systems
PCV	Pressure Closing Valve
PICS	Personal Ice Cooling System
PLSS	Personal Life Support System
PPE	Personnel Protection Equipment
QD	Quick Disconnect
RAC	Respiratory Advisory Committee
RV	Relief Valve
SAR	Supplied Air Respirators
SCBA	Self-Contained Breathing Apparatus
SII	Space Industries Inc.
SLPM	Standard Liters per Minute
SPF	Super Plastically Formed

Appendix A: Requirements Matrix

First Application

Source	#	Requirement	Cost
NIOSH	84.11 (a)	Complete written description together with drawings and specifications showing full details of construction and the materials used.	OSS man hours
OSH	84.11 (b)	Drawings shall be titled, numbered, and dated; any revision dates shall be shown on the drawings and the purpose of each revision being sought shall be shown.	OSS man hours
NIOSH	84.11 (c)	Proposed plan for quality control which meets the requirements in subpart E.	OSS man hours
NIOSH	84.41 (a)	Each quality control plan shall contain provisions for the management of quality, including requirements for the production of quality data and the use of QC records; control of engineering drawings, documentations, and changes; control and calibration of measuring and test equipment; control of purchased material to include incoming inspection; lot identification, control of processes, manufacturing, fabrication, and assembly work; audit of final inspection of the completed product; organizational structure necessary to carry out these provisions.	OSS man hours
NIOSH	84.41 (b-e)	Each provision for incoming and final inspection in the quality control plan shall include a procedure for the selection of a sample of respirators and components for testing. (MIL-STD-414). The sampling procedure shall include a list of the characteristics to be tested. Those characteristics shall be classified according to the potential effect of such defect: critical, major A, major B, minor. The QC inspection test method for each characteristic shall be described in detail.	OSS man hours
NIOSH	84.11 (d)	Statement that the respirator has been pretested by the applicant as prescribed in 84.64 and shall include the results of such tests.	OSS man hours
NIOSH	84.64 (a)	Prior to making or filing any application for approval the applicant shall conduct examinations, inspections, and tests of respirator performance which are equal to or exceed the severity of those prescribed in this part.	Man hours Testing fees or lab equipment purchase
IOSH	84.64 (b)	The applicant shall provide a statement to the Institute showing the types and results of the examinations, inspections, and tests required and state that the respirator meets the minimum requirements of subparts H through L. Complete examination, inspection, and test data shall be retained on file by the applicant and submitted upon request.	Man hours
NIOSH	84.12 (b)	The applicant shall deliver the number of completely assembled respirators and component parts required for testing.	Hardware buildup
NIOSH	84.20	Fee for an SCBA of 1 hour or more	$3500
NIOSH	84.22 (b)	The institute reserves the right to conduct any examination, inspection, or test it deems necessary to determine the quality and effectiveness of any respirator or component or subassembly.	$100 per man day for additional tests and inspections.
NIOSH	84.33 (a)	Full-scale reproductions of approval labels and markings, and a sketch or description of the method of application and position. Instructions for the use and maintenance of the respirator shall be submitted to the Institute for approval.	Manuals
NFPA	2-3.1	Four identical SCBA that are selected from the manufacturer's production SCBA shall be subjected to the NFPA tests.	Hardware
NFPA	2-3.2	SCBA shall be initially tested and shall meet the performance requirements of three separate test series.	Lab fees Travel
NFPA	2-3.3	SCBA components shall be initially tested and shall meet the performance requirements of one test series.	Lab fees
NFPA	2-3.10	Inspection by the certification organization shall include a review of all product labels to ensure that all required label attachments, compliance statements, certification statements, and other product information.	Label artwork and tools
NFPA	2-3.11	Inspection by the certification organization shall include a review of the user information to ensure that the information has been developed and is available.	Audit/application
PA	3-2.2	Upon request at the time of purchase, the manufacturer shall provide an information sheet that documents at least the following: (a) performance tests conducted at time of manufacture and the results, (b) date of manufacture, (c) model number, (d) serial number, (e) lot number, (f)	Man hours to prepare information

		hydrostatic test dates and results, if applicable	
NFPA	3-2.3	Information or training materials regarding pre-use shall be provided at least on the following areas: (a) safety considerations, (b) limitations of use, (c) charging breathing gas cylinders, (d) breathing gas quality, (e) marking recommendations and restrictions, (f) warranty information, (g) recommended storage practices, (h) mounting on/in vehicles or fire apparatus.	Man hours to prepare manual
NFPA	3-2.4	Information or training materials regarding periodic inspections shall be provided at least on inspection frequency and details.	Man hours to prepare manual
NFPA	3-2.5	Information or training materials regarding donning and doffing shall be provided at least on the following areas: (a) donning and doffing procedures, (b) adjustment procedures, (c) interface issues.	Man hours to prepare manual
NFPA	3-2.6	Information or training materials regarding use shall be provided at least on the following areas: (a) pre-use checks, (b) proper use consistent with NFPA 1500.	Man hours to prepare manual
NFPA	3-2.7	Information or training materials regarding periodic maintenance and cleaning shall be provided at least on the following areas: (a) cleaning instructions and precautions, (b) disinfecting procedures, (c) maintenance frequency and details, (d) methods of repair, where applicable.	Man hours to prepare manual
NFPA	3-2.8	Information or training materials regarding retirement shall be provided at least on replacement/retirement considerations.	Man hours to prepare manual
NFPA	2-6.2	The manufacturer shall be registered to ISO 9001	Freebie!
NFPA	2-6.3	All subassemblies of SCBA defined on the NIOSH approval label and final assembly of SCBA components into an SCBA shall be accomplished in a facility that is registered at least to ISO 9002.	
NFPA	2-2.9	The certification organization shall require the manufacturer to have a product recall system as part of the manufacturer's quality assurance program.	Man hours Slush fund to cover hardware replacement?

plication for design changes

Source	#	Requirement	Cost
NIOSH	84.35	Applications shall be submitted as for an original certificate of approval, with a request for a modification. This includes drawings and quality plan. Additional testing will be determined by the Institute.	Testing and hardware determined by the Institute.
NIOSH	84.36	An approved respirator for which a formal certificate of modification has been issued shall be delivered as soon as it is commercially produced.	Hardware
NFPA	2-3.9	Any modifications made to an SCBA, or any accessories provided for an SCBA, shall require the retesting and meeting of the performance requirements of all those individual tests that the certification organization determines could be affected by such changes.	Testing and hardware

Yearly Recertification

Source	#	Requirement	Cost
NFPA	2-3.4	After certification, SCBA shall be tested annually within 12 months from previous tests and shall meet the performance requirements of one test series.	Lab Fees Hardware Man hours Travel
NFPA	2-3.4.1	Every fifth year the SCBA shall meet the performance requirements of three test series.	Lab Fees Hardware Man hours Travel

In-house Maintenance/Audits

Source	#	Requirement	Cost
NIOSH	84.31 (a) (b)	The certificate of approval shall contain a classification and a description of the respirator for which it is issued. It shall specifically set forth any restrictions or limitations on the respirator's use.	None
OSH	84.31 (c)	Each certificate of approval shall be accompanied by the drawings submitted. These drawings shall be referenced in the certificate and shall be maintained by the applicant. The drawings shall set forth in detail the design and construction requirements which shall be met by the applicant during commercial production.	CDM file maintenance
NIOSH	84.41 (f-g)	Each item shall be 100% inspected for critical characteristics and all defective items shall be rejected. The Acceptable Quality Level for each defect shall be: major A, 1.0%; major B 2.5%; Minor 4.0%.	Possible destructive testing, hardware costs
NIOSH	84.43 (a)	The applicant shall keep quality control inspection records sufficient to carry out the procedures required in MIL-STD-414.	CDM/QA file maintenance
NIOSH	84.43 (b)	The Institute reserves the right to have its representatives inspect the applicant's quality control test methods, equipment, and records, and to interview any employee or agent of the applicant.	Audit
NFPA	2-2.5	The certification organization shall require the manufacturer to establish and maintain a program or production inspection and testing. The certification organization shall audit the manufacturer's quality assurance program.	Audit
NFPA	2-2.6	The certification organization shall have a follow-up inspection program with at least two random and unannounced visits per 12-month period. Sample product shall be selected at random from the production line, from in-house stock, or from the open market. Samples shall be inspected and tested to verify continued compliance.	Audit Sample hardware
NFPA	2-4.2	The manufacturer shall maintain all design and performance inspection and test data from the certification organization used in the recertification of manufacturer models and components.	CDM file maintenance
NFPA	3-2.2	Upon request at the time of purchase, the manufacturer shall provide an information sheet that documents at least the following: (a) performance tests conducted at time of manufacture and the results, (b) date of manufacture, (c) model number, (d) serial number, (e) lot number, (f) hydrostatic test dates and results, if applicable	Man hours to prepare information

Requirements Matrix

(The following is a synopsis of product and contract requirements for reference only.
Persons responsible for compliance should refer to the original document(s).)

Project Name:		Product Name:		
Customer:		Contract No.		
Item	Requirement[1]	Source[2]	Test Method	Comments
Certifications				
1.	84.30 (c): If the submitted respirators are stated to be prototypes, the Institute will examine, inspect, and test them. But, if the prototype meets the requirements, the Institute may require units made on regular production tooling for further examination, inspection, and testing prior to approval.	NIOSH		This affects how many units and what level of maturity the submittal units must be. If the initial units are considered prototype (by NIOSH's definition), additional production units could be required.
2.	84.53 (a): Service Time Classification	NIOSH		Respirators are classified for their approved use time.
3.	84.63 (a): Each respirator and component shall meet the applicable requirements in subparts H through L.	NIOSH		Subpart H refers to SCBA.
4.	84.81 (a): Liquefied breathing gas containers shall meet the minimum requirements of the DOT for interstate shipment of such containers when fully charged.	NIOSH	See DOT requirements	DOT certification meets this requirement.
5.	2-1.1: Prior to certification of SCBA to NFPA, SCBA shall be NIOSH certified.	NFPA		
6.	2-1.1.2: SCBA shall have a NIOSH certification as positive pressure.	NFPA		

	(2-1.1.3: SCBA that are NIOSH certified as positive pressure but capable of supplying air to the user in a negative pressure demand-type mode shall not be certified to this standard.)			
7.	4.1.1: Intrinsically safe electrical circuits	NFPA	Must meet the requirements for Class I, Division I hazardous locations specified in ANSI/UL 913, Standard for Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, II, and III, Division I Hazardous Locations.	
8.	178.35 (a) Compliance with the requirements of this subpart is required in all details.	DOT		
Sustaining Certification				
9.	107.109 Application for renewal.	DOT		
Quality System Requirements				
10.	Subpart E: Quality Control	NIOSH	Quality Evaluation	Unclear how these requirements flowdown from the applicant to critical suppliers or subassemblies.
11.	2-5: Manufacturer's Quality Assurance Program	NFPA	MVE and OSS quality systems.	Some of these requirements will flowdown to the dewar manufacturer.
12.	2-6.3: All subassemblies of SCBA defined on the NIOSH approval label and final assembly of SCBA components shall be accomplished in a facility that is registered at least to ISO 9002.	NFPA	MVE and OSS quality systems.	
13.	2-6.2: The manufacturer shall be registered to ISO 9001.	NFPA	MVE and OSS quality systems.	

14.	6.0 Quality Assurance requirements shall be per NIOSH and NFPA.	EG&G		
Application Documents				
15.	84.11 (a): Application shall contain a complete written description with drawings and specifications showing full details of construction and materials	NIOSH		Needed for NIOSH application. The MVE agreement extends this requirement to MVE.
16.	84.11 (b): Drawings shall be titled, numbered, and dated; any revision dates shall be shown and the purpose described.	NIOSH		Needed for NIOSH application. The MVE agreement extends this requirement to MVE.
17.	84.11 (c): Proposed quality control plan.	NIOSH		Needed for NIOSH application. The MVE agreement extends this requirement to MVE.
18.	84.11 (d): Statement that the respirator has been pretested by the applicant including test results.	NIOSH	As listed in 84.64.	Needed for NIOSH application.
19.	84.11 (e): Statement that the respirator and component parts submitted are either prototypes, or made on regular production tooling, with no operation included which will not be incorporated in regular production processing.	NIOSH		Needed for NIOSH application.
20.	84.64 (a): Prior to applying for approval, the applicant shall conduct examination, inspections, and tests for respirator performance which are equal to or exceed the severity of those prescribed by NIOSH.	NIOSH	As a minimum, the tests and requirements described in 42 CFR, part 84, subparts A-H.	
21.	84.64 (b): The applicant shall	NIOSH		

	on the NIOSH approval labels, shall be marked directly on the component with either the lot number, serial number, or year and month of manufacture.			
46.	172.400a Exceptions from labeling (a) Notwithstanding the provisions of 172.400, a label is not required on – (iv) durably and legibly marked in accordance with CGA Pamphlet C-7, appendix A.	DOT		
47.	178.3 (a) Each packaging represented as manufactured to a DOT specification must be marked with specification markings conforming to the applicable specification and with the following:	DOT		
48.	178.3 (a) (1) In an unobstructed area, with letters, and numerals identifying the standard or specification.	DOT		In our case the exemption number.
49.	178.3 (a) (2) Unless otherwise specified, with the name and address or symbol of the packaging manufacturer.	DOT		
50.	178.3 (a) (3) The markings must be stamped, embossed, burned, printed or otherwise marked on the packaging to provide adequate accessibility, permanency, contrast, and legibility so as to be readily apparent and understood.	DOT		
51.	178.3 (a) (4) Unless otherwise specified, letters and numerals	DOT		

	must be at least 12.0 mm in height except that for packagings of less than or equal to 7.9 gallons capacity for liquids the height must be at least 6.0 mm. For packagings having a capacity of 1 gallon or less, letters and numerals must be of an appropriate size.			
52.	178.35 (f) Markings on a DOT specification cylinder must conform to applicable requirements. (1) Each cylinder must be marked with the following information: (i) The DOT specification marking must appear first, followed immediately by the service pressure. (ii) The serial number must be placed just below or immediately following the DOT specification marking. (iii) A symbol (letters) must be placed just below, immediately before or following the serial number. Other variations in sequence of markings are authorized only when necessitated by a lack of space. The symbol and numbers must be those of the manufacturer. The symbol must be registered with the Associate Administrator. (iv) The inspector's official mark and date of test must be placed near the serial number.	DOT		
53.	178.35 (5) The size of each marking must be at least 0.25" or as space permits.	DOT		

	provide a statement to the Institute showing the types and results of the examinations, inspections, and tests required and state that the respirator meets the minimum requirements of subparts H-L.			
22.	84.86: Each applicant shall certify that the materials employed in the construction of component parts exposed to oxygen pressures above atmospheric pressure are safe and compatible for their intended use.	NIOSH	Design evaluation	
23.	107.105 (d) Justification of exemption proposal. The application must demonstrate that an exemption achieves a level of safety at least equal to that required by regulation, or if a required safety level does not exist.	DOT	DOT test plan.	
24.	Failure Modes and Effects Analysis	AWPS		Final version should be included in the AWPs final report. May also be required by NIOSH.
Manufacturing and Inspection Requirements				
25.	173.34 (i) Repairs on DOT-4 series welded or brazed cylinders are authorized to be made by welding or brazing. Such repairs must be made by a manufacturer of these types of DOT cylinders or by a repair facility approved by the Associate Administrator for Hazardous Materials Safety.	DOT		
26.	173.34 (l) Rebuilding of DOT-4	DOT		

	series welded or brazed cylinders is authorized.			
27.	178.35 (b) Inspections and analyses. Chemical analyses and tests as specified must be made within the United States unless otherwise approved in writing. Inspections and verifications must be performed by _ (2) For DOT specifications ...4L ... manufactured in the United States, a competent inspector of the manufacturer.	DOT		
28.	178.35 (c) Duties of inspector. The inspector shall determine that each cylinder made is in conformance with the applicable specification, the inspector shall perform the following; (2) Verify physical properties of each lot of raw material by analysis or by obtaining certified analysis : Provided that a certificate from the manufacturer thereof, giving sufficient data to indicate compliance with requirements, is acceptable when verified by check analyses of ASTM D638 Standard Slabs molded concurrently with the inner vessel. (3) Verify compliance with all specification requirements. Obtain samples for all tests. Obtain samples for check physical properties, where required. (4) Furnish complete test reports	DOT		Requirement changed per exemption.

	required by this exemption to the maker of the inner vessel and upon request to the purchaser.			
29.	178.35 (d) Materials with seams, cold slugs, cracks, laminations, or other detrimental defects, not authorized. No defect acceptable that is likely to weaken the finished vessel appreciably; reasonably smooth and uniform surface finish required.	DOT		Inspection criteria for inner vessels.
30.	178.35 (g) Inspector's report. Each inspector shall prepare a report containing, at a minimum, the applicable information listed in CGA Pamphlet C-11. Any additional information or markings that are required by the applicable specification must be shown on the test report. The signature of the inspector on the reports certifies that the processes of manufacture of cylinders were observed and found satisfactory.	DOT		
31.	178.35 (h) Report retention. The manufacturer of the cylinders shall retain the reports required by this subpart for 15 years from the original test date of the cylinder.	DOT		
32.	178.57 (d) (5) Welding procedures and operators must be qualified in accordance with CGA Pamphlet C-3.	DOT		
33.	178.57 (e) (3) For welding the outer jacket, each procedure and	DOT		

	operator must be qualified in accordance with the sections of CGA Pamphlet C-3 that apply.			
34.	178.57 (g) Heat treatment (1) Inner vessel. Stress relief of the molded halves of inner vessel is permitted as necessary provided that the angle of the joining surfaces are within the drawing tolerances after heat treating (no distortions permitted). (2) Outer vessel (i) Titanium outer vessel may be vacuum annealed after chemical cleaning in accordance with ASTM B600. (ii) Steel. Heat treatment after forming is not permitted. (iii) Other metals. Heat treatment as appropriate.	DOT		
35.	178.57 (i) Pressure test. After assembly, each inner vessel, before insulating and jacketing must be examined under a pressure of at least two times the service pressure maintained for at least 30 seconds without evidence of leakage, visible distortion or other defect. Pressure gauge must permit reading to an accuracy of 1 percent.	DOT		
36.	178.57 (j) (1) Inner vessel. ASTM D638 Standard Slabs will be prepared from the same material and tested for physical properties to verify conformance with the minimum physical properties listed	DOT		

	in 178.57 (o) (1) Table 1. Determine flexural strength, flexural modulus, tensile strength, and elongation on 2 specimens selected from each lot of raw material and in the same condition as that of the completed vessel.			
37.	178.57 (j) (2) Glue joint. Following the OSS gluing procedure, LCP Inner Vessel Epoxying Procedure, prepare two specimens using ASTM D638 Standard Slabs. The slabs shall be continuously glued over their entire width and overlap each other one inch. Samples will then be pulled to failure in the tensile test apparatus.	DOT		
38.	178.57 (k) Acceptable results for physical tests. (a) Physical properties must meet the limits specified in 178.57 (o) (1) Table 1 of this exemption for the LCP. (b) Failure of the glued specimens must occur only in the base material.	DOT		
39.	178.57 (l) Tests of welds. Not required.	DOT		
40.	178.57 (m) Radiographic examination. Cylinders must be subject to a radiographic examination as follows: (1) Inspection and acceptability must conform to the standards set forth in CGA Pamphlet C-3. (2) One finished longitudinal seam must be	DOT		

	selected at random from each lot of 100 or less successively produced and be radiographed throughout its entire length.			
41.	178.57 (n) Rejected cylinders. Reheat treatment of rejected cylinders is authorized. Subsequent thereto, cylinders must pass all prescribed tests to be acceptable. Welds may be repaired by suitable methods of fusion welding.	DOT		
42.	178.57 (q) Inspector's report. In addition to the information required by 178.35, the inspector's reports must contain information on: (1) The jacket material and insulation type; (2) The design service temperature; and (3) The impact test results, on a lot basis.	DOT		
Labeling Requirements				
43.	84.33 (g): Each respirator, respirator component, and respirator container shall be labeled with the name of the applicant, and the name and letters or numbers by which the respirator or respirator component is designated for trade purposes, and the lot number, serial number, or approximate date of manufacture.	NIOSH	Manufacturing Design Evaluation	
44.	84.81 (b): Containers shall be permanently and legibly marked to identify their contents.	NIOSH	Design evaluation	
45.	3-1.7: SCBA components, as listed	NFPA		

54.	178.57 (c) Material must be identified by any suitable method.	DOT		
55.	178.57 (p) DOT-E 11375 in lieu of DOT-4L, followed by the service pressure.	DOT		
56.	Special Provisions: d. Each packaging manufactured under the authority of this exemption must be marked with a registration symbol designated by the Office of Hazardous Materials Exemptions and Approvals for a specific manufacturing facility.	DOT		
Undocumented Requirements				
57.	84.22 (b): The Institute reserves the right to conduct any examination, inspection, or test it deems necessary to determine the quality and effectiveness of any respirator assembly or respirator component or subassembly.	NIOSH	TBD	
58.	84.63 (c): The Institute reserves the right to require any additional requirements deemed necessary to establish the quality, effectiveness, and safety of any respirator.	NIOSH	TBD	
System Design Features				
59.	84.49 (b): Oxygen, including liquid oxygen, shall contain not less than 99.0 percent pure O2, not more than 0.03% carbon dioxide, and not more than 0.001% carbon monoxide. Containers used for oxygen must not be treated with	NIOSH	Gas analysis.	The "spirit" of container purity could apply.

	any toxic, sleep-inducing, narcosis-producing, or respiratory tract irritating compounds.			
60.	84.52: Respirators shall be classified as approved for use against any or all of the following hazards (a) oxygen deficiency (b) gases and vapors (c) particles, including dusts, fumes and mists.	NIOSH	Design Evaluation	
61.	84.61 (a): Respirators will not be accepted by the Institute for examination, inspection, and testing unless they are designed on sound engineering and scientific principles, constructed of suitable materials and evidence good workmanship.	NIOSH	Design Evaluation	
62.	84.70: Self-contained breathing apparatus; description	NIOSH	Design evaluation	Backpack is an (2) Open-circuit apparatus, (ii) pressure-demand-type apparatus
63.	84.71 (a): Each SCBA shall contain the following component parts (1) facepiece or mouthpiece and noseclip (2) respirable breathing gas container (3) supply of respirable breathing gas (4) gas pressure or liquid level gages (5) timer (6) remaining service life indicator or warning device (7) hand-operated valves (8) breathing bag (9) safety relief valve or safety relief system (10) harness.	NIOSH	Design evaluation	
64.	84.73 (a): Each apparatus shall be equipped with a suitable harness.	NIOSH	Design evaluation	

65.	84.79 (a): Breathing gas used to supply apparatus shall be respirable and contain no less than 19.5 (dry atmosphere) volume percent of oxygen.	NIOSH	Gas analysis.	
66.	84.79 (d): Compressed, liquefied breathing air shall meet the applicable minimum grade requirements for Type II liquid air set forth in the Compressed Gas Association Commodity Specification for Air, G-71, 1966.	NIOSH	TBD	
67.	84.82 (i)(2): Apparatus using liquefied breathing gas shall be equipped with gages visible to the wearer which indicate the remaining liquid content in the container.	NIOSH	Design evaluation	
68.	84.83 (a): Elapsed time indicators shall be provided for apparatus with a chemical oxygen source, except: (2) liquefied breathing gas apparatus equipped with gages visible to the wearer which indicate the remaining liquid content in the container.	NIOSH	Design evaluation	
69.	84.89: Weight requirement (a) The completely assembled and charged apparatus shall not weigh more than 35 pounds; however, where the weight decreases by more than 25 percent of its initial charged weight during its rated service life, the maximum allowable weight shall be 40 pounds. (b) An	NIOSH	Design evaluation	If we use cooling as a justification for a 40 pound 2-hour unit, the water and LCG could be included in the total weight. We do meet the first justification for weight reduction.

	apparatus which contributes materially to the wearer's comfort, e.g. a cooling system, shall not weigh more than 40 pounds completely assembled and fully charged regardless of the decrease in weight during use.			
70.	4.1.2: Free of rough spots, burrs, or sharp edges.	NFPA	Design Evaluation	
71.	178.35 (e) Pressure relief devices and pressure control valves. Each finished assembly must be equipped with pressure relief devices and pressure control valves as prescribed in 49 CFR 173.34(d) and 173.316. Additionally the vessel shall be equipped with a rotating pick-up and vent assembly that maintains the vent in the ullage space regardless of vessel orientation.	DOT		
72.	3.0.1 The size of the SCBA shall be no larger than 5.375" thick, 13.125" wide, and 23.250" long.	EG&G	Design Evaluation	This was modified from the original size requirement of 5"x12"x21".
73.	Backpack is 40 pounds fully charged	AWPS	Design evaluation	Design goal, results should be included in final report.
74.	Audible and visual low air warning	AWPS	Design evaluation	Design goal, results should be included in final report.
System Performance Requirements				
75.	84.90: Breathing resistance; inhalation (a) Resistance to inhalation airflow will be measured in the facepiece while the apparatus is operated by a	NIOSH	As defined in 84.90.	

	breathing machine. (b) The inhalation resistance of open-circuit apparatus shall not exceed 1.25 inch water-column height (at a flow rate of 120 liters per minute).			
76.	84.91: Breathing resistance; exhalation (a) Resistance to exhalation airflow will be measured in the facepiece with air flowing at a continuous rate of 85 liters per minute. (c) The exhalation resistance of pressure-demand apparatus shall not exceed the static pressure in the facepiece by more than 2 inches water column height. (d) The static pressure (at zero flow) in the facepiece shall not exceed 1.5 inches water-column height.	NIOSH	As defined in 84.91.	
77.	84.93: Gas flow test; open-circuit apparatus (a) A static-flow test will be performed on all open-circuit apparatus. (b) The flow from the apparatus shall be greater than 200 liters per minute when the pressure in the facepiece of demand-apparatus is lowered by 2 inches water-column height when full container pressure is applied. (c) Where pressure demand apparatus are tested, the flow will be measured at zero gage pressure in the facepiece.	NIOSH	As defined in 84.93.	
78.	84.95: Service time test; open-circuit apparatus (a) service time	NIOSH	As defined in 84.95.	

	will be measured with a breathing machine as described in 84.88 (b) The open-circuit apparatus will be classified according to the length of time it supplies air to the breathing machine. (c) the service time obtained on this test will be used to classify the apparatus.			
79.	84.97 (a) (1): Test for carbon dioxide in inspired gas, open-circuit apparatus. The concentration of carbon dioxide in inspired gas will be measured at the mouth. (c) The maximum average concentration during the inhalation portion of the breathing cycle shall not exceed 2.0 percent for a one hour unit and 1.5 percent for a two hour unit.	NIOSH	84.97 (a) (1-5) The SCBA is attached to a breathing machine. The breathing rate will be 14.5 respirations per minute with a minute volume of 10.5 liters. A concentration of 5 percent carbon dioxide in air will be exhaled into the facepiece.	
80.	84.98 (a-f): The applicant shall specify the minimum temperature for safe operation. At that temperature the apparatus shall (e)(1) function satisfactorily on duplicate tests (2) the wearer shall have sufficient unobscured vision to perform the work (3) the wearer shall not experience undue discomfort because of airflow restriction or other changes in the operation of the apparatus. Auxiliary low-temperature parts which are commercially available may be used.	NIOSH	84.98 (a-d) The apparatus will be precooled at the specified minimum temperature for 4 hours. The apparatus will be worn in the low temperature chamber for 30 minutes. Alternate 1-minute periods of exercise, stepping onto and off an 8.5" box at a rate of 30 cycles per minute, and rest will be performed. Duplicate tests will be performed by two people.	
81.	84.99 (a-g) Manned testing general requirements. Test subjects are	NIOSH		Applies to all manned tests.

	institute personnel trained in the use of SCBA. All man tests will be conducted by the Institute. The apparatus will be examined before each man test. Breathing resistance will be measured and the subject's pulse and respiration rate will be recorded during each 2 minute sample period in tests 1-4. Man tests 1-6 will be conducted in duplicate. If the man tests are not completed through no fault of the apparatus, the test will be repeated.			
82.	84.100: Man tests 1-4 are conducted to (a) Familiarize the wearer with the apparatus; (b) Provide for a gradual increase in activity; (c) Evaluate the apparatus under different types of work and physical orientation; (d) Provide information on the operating and breathing characteristics of the apparatus during actual use.	NIOSH	Subpart H of Part 84, Tables 1-4 Test 1 is a combination of 18 minute 3 mph treadmills and 2 minute sampling/reading periods. Test 2 is a combination of 3 mph treadmill work, carrying a 50 pound weight over an overcast, climbing a vertical treadmill, and carrying a 45 pound weight during a 3 mph treadmill. Test 3 is a combination of 3 mph treadmill, 6 mph treadmill, pulling a 45 pound weight to 5 feet, lay on side, and lay on back. Test 4 is a combination of 3 mph treadmill, vertical treadmill, pulling a 45 pound weight to 5 feet, carrying a 50 pound weight over an overcast, 6 mph treadmill, and carrying a 45 pound weight during a 3 mph treadmill.	

83.	84.101: Man test 5 will be conducted to determine the maximum service time of the SCBA while the user is at rest. Samples of inspiration shall be taken and shall meet the minimum requirement for oxygen specified in 84.79 (a) and the maximum allowable concentration of carbon dioxide specified in 84.97 (c).	NIOSH	84.101 The wearer sits at rest and will manipulate the devices controlling the supply of breathing gas to the advantage of the apparatus. Samples of inspiration shall be taken once every 15 minutes.	
84.	84.102: Man test 6 will be conducted on liquefied breathing gas apparatus only. This test will be conducted to evaluate operation of the apparatus in other than vertical positions. The oxygen content of the gas will be continuously measured.	NIOSH	84.102 The wearer will lie face down for ¼ the service life of the apparatus with a full charge and then a ¼ full charge. The test is repeated with the wearer lying on each side and on his back.	Pass/fail criteria for oxygen percentage is defined in 84.79 (a).
85.	84.103 (a-c): Man test performance requirements. The apparatus shall satisfy the respiratory requirements of the wearer for the classified service time. Fogging of the eyepiece shall not obscure the wearer's vision and the wearer shall not experience undue discomfort because of fit or other characteristics. When the ambient temperature during testing is 75 ± 10° F the maximum temperature of inspired air recorded during man tests shall not exceed 115° F in 0-50 percent relative humidity of inspired air or 105° F in 50-100 percent relative humidity of inspired	NIOSH		Applies to man test 1-6.

	air.			
86.	84.104: (a) Each apparatus will be tested for tightness by persons wearing it in an atmosphere of 1,000 p.p.m. isoamyl acetate.	NIOSH	84.104 (b) Six persons will each wear the apparatus in the test concentrations specified in (a) for 2 minutes and none shall detect the odor or taste of the test vapor.	"Banana oil" test.
87.	2-1.1.2: SCBA shall have a NIOSH certified rated service time of at least 30 minutes.	NFPA	NIOSH service time test.	Included in NIOSH testing and certification.
88.	4.1.3, 4.1.4: Accessories attached to the SCBA shall not interfere with the function of the unit or any of its components.	NFPA	All NFPA tests.	The unit with the accessory attached must meet all the requirements of NFPA.
89.	5-1.1: Air Flow Performance	NFPA	6-1, Air Flow Performance Test	Pack is placed on the breathing machine at 103 L/min and 30 breaths/min. Facepiece pressure shall not be less than 0.00 in. water column and shall not be greater than 3.5 in. water column above ambient pressure for the duration of the test.
90.	5-2: Environmental Temperature Performance	NFPA	6-2, Environmental Temperature Tests	For all four conditions the facepiece pressure shall not be less than 0.00 in. water column and shall not be greater than 3.5 in. water column above ambient pressure for the duration of the test. Breathing rate is NFPA. 1) The unit is cold soaked at -25° F for 12 hours and then the air flow performance test is repeated at that temperature. 2) The unit is hot soaked at 160° F for 12 hours and then the air flow performance test is repeated at that temperature. 3) The unit is hot soaked at 160° F for 12 hours and then the air flow performance test is repeated at -25° F. 4) The unit is cold

				soaked at -25° F for 12 hours and then the air flow performance test is repeated at 160° F.
91.	5-3: Vibration Resistance Performance	NFPA	6-3, Vibration Tests	The unit is shook unrestrained in a plywood box for 90 minutes with the cylinder axis perpendicular to the direction of the tester movement and for 90 minutes with the cylinder axis parallel to the direction of the tester movement. The air flow performance test is repeated at the NFPA breathing rate and the facepiece pressure shall not be less than 0.00 in. water column and shall not be greater than 3.5 in. water column above ambient pressure for the duration.
92.	5-7: Accelerated Corrosion Resistance Performance	NFPA	6-7, Accelerated Corrosion Test	A fully charged unit on a mannequin is sprayed with a salt fog for 48 hours. Then it is stored at ambient for 48 hours. The air flow performance test is repeated at the NFPA breathing rate and the facepiece pressure shall not be less than 0.00 in. water column and shall not be greater than 3.5 in. water column above ambient pressure for the duration.
93.	5-8: Particulate Resistance Performance	NFPA	6-8, Particulate Test	A charged unit is placed on a mannequin and subjected to sand and dust for one hour while breathing at the NIOSH breathing rate. Halfway through the test the mannequin is rotated 180°. The unit is brushed off and the air flow performance test is repeated at the NFPA breathing rate and the facepiece pressure shall not be less than 0.00 in.

				water column and shall not be greater than 3.5 in. water column above ambient pressure for the duration.
94.	5-11: Heat and Flame Resistance Performance	NFPA	6-11, Heat and Flame Test	The complete unit is placed on a mannequin in its correct wearing position. The mannequin, breathing at 40 L/min and 12 breaths/min, is placed in a circulating hot air oven at 203° F for 15 minutes. At the end of the exposure, ventilation rate is increased to 103 L/min. Within 20 seconds after the heat soak it is exposed to direct flame for 10 seconds. The mannequin is then raised 6 in. and dropped freely. Facepiece pressure shall not be less than 0.00 in. water column and shall not be greater than 3.5 in. water column above ambient pressure for the duration of the test. No component may have an afterflame of more than 2.2 seconds or separate or fail in a way that would cause it to be used or worn in a position not specified by the manufacturer. The facepiece lens shall not obscure vision below the 20/100 vision criterion.
95.	3.0.1 The unit shall have an 8 hour stand by time after which it will have a 60 minute NIOSH duration and a 55.6 minute after a 16 hour stand by time.	EG&G	NIOSH service time test after listed stand by times.	The original requirement was for a minimum non-vented stand-by time of 16 hours.
96.	All position PLSS	AWPS	Tilt tests, manned tests	Design goal, results should be included in final report.
97.	AWPS backpack provides 2 hours of breathing air at NIOSH rate.	AWPS	NIOSH service time test.	Design goal, results should be included in final report.
98.	Backpack and LCG shall provide	AWPS	Manned test protocols	Design goal, results should be included

	effective cooling at work rates from 100 to 500 watts for up to 2 hours			in final report.
99.	Pressure demand mode only, provide positive pressure at breathing rates up to 120 L/min	AWPS	Breathing test	Design goal, results should be included in final report.
100.	Air Temperature	User	TBD	Function of the AHX in various environments. Set limits for comfortable and safe breathing air temperature extremes during normal and failure mode operations.
101.	Drop test	User	TBD	Unclear whether or not there is a standard for this. DOT does have some drop tests for cylinders that may be used as a baseline.
Component/Subsystem Design Features				
102.	84.61 (c): Components replaced during or after use shall be constructed of materials which will not be damaged by normal handling.	NIOSH	Design Evaluation	
103.	84.62 (a): Component parts shall be (1) designed, constructed, and fitted to insure against creation of any hazard to the wearer; (2) Assembled to permit easy access for inspection and repair of functional parts; (3) Assembled to permit easy access to parts which require periodic cleaning and disinfecting.	NIOSH	Design Evaluation	
104.	84.62 (b): Replacement parts shall be designed and constructed to permit easy installation and maintenance.	NIOSH	Design Evaluation	

105.	84.61 (b): Respirator components which contact the wearer's skin shall be made of nonirritating materials.	NIOSH	Design Evaluation	
106.	84.73 (b): Harnesses shall be designed and constructed to permit easy removal and replacement of apparatus parts.	NIOSH	Design evaluation	
107.	84.78: Head harnesses; minimum requirements.	NIOSH	Design evaluation	
108.	84.72: Flexible breathing tubes used with the SCBA shall be designed and constructed to prevent: (a) restriction of free head movement; (b) disturbance of the fit of facepieces and mouthpieces; (c) interference with the wearer's activities; (d) shutoff of airflow due to kinking or from chin or arm pressure.	NIOSH	Design evaluation	
109.	84.61 (d): Mouthpieces, hoods, helmets, and facepieces shall be constructed of materials which will with stand repeated disinfection as recommended by the manufacturer in the user manual.	NIOSH	Design Evaluation	
110.	84.75: Half-mask facepieces, full facepieces, mouthpieces; fit; minimum requirements.	NIOSH	Design evaluation	
111.	84.76: Facepieces; eyepieces; minimum requirements.	NIOSH	Design evaluation	
112.	84.82 (b): Liquid-level gages shall be calibrated in fractions of total container capacity, or in units of	NIOSH	Design evaluation	

	liquid volume.			
113.	84.82 (g): Where gages are connected to the apparatus through a gage line, the gage and line shall be capable of being isolated from the apparatus except where the failure of the gage or line would not impair the performance or service life of the apparatus.	NIOSH	Design evaluation	
114.	4-2: End of service time indicators. There must be two, one shall not be solely auditory, and failure of either shall not affect the activation and operation of the other. Each indicator shall meet the activation requirements of 42 CFR 84.	NFPA	Design Evaluation	This section of the NFPA document has an effective date of September 1, 1999.
115.	84.83 (b): The timer or other indicator shall be accurately calibrated in minutes of remaining service life.	NIOSH	Design evaluation	
116.	84.83 (e): Remaining service-life indicators or warning devices shall be provided in addition to a pressure gage and shall operate automatically without preadjustment by the wearer.	NIOSH	Design evaluation	This requirement specifies compressed gas, but the NFPA requirements specify indicators that meet the requirements of 42 CFR 84.
117.	84.83 (f): Each remaining service-life indicator or warning device shall give an alarm when the remaining service life is reduced to 20 to 25 percent of its rated service time.	NIOSH	Design evaluation	
118.	84.77 (a-b): Inhalation and exhalation valves shall be provided where necessary and protected	NIOSH	Design evaluation	

	against damage and distortion. Exhalation valves shall be protected against external influence and designed and constructed to prevent inward leakage of contaminated air.			
119.	84.84 (a): Hand-operated valves shall be designed and constructed to prevent removal of the stem from the valve body during normal usage.	NIOSH	Design evaluation	
120.	84.84 (b): Valves shall be designed or positioned to prevent accidental opening and closing, and damage from external forces.	NIOSH	Design evaluation	
121.	84.84 (c): Valves operated during use of the apparatus shall be installed in locations where they can be readily adjusted by the wearer.	NIOSH	Design evaluation	
122.	84.84 (d): Main-line valves, designed and constructed to conserve gas in the event of a regulator of demand valve failure, shall be provided in addition to gas container valves, except when such failure will not affect performance.	NIOSH	Design evaluation	
123.	84.84 (e): Hand-operated bypass systems designed and constructed to permit the wearer to breathe and to conserve his gas supply in the event of a regulator or demand valve failure, shall be provided where necessary.	NIOSH	Design evaluation	

124.	84.84 (f-g): Valves installed on apparatus shall be clearly distinguishable from one another by sight and touch. The bypass system valve control shall be red.	NIOSH	Design evaluation	
125.	173.316 (5) An aluminum valve, pipe or fitting may not be installed on any cylinder used to transport any flammable cryogenic liquid.	DOT		
126.	173.316 (6) Each cylinder must be provided with one or more pressure relief devices, which must be installed and maintained in compliance with the requirements of this subchapter.	DOT		
127.	173.316 (7) Each pressure relief device must be installed and located so that the cooling effect of the contents during venting will not prevent effective operation of the device.	DOT		
128.	173.316 (b) Pressure control systems. Each cylinder containing a cryogenic liquid must have a pressure control system that conforms to 173.34 (d) and is designed and installed so that it will prevent the cylinder from becoming liquid full.	DOT		
129.	178.57 (a) (1) Type and size. Inner vessel halves must be glued, and outer vessel halves must be fusion welded. Size must not be over 9.5 pounds water capacity.	DOT		

130.	178.57 (a) (2) The service pressure must be 40 psig maximum.	DOT		
131.	178.57 (a) (3) The design service temperature is –320° F.	DOT		
132.	178.57 (d) (1) Inner vessel. By injection molding of vessel halves and glueing; mold sprue and flashing, dirt and scale to be removed as necessary to afford proper inspection. Molding must be in accordance with the procedures contained in application for exemption. The vessel halves (heads) must be seamless. The heads must be reasonably true to shape, and the skirts must be reasonably true to round. The inner vessel halves and the center hub assembly shall be glued in accordance with OSS 21200-70020 on file with the Office of Hazardous Materials Exemptions and Approvals.	DOT		
133.	178.57 (d) (2) Outer vessel. The vessel halves (heads) must be seamless. By best appliances and methods; dirt and scale to be removed as necessary to afford proper inspection. When required, titanium shall be cleaned in accordance with ASTM B600.	DOT		
134.	178.57 (e) (1) All seams of the outer jacket must be fusion welded. Only butt, edge, or joggle butt joints for the circumferential jacket seam	DOT		

	are authorized. Transition penetrations or tube penetrations may be fillet welded. All joints in the outer vessel must be in reasonably true alignment.			
135.	178.57 (e) (2) All attachments to the sidewalls and heads of the outer jacket must be by fusion welding and must be of a weldable material.	DOT		
136.	178.57 (e) (4) Brazing and soldering are permitted only for joints not made directly to the outer jacket body.	DOT		
137.	178.57 (h) Openings in vessels. Inner vessel. Openings permitted in hub section only. The opening shall not exceed 0.19 square inches. Openings in the inner vessel shall access the center hub which shall be glued to the inner vessel. Attachments to the center hub may be made by welding, brazing, soldering, or mechanical attachment.	DOT		
Component/Subsystem Performance Requirements				
138.	84.82 (d): (1) Dial-indicating gages shall be reliable to within ±5 percent of full scale when tested both up and down the scale at each of 5 equal intervals; (2) The full-scale graduation of dial-indicating gages shall not exceed 150 percent of the maximum rated cylinder pressures specified for the	NIOSH	Design evaluation	This could be applied to the capacitance gage.

	container in applicable DOT specifications.			
139.	84.82 (f): The loss of gas through a broken gage or severed gage connection shall not exceed 70 liters per minute when the liquid level is at one-half.	NIOSH	Design evaluation, failure mode testing.	
140.	84.92: Exhalation valve leakage test (a) Dry exhalation valves and valve seats will be subjected to a suction of 1 inch water-column height while in a normal operating position. (b) Leakage between the valve and the valve seat shall not exceed 30 milliliters per minute.	NIOSH	As defined in 84.92.	
141.	5-4: Fabric Flame Resistance Performance (Textile components only)	NFPA	6-4, Fabric Flame Tests	Textile components are tested according to FTMS 191A, method 5903.1 (vertical flame). Afterflame and char length are reported. Maximum average char length is 4.0 in. and maximum average afterflame is 2.0 seconds. No sample may melt or drip.
142.	5-5: Fabric Heat Resistance Performance	NFPA	6-5, Fabric Heat Tests	Sample materials are placed in the center of a circulating air oven and exposed to 500° F for 5 minutes. No sample may melt or ignite.
143.	5-6: Thread Heat Resistance Performance	NFPA	6-6, Thread Heat Test FTMS 191A, Method 1534, conducted at a temperature of 500°F, +10°/-0°F	Sewing thread may not melt or ignite below 500° F.
144.	5-9: Facepiece Lens Abrasion Resistance Performance	NFPA	6-9, Facepiece Lens Abrasion Test	Samples are taken to represent the lens over the left and right eye. Samples are abraded with a light grit sandpaper for 200 cycles. The haze is measured

				before and after abrasion. The average delta haze may not exceed 14 percent.
145.	5-10: Communications Performance (only if communication components are incorporated into SCBA)	NFPA	6-10, Communication Test ANSI S3.2, Method for Measuring the Intelligibility of Speech over Communication Systems	
146.	The Dewar will be capable of holding a vacuum (30 microns ambient) for a minimum of one year.	MVE	TBD	
147.	178.57 (d) (3) Insulation. The space between the inner vessel and the jacket shall be insulated. The insulating material must be fire resistant. If a vacuum is maintained in the insulation space, the evacuated jacket shall be designed for a minimum collapsing pressure of 30 psi differential. The construction must be such that the total heat transfer, from the atmosphere at ambient temperatures to the contents of the inner vessel, will not exceed 0.008 Btu per hour, per Fahrenheit degree differential in temperature, per pound of water capacity of the inner vessel.	DOT		
148.	173.34 (d) Pressure relief device systems. No person may offer a cylinder charged with a compressed gas for transportation unless the cylinder is equipped with one or more pressure relief devices sized and selected as to type,		CGA Pamphlet C-14 (bonfire test) CGA Pamphlet S-1.1 (relief device)	

	location, and quantity and tested in accordance with CGA Pamphlet S-1.1 (except paragraph 9.1.1.1). The pressure relief device system must be capable or preventing rupture of the normally charged cylinder when subjected to a fire test conducted in accordance with CGA Pamphlet C-14. Safety relief devices must be tested for leaks before the charged cylinder is shipped from the cylinder filling plant.			
149.	178.57 (b) Material (1) Inner containment vessel. Designations and limiting physical properties of the LCP authorized by this specification shall be as shown in 178.57 (o)(1) Table 1 of this exemption. (2) Outer jacket. Any metal may be used subject to the requirements of 178.57 (o)(2) of this exemption.	DOT		
150.	178.57 (f) Wall thickness. The minimum wall thickness of the inner containment vessel and the outer jacket shall be calculated using finite element analysis. Using FEA the calculated wall stress at minimum required test pressure shall not exceed one-third of the minimum tensile strength of the base material as required in 178.57 (o).	DOT		
151.	178.57 (o) Authorized materials of construction. (1) Inner containment	DOT		

	vessel. LCP of uniform quality. Chemical analysis must conform to Hoechst Celanese Vectra A130. See Table 1 – Authorized Materials.			
152.	178.57 (o) (2) Outer vessel. Must be constructed of any metal that meets the structural requirements established by the FEA where the calculated wall stress shall not exceed one-third of the minimum tensile strength of the base metal. The minimum wall thickness of the outer jacket shall be determined based on the results of the FEA.	DOT		
Contract Deliverables/Customer Goals				
153.	Operators, Service, and Training manuals for production version AWPS	AWPS		Contract deliverable
154.	Final Report	AWPS		Contract deliverable
155.	3.1.1 Preliminary Submittals a) Quality Assurance Plan per NIOSH and NFPA 1981. b) Welding procedures and welder qualifications. c) NIOSH and NFPA testing plans. d) Professional Engineering registration certificate for the chief design engineer n charge of vessel design. e) Written approval from the Associate Administrator for Hazardous Materials Safety for inspectors to perform inspections and verifications during vessel	EG&G		Contract Deliverable

	fabrication.			
156.	3.1.2 Pre-Fabrication Submittals Prior to ordering any material or commencing any fabrication work on the SCBAs the Subcontractor shall submit all documents listed below a) Specifications b) Design calculations c) Detailed design and shop fabrication drawings d) Parts list and materials of construction e) Detailed project and production schedules.	EG&G		Contract Deliverable
157.	3.1.3 Mid-Project Submittals Upon successful completion of pretesting of the SCBAs per the NIOSH requirements, the subcontractor shall submit a report containing the following: a) Tests and testing methods utilized. b) Testing data and results. c) Final production schedule.	EG&G		Contract Deliverable
158.	3.1.4 Final Submittals Upon completion of construction the following shall be submitted: a) Detailed design and shop fabrication drawings b) Material specifications c) quality assurance inspection reports d) Complete test reports required by 49 CFR used for vessel design and fabrication, including radiograph inspection data (original film). e) Complete testing data and reports required by NIOSH and NFPA for certification.	EG&G		Contract Deliverable
159.	2 IUOE evaluations	AWPS		Design goal, results should be included

				in final report.
160.	Recharge station for use with AWPS. With this recharge station the backpack should be refilled in a time similar to a high pressure bottle - approximately 5 minutes	AWPS	Design evaluation	Design goal, results should be included in final report.
161.	System design optimization of fabrication and assembly	AWPS	Design evaluation	Design goal, results should be included in final report.
162.	PLSS outer shell will provide for ease of decontamination	AWPS	Design evaluation	Design goal, results should be included in final report.
163.	NIOSH certified as an SCBA	AWPS	NIOSH requirements	Design goal, results should be included in final report.
164.	3.0 The SCBA shall meet or exceed the requirements of and be certified by NIOSH and NFPA 1981.	EG&G	NIOSH and NFPA tests as listed.	
165.	3.0.1 The SCBA shall be open-circuit, pressure demand (positive pressure) and shall not be capable of supplying air to the user in a negative pressure, demand type mode.	EG&G	NFPA certification	
166.	3.0.1 The SCBA shall be fitted with a full facepiece.	EG&G	Design Evaluation	
167.	3.0.1 The breathing air source for the SCBA may be compressed, liquid, or super critical air.	EG&G	Design Evaluation	
168.	3.0.1 The SCBA shall have a minimum rated duration of one hour.	EG&G	NIOSH certification	The EG&G unit is a one hour SCBA.
169.	3.1.3 SCBAs that will be submitted to NIOSH to testing/certification, shall be made on regular production tooling, with no	EG&G		Contract requirement

	operation included which will not be incorporated in regular production processing.			
170.	3.2 The SCBA design shall meet or exceed the requirements of NIOSH 42 CFR, part 84, Subparts A-H and NFPA 1981.	EG&G		
171.	4.0 Construction shall be per the requirements of NIOSH and NFPA.	EG&G		
172.	5.0 Inspection and tests shall be per the requirements of NIOSH and NFPA.	EG&G		
173.	7.0 Packing and marking for shipment shall be in accordance with the requirements of 49 CFR.	EG&G		
174.	3.0.2 Communication capabilities shall be added to the LAP mask while meeting the requirements of NFPA and NIOSH.	EG&G		Contract deliverable. This could be tested per the communications requirements of NFPA and electrical component requirements of NIOSH.
175.	3.0.2.2 The subcontractor shall install in each mask the following: a) Microphone (CFE David Clark P/N 09168P-28) b) 2 pin Lemo receptacle (P/N HGG-0B-3-02-C-T-L-P) c) Cord and plug assembly (Roanwell P/N 604221001-603.	EG&G		Contract deliverable.
Requirements for Use				
176.	173.34 (f) A cylinder which has been subjected to the action of fire must not again be placed in service until it has been properly reconditioned (3) the inner cylinders made under specification DOT-4L (178.57) may be used	DOT		Does this mean firefighters? Do we need to explain this to the DOT?

	again after passing the original hydrostatic test.			
177.				

[1] Paragraph numbers listed in these blocks refer to the documents listed in "Source".

[2] NIOSH denotes requirements dictated by the National Institute of Occupational Safety and Health, 42 CFR Part 84.
NFPA refers to requirements imposed by NFPA 1981 Standard on Open-Circuit Self-Contained Breathing Apparatus for the Fire Service, 1997 Edition.
User denotes requirements that are necessary to produce a safe and competitive product in the industry.
AWPS denotes requirements from the Advanced Worker Protection System Contract with the Department of Energy.
EG&G denotes requirements listed in contract EO5712 and subsequent modifications and KSC 81KO5198 Specification for Liquid Air Pack Performance.
Scott denotes requirements included in the Scott source control drawing for the OSS product and/or the Scott agreement.
DOT denotes requirements imposed by 49 CFR 106, 107, 171-180 and the OSS exemption DOT-E 11375.
MVE denotes requirements included in the agreement between MVE and OSS.

Appendix B: DOT Submittal Report

JAN 14 1998

U.S. Department
of Transportation

**Research and
Special Programs
Administration**

400 Seventh Street, S.W.
Washington, D.C. 20590

DOT-E 11739

EXPIRATION DATE: December 31, 1999

(FOR RENEWAL, SEE 49 CFR 107.109)

1. GRANTEE: Oceaneering Space Systems
Houston, TX

2. PURPOSE AND LIMITATIONS:

a. This exemption authorizes the manufacture, mark, sale and use of a non-DOT specification breathing apparatus to be used for the transportation in commerce of air, refrigerated liquid. This exemption provides no relief from any Hazardous Material Regulation other than as specifically stated herein.

b. An exemption authorization to manufacture, mark, sell, and transport only represents certification of safety for a package when it is an article of commerce in transportation. The safety analyses performed in development of this exemption only considered the hazards and risks associated with transportation in commerce. The safety analyses did not consider the hazards and risks associated with consumer use, use as a component of a transport vehicle or other device, or other uses not associated with transportation in commerce.

3. REGULATORY SYSTEM AFFECTED: 49 CFR Parts 106, 107 and 171-180.

4. REGULATIONS FROM WHICH EXEMPTED: 49 CFR Sections 173.316(c) in that the prescribed packaging is not listed as an authorized packaging, and portions of 178.57 as specified herein.

5. BASIS: This exemption is based on the application of Oceaneering Space Systems (OSS) dated July 11, 1996 submitted in accordance with 49 CFR 107.105 and the public proceeding thereon.

6. HAZARDOUS MATERIALS (49 CFR 172.101):

Hazardous materials description -- proper shipping name	Hazard Class/ Division	Identi- fication Number	Packing Group
Air, refrigerated liquid	2.2	UN1003	N/A

7. PACKAGING(S) and SAFETY CONTROL MEASURES:

a. PACKAGING - Packaging prescribed is a non-DOT specification breathing apparatus consisting of an injection molded plastic inner vessel within a steel or titanium vacuum jacket outer vessel. The inner vessel contains the air, refrigerated liquid and must be designed with a burst pressure of no less than 2.5 times the service pressure. The container must be in conformance with the DOT-4L cylinder (§178.57) except as follows:

§178.57-2 Type, Size, Service Pressure, and Design Service Temperature.

(a) Type and size. Inner vessel halves must be glued, and outer vessel halves must be fusion welded. Size must not be over 17 pounds water capacity.

(b) The service pressure must be 40 psig maximum.

(c) The design service temperature is -320°F.

§178.57-4 Duties of inspector.

(a) * * *

(b) Verify physical properties of each lot of raw material by analysis or by obtaining certified analysis: Provided that a certificate from the manufacturer thereof, giving sufficient data to indicate compliance with requirements, is acceptable when verified by check analyses of ASTM D638 Standard Slabs molded concurrently with the inner vessel.

(c) Verify compliance with all specification requirements. Obtain samples for all tests. Obtain samples for check physical properties, where required. * * *

(d) Furnish complete test reports required by this exemption to the maker of the inner vessel and, upon request, to the purchaser. * * *

§178.57-5 Material.

(a) Inner containment vessel. Designations and limiting physical properties of the liquid crystal polymer (LCP) authorized by this specification shall be as shown in §178.57-21(a) Table 1 of this exemption.

(b) Outer jacket. Titanium or steel may be used subject to the requirements of §178.57-21(b).

§178.57-7 Defects.

(a) Materials with seams, cold slugs, cracks, laminations, or other detrimental defects, not authorized. No defect acceptable that is likely to weaken the finished vessel appreciably; reasonably smooth and uniform surface finish required.

§178.57-8 Manufacture.

(a) Inner vessel. By injection molding of vessel halves and glueing; mold sprue and flashing, dirt and scale to be removed as necessary to afford proper inspection. Molding must be in accordance with the application for exemption. The vessel halves (heads) must be seamless. The heads must be reasonably true to shape, shall have no abrupt shape changes and the skirts must be reasonably true to round. The inner vessel halves and the center hub assembly shall be glued in accordance with OSS LCP Inner Vessel Epoxying Procedure dated 3/11/96 and modified 6/10/96.

(b) Outer vessel. The vessel halves (heads) must be seamless. By best appliances and methods; dirt and scale to be removed as necessary to afford proper inspection. When required, titanium shall be cleaned in accordance with ASTM B600 Standard Guide for Descaling and Cleaning Titanium and Titanium Alloy Surfaces.

(c) Insulation. The space between the inner vessel and the jacket shall be insulated. The insulating material must be fire resistant. If a vacuum is maintained in the insulation space, the evacuated jacket shall be designed for a minimum collapsing pressure of 30 psi differential whether made of steel or titanium. The construction must be such that the total heat transfer, from the atmosphere at ambient temperatures to the contents of the inner vessel, will not exceed 0.008 Btu per hour, per Fahrenheit degree differential in temperature, per pound of water capacity of the inner vessel.

§178.57-9 Welding.

(a) All seams of the outer jacket must be fusion welded. Only butt or joggle butt joints for the circumferential jacket seam are authorized. Transition penetrations or tube penetrations may be fillet welded. All joints in the outer vessel must be in reasonably true alignment.

(b) All attachments to the sidewalls and heads of the outer jacket must be by fusion welding and must be of a weldable material.

(c) For welding the outer jacket, each procedure and operator must be qualified in accordance with the sections of CGA Pamphlet C-3 that apply.

(d) Brazing and soldering are permitted only for joints not made directly to the outer jacket body.

§178.57-10 Wall thickness.

(a) Inner vessel. The minimum wall thickness of the inner containment vessel shall be calculated using Finite Element Analysis (FEA). Using FEA the calculated wall stress at minimum required test pressure shall not exceed one-third of the minimum tensile strength of the base material as required in §178.57-21.

(b) Outer vessel. The minimum wall thickness of the outer jacket shall be calculated using FEA. Using FEA the calculated wall stress at an external pressure of 30 psi shall not exceed the yield strength of the base metal determined as required in §178.57-21.

§178.57-11 Heat treatment.

(a) Inner vessel. Stress relief of the molded halves of inner vessel is permitted as necessary provided that the angle of the joining surfaces are within the drawing tolerances after heat treating (no distortions permitted).

(b) Outer vessel.

(1) Titanium. Titanium outer vessel may be vacuum annealed after chemical cleaning in accordance with ASTM B600 Standard Guide for Descaling and Cleaning Titanium and Titanium Alloy Surfaces.

(2) Steel. Heat treatment after forming is not permitted.

§178.57-12 Openings in Vessels.

(a) Inner vessel. Openings permitted in hub section only. The opening shall not exceed 0.19 square inches. Openings in the inner vessel shall access the center hub which shall be glued to the inner vessel. Attachments to the center hub may be made by welding, brazing, soldering, mechanical attachment, or threading.

(b) Outer vessel. Openings permitted only in areas not adjacent to knuckle radius. Center line of opening must be one diameter or more away from knuckle radius or weld seam. Openings must be circular and shall not exceed ½ inch diameter. Attachments to the outer vessel may be made by welding, brazing, soldering, mechanical attachment, or threading.

§178.57-13 Pressure relief devices and pressure control valves.

Each finished assembly must be equipped with pressure relief devices and pressure control valves as prescribed in 49 CFR §173.34(d) and 173.316. Additionally the vessel shall be equipped with a rotating pick-up and vent assembly that maintains the vent in the ullage space regardless of vessel orientation.

§178.57-14 Pressure test.

(a) After assembly, each inner vessel, before insulating and jacketing must be examined under a pressure of at least two times the service pressure maintained for at least 30 seconds without evidence of leakage, visible distortion or other defect. Pressure gauge must permit reading to an accuracy of 1 percent.

§178.57-15 Physical test.

(a) Inner vessel. Concurrent with part molding, ASTM D638 Standard Slabs will be prepared from the same material and tested for physical properties to verify conformance with the minimum physical properties listed in §178.57-21(a) Table 1 of this exemption. Determine yield strength, tensile strength, and elongation on 2 specimens selected from each lot of raw material and in the same condition as that of the completed vessel.

(b) Glue joint. Following the OSS gluing procedure, LCP Inner Vessel Epoxying Procedure, prepare two specimens using ASTM D638 Standard Slabs. The slabs shall be continuously glued over their entire width and overlap each other one inch. The samples shall be cured and allowed to set for 7 days. Samples will then be pulled to failure in the tensile test apparatus.

§178.57-16 Acceptable results for physical tests.

(a) Physical properties must meet the limits specified in §178.57-21(a) Table 1 of this exemption for the LCP.

(b) Failure of the glued specimens must occur only in the base material.

§178.57-17 Tests of welds.

Not required.

§178.57-20 Marking.

(a) * * *

(1) DOT-E 11739 in lieu of DOT-4L, followed by the service pressure.

* * *

§178.57-21 Authorized materials of construction.

(a) Inner containment vessel. Liquid Crystal Polymer of uniform quality. Chemical analysis must conform to Hoechst Celanese Vectra A130. The following chemical analyses and physical properties are authorized:

TABLE 1 - AUTHORIZED MATERIALS

Designation	Chemical Analysis, Limits in Percent
Glass Fiber	29 to 31
Vectra Copolyester Resin Grade A950	Remainder

Physical Properties

Tensile strength at break, psi (minimum)	30,000
Tensile modulus, psi	3,200,000
Flexural strength, psi	37,000
Flexural modulus, psi	2,100,000
Compressive strength, psi (deflection)	20,000

Compressive modulus, psi	1,700,000
Shear strength, psi	17,800
Izod impact strength, notched ft-lb/in	2.8
Tensile impact strength, ft-lb/in^2	40
Elongation at break, percent	2.2

CHECK ANALYSIS TOLERANCES

Elements	Limit or maximum of specified range, percent	Permissible variation in product analysis
Glass fiber	30	±1.0

(b) Outer vessel. Must be constructed of steel or titanium. Steel: Electric furnace steel of uniform quality. Chemical analysis must conform to ASTM A240, Type 304 stainless steel. Titanium: Alloy Ti-6Al-4V must conform to AMS 4911H.

b. OPERATIONAL CONTROLS - The service life of the prescribed container is limited to 15 years.

8. SPECIAL PROVISIONS:

a. Offerors for transportation of the hazardous materials specified in this exemption may use the packaging described in this exemption for the transportation of such hazardous materials provided no modifications or changes are made to the packages, all terms of this exemption are complied with, and a copy of the current exemption is maintained at each facility from which such offering occurs.

b. Each packaging manufactured under the authority of this exemption must be either (1) marked with the name of the manufacturer and location (city and state) of the facility at which it is manufactured or (2) marked with a registration symbol designated by the Office of Hazardous Materials Exemptions and Approvals Program for a specific manufacturing facility.

c. A copy of this exemption, in its current status, must be maintained at each manufacturing facility at which this packaging is manufactured and must be made available to a DOT representative upon request.

d. Shippers using the packaging covered by this exemption must comply with all provisions of this exemption, and all other applicable requirements contained in 49 CFR Parts 171-180 that apply to the hazardous materials authorized and to a DOT Specification 4L cylinders.

e. Design qualification testing must be performed in accordance with the OSS July 11, 1996 application for exemption, with acceptable results. The final test report must be on file with the Office of Hazardous Materials Exemptions and Approvals before initial shipment.

9. MODES OF TRANSPORTATION AUTHORIZED: Motor vehicle, rail freight, cargo vessel, and cargo aircraft only.

10. MODAL REQUIREMENTS: A copy of this exemption must be carried aboard each cargo vessel or aircraft used to transport packages covered by this exemption. The shipper shall furnish a copy of this exemption to the air carrier before or at the time the shipment is tendered.

11. COMPLIANCE: Failure by a person to comply with any of the following may result in suspension or revocation of this exemption and penalties prescribed by the Federal hazardous materials transportation law, 49 U.S.C. Section 5101 et seq:

- o All terms and conditions prescribed in this exemption and the Hazardous Materials Regulations, Parts 171-180.
- o Registration required by 49 CFR 107.601 et seq., when applicable.

Each "Hazmat employee", as defined in 49 CFR 171.8, who performs a function subject to this exemption must receive training on the requirements and conditions of this exemption in addition to the training required by 49 CFR 172.700 through 172.704.

No person may use or apply this exemption, including display of its number, when the exemption has expired or is otherwise no longer in effect.

12. REPORTING REQUIREMENTS: The carrier is required to report any incident involving loss of packaging contents or packaging failure to the Associate Administrator for Hazardous Materials Safety (AAHMS) as soon as practicable. (49 CFR 171.15 and 171.16 apply to any activity undertaken under the authority of this exemption.) In addition, the holder(s) of this exemption must also inform the AAHMS, in writing, as soon as practicable of any incidents involving the package and shipments made under this exemption.

Issued at Washington, D.C.

JAN 14 1998

Alan I. Roberts
Associate Administrator
for Hazardous Materials Safety

(DATE)

Address all inquiries to: Associate Administrator for Hazardous Materials Safety, Research and Special Programs Administration, Department of Transportation, Washington, D.C. 20590. Attention: DHM-31.

The original of this exemption is on file at the above office. Photo reproductions and legible reductions of this exemption are permitted. Any alteration of this exemption is prohibited.

Dist: FHWA, FRA, FAA, USCG
PO: CWF

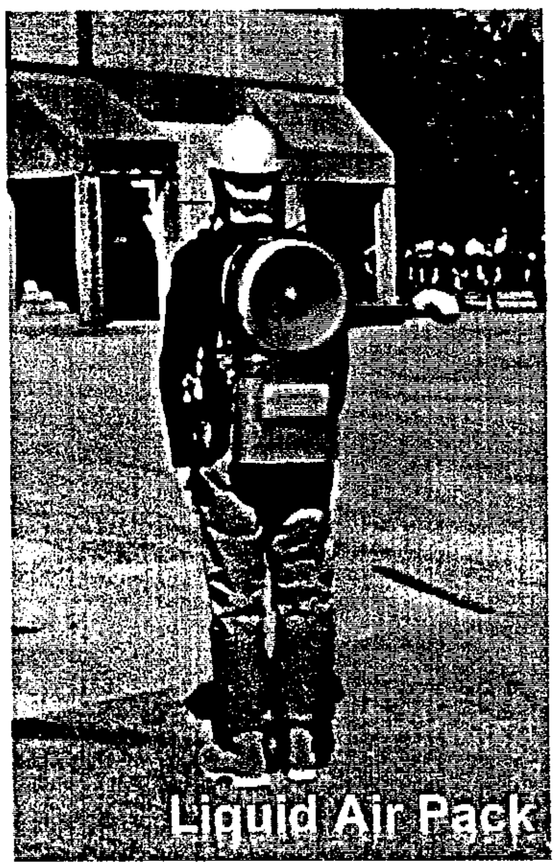
OCEANEERING
SPACE SYSTEMS

FINAL REPORT

for

DOT - E 11739

July 31, 1998



OCEANEERING
SPACE SYSTEMS

July 31, 1998

Ms. Susan Hedgepath
Approvals and Exemptions
Associate Administrator for Hazardous Material Safety
U.S. Department of Transportation
Washington, DC 20590-0001

Reference: DOT E-11739

Dear Ms. Hedgepath:

Even though the Exemption has issued for Oceaneering Space System's (OSS) pressure vessel, it was with the understanding that OSS would complete the testing and submit those results in the form of a Final Report as we did for DOT E - 11375.

Three copies of that Final Report are herewith enclosed for your files.

The Report includes the results to the testing performed according to §178.CC-12 "Design Qualification Tests" and any supplemental information that is necessary to explain those results as appropriate.

As usual, we are prepared to help clarify any portion of the information. Please do not hesitate to call at (281) 228 - 5411 if there are any questions.

Sincerely,

Robert J. Richter

16665 SPACE CENTER BLVD., HOUSTON, TEXAS 77058-2268
(281) 228-5300 FAX: (281) 228-5546

TABLE OF CONTENTS

QUALIFICATION TEST RESULTS

§178.CC-12 (c) (2) Cryogenic Cycling and Burst Tests

SCOPE: To perform the tests according to provisions of §178.CC-12 (c) (2) Design Qualification Tests as referenced in DOT-E 11739 dated Jan. 14, 1998.

Tests to be covered by this Report:

	Test Number	No. of Cycles
Cryogenic Cycling Tests	#1	0
(As described in MOS 975EP058-copy attached)	#2	0
	#3	0
	#4	100
	#5	100
	#6	100
	#7	1000
	#8	1000
	#9	1000

Items Included in Each Test:

Gluing Procedures (19801- 70018 & 19801 - 70020)- copy of each attached

Test Setup & Test Results (MOS 975EP058-copy attached)

Summary of Results:

A summary of the individual results and averages appears below. The averages have been extrapolated to 10,000 cycles as required by the Acceptable Test Results §178.CC-13 (b) with a result of 169 psi which meets the acceptance criteria of 2.6 times the design pressure of 54.7 or 142 psi with no single value less than 2.5 times the design pressure or 137 psi. These tests were judged to be successful by OSS Inspection (Final Acceptance Stamp dated 2/24/98).

OCEANEERING SPACE SYSTEMS

16665 Space Center Blvd
Houston, TX 77058

MOS
Manufacturing Operation Sheet

1. MOS No. 975EP058	Page 1 of 4	3. Need Date: 9/12/97
4. Type	A. Configuration Change ____ Perm ____ Temp ____ B. Nonconfiguration Change X	
5. MOD Sheet(s) No(s)	6. Contract/ Job No. 77933.150 0	7. Part/Model No. N/A 19801-10002
8. Applicable Documentation 19801-70018, LCP to LCP Glue procedure 19801-70020, LCP to SS Glue procedure	9. ADP Update? N/A	10. Serial Number N/A
11. TimeCycle Used (Yes/No) N/A	12. System AWPS	
13. Short Title of TPS	AWPS Inner Vessel Assembly, Cryo Cycle, and Cryo Burst for DOT LCP Property Correlation	

Oper Seq No.	14. Operations (Print, Type, or Write Legibly)	Verification 15. Tech	16. Insp
1 7-14-M, 7-37-F 7-39-M, 7-34-F	Scope: This MOS epoxies 7 inner vessel assemblies together as controlled units (NOTE: Two inner vessel assemblies that were not used from MOS 975EP029 will be used in addition to these 7 units for a total of 9 units). The 9 units will have latest tension rings epoxied on, then they will be cryo cycle tested and cryo burst at operating temperature. The burst pressures are to be used for correlation w/tensile coupons per OSS doc. 19801-70006.		
2	(NOTE: Steps 2 through 5 are to epoxy the vessel halves together) Obtain materials listed below from QC inspection and record Lot #: 1. P/n 19801-20037-001, Inner Vessel Half, Male, Backpack (x7). Use vessels numbered 17, 18, 31, 32, 33, 34, 49. Record Lot # M15117. 2. P/n 19801-20036-001, Inner Vessel Half, Female, Backpack (x7). Use vessels numbered 17, 21, 25, 45, 47, 51, 52. Record Lot # M15116. 3. P/n 19801-20102-001, Ring, Tension, Backpack (x18). Record Lot # 25372.	JOE D 10-16-97	OCEANEERING 11 10-16-97

17. Originator [signature]	Date 9/12/97	18. Final Acceptance Stamp OCEANEERING 13	Date 2-24-98
19. Engineer [signature]	Date 9/12/97	20. Quality Engineer M. Wagner	Date 9/12/97

OSS Form No.5175

Manufacturing Operation Sheet **Continuation Sheet**	MOS No. 975EP058 MOD No. Page 2 of 4

Oper. Seq. No.	Operation	Verification Tech	Verification Insp
3	Obtain the following uncontrolled materials: 1. Crest 3170 epoxy. 2. Hysol EA9309.3NA epoxy. 3. .25" OD stainless steel tubing for fill and vent lines.	JHF	
4	For seven male vessel halves, drill 2 holes on the vertical wall of the hub, at an angle of 15 to 25 degrees above horizontal, 60 to 90 degrees apart, using a Letter F drill bit. Glue a vent and fill tube into the hub of each male vessel using Hysol epoxy following manufacturer's mix and cure procedures.	JHF	
5	Glue 7 pairs of male and female halves together per attached LCP to LCP glueing procedure.	1-20-98	
6	(NOTE: Steps 6 through 9 are to put the 18 rings on the 9 vessels.) Place aluminum tension rings in oven at 200 ± 20 °C for .5 + .5,-.1 hours.	1-21-98	
7	Slip hot rings onto glued together, room temperature LCP vessel, making sure rings are fully seated by lightly tapping with a soft mallet (wood, rubber, rawhide).	1-21-98	
8	Allow rings to cool to room temperature ± 20 °C before moving assembled vessel.	1-21-98	
9	Mix Hysol EA9309.3NA epoxy per manufacturer's instructions. Brush into gap between chamfer of ring and side wall of vessel. Cure at 80 ± 5 C for at least 1 hr.	1-22-98	
10	(NOTE: Steps 10 through 14 describe the cycle testing procedure.) Calibrate pressure transducer by plumbing it to a calibrated analog pressure gage. Record gage and transducer pressures at a static pressure between 50 and 70 psi. Attach additional pages if necessary.		OCEANEERING 10 1/28/98
	Record date and test: 1-28-98 Record calibrated gage metrology: M23256 (11/25/98) Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi.	1-28-98	OCEANEERING 10 1/28/98
	Record date and test: 1/29/98 Cycle Test Record calibrated gage metrology: M23256 (11/25/98 Record calibrated gage pressure: 70 psi. Record pressure transducer pressure: 70 psi.		OCEANEERING 10 1/29/98
	Record date and test: FEB 0 3 1998 Cycle Test Record calibrated gage metrology: M23256 Exp 11-25-98 Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi.		OCEANEERING 3 FEB 0 3 1998

Manufacturing Operation Sheet Continuation Sheet	
	MOS No. 975EP058
	MOD No.
	Page 3 of 4

Oper. Seq. No.	Operation	Verification Tech	Verification Insp
10 cont.	Record date and test: 2-6-98 Record calibrated gage metrology: M23256 EXP 11/25/98 Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi.	2-6-98	OCEANEERING 10 2/6/98
	Record date and test: 2-9-98 Record calibrated gage metrology: 2-9-98 M23256 exp: 11/25/98 Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi.	2-9-98	OCEANEERING 8 2/9/98
	Record date and test: 2-10-98 Record calibrated gage metrology: M23256 exp: 11/25/98. Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi.	2-10-98	OCEANEERING 8 2/10/98
	Record date and test: 2-12-98 Record calibrated gage metrology: MS23256 exp: 11/25/98. Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi.	2-12-98	OCEANEERING 8 2/12/98
	Record date and test: 2-19-98 Record calibrated gage metrology: MS23256 exp 11-25-98. Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi.	2-19-98	OCEANEERING 13 2-19-98
	Record date and test: 2-20-98 Record calibrated gage metrology: M23256 Exp: 11/25/98 Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi.	2-20-98	OCEANEERING 8 2/20/98
	Record date and test: 2-23-98 Record calibrated gage metrology: M23256 Exp 11/25/98 Record calibrated gage pressure: 50 psi. Record pressure transducer pressure: 50 psi. Note: use back of this page for additional calibration if necessary	2-23-98	OCEANEERING 8 2/23/98
11	Set up pressure cycling to pressurize the vessel to between 55 (operating pressure) and 60 psi at not more than 4 time per minute. Minimum pressure should not be more than 15 psi.	1-26-98 2-24-98	
12	Fill vessel with liquid nitrogen.	↕	
13	Cycle 3 vessels 1000 times and 3 different vessels 100 times as described in step 4, both followed by 30 cycles to between 82 (test pressure) and 87 psi at not more than 4 cycles per minute. Minimum pressure should not be more than 15 psi.	1-26-98 2-24-98	

Manufacturing Operation Sheet Continuation Sheet	MOS No. 975EP058
	MOD No.
	Page 4 of 4

Oper. Seq. No.	Operation	Verification Tech	Verification Insp
14	Following the cycles, fill each vessel with liquid nitrogen and allow to self pressurize to burst. Record burst pressure:	1-26-98 2-24-98	8 2/23/98

	Cycles	Vessel #'s	Burst Pressure (psi)
#1	0	7-18-M 7-21-F	180
2	0	7-4-M 7-15-F	183
3	0	7-34-M 7-17-F	176
4	100	7-6-M, 7-11-F	178
5	100	7-32-M 7-45-F	174
6	100	7-17M 7-25-F	190
7	1000	7-49-M 7-51-F	184
8	1000	7-47-M 7-33F	145
#9	1000	7-31-M, 7-52-F	186

Oper. Seq. No.	Operation	Tech	Insp
MIP 15	Failure occurs if any of the following conditions exist: 1. Vessel fails due to anything except LCP failure (i.e., glue joint failure, tube penetration failure, tension ring slip-off failure). 2. Any single burst pressure is less than 137 psi. (2.5 x 54.7) 3. The average burst pressure of the 3 vessels in any single cycle group is less than 142 psi. (2.6 x 54.7)		
16	Close this MOS.		13 2-24-98

OSS Form 5175

Test Number	Date	Cycles	Results	Comments
#1	2/29/98	0	180 psi	
#2	2/29/98	0	183 psi	
#3	2/24/98	0	176 psi	
#4	1/29/98	100	178 psi	
#5	2/ 3/98	100	174 psi	
#6	2/ 6/98	100	190 psi	
#7	2/20/98	1000	184 psi	
#8	2/11/98	1000	145 psi	
#9	2/20/98	1000	186 psi	

Averages	Results
0 cycles	180 psi
100 cycles	181 psi
1000 cycles	172 psi

§178.CC-12 (c) (3) Creep Rupture Test

SCOPE: To perform the tests according to provisions of §178.CC-12 (c) (3) Design Qualification Tests as referenced in DOT-E 11739 dated Jan. 14, 1998.

Tests to be covered by this Report:

	Test Number	No. of Hours
Creep Rupture Tests (recorded in Lab Notebook #3 pages 6-7, 13, 39-40)	#1	1000
	#2	1000
	#3	1000
	Vessel #7	0
	Vessel #9	0
	#8	0

Items Included in Each Test:

Gluing Procedures (19801- 70018 & 19801 - 70020)

Test Setup (same as Cryo Cycling) **& Test Results**

Summary of Results:

A summary of the individual results and averages appears below. The averages have been extrapolated to 50,000 hours as required by the Acceptable Test Results §178.CC-13 (c) (2) with a result of 128 psi which is slightly below the acceptance criteria of 2.6 times the design pressure of 54.7 or 142 psi with no single value less than 2.5 times the design pressure or 137 psi (lowest single value was 131 psi). While these test results were slightly below the limits, there were consistent with the values that were obtained in other hydro (ambient) testing. The results were judged to be acceptable since no adverse creep characteristics were observed (permanent deformation) nor physical properties degradation (curve and extrapolation portion of the curve was almost flat over the entire time frame).

Test Number	Date	Hours	Results	Comments
Creep Test #1	6/18/97	1000	133 psi	
Creep Test #2	6/18/97	1000	131 psi	
Creep Test #3	6/18/97	1000	132 psi	
#8	6/25/97	0	136 psi	
Vessel #7	10/20/97	0	134 psi	
Vessel #9	10/20/97	0	139 psi	

Averages	Results
0 hours	136 psi
1000 hours	132 psi

§178.CC-12 (d) Outer Vessel Testing

SCOPE: To verify the design of the outer jacket that contains the pressure vessel (together called a dewar). Since that jacket has a vacuum contained between it and the pressure vessel, the jacket is designed to withstand a 30 psi external pressure without collapse. This is in accordance with §178.57-8 of CFR 49 and §178.CC-8 (c) as referenced in DOT-E 11739.

TEST EQUIPMENT:
A Production Dewar
Three (3) dial indicators (calibrated)
Pressure Chamber
Calibrated Pressure Gage

TEST PROCEDURE:
The production dewar is pressurized to the operating pressure of approximately 40 psig and capped off. The jacket is evacuated to a pressure of no less than 10^{-3} torr. The vessel assembly is strapped to a suitable test platform and instrumented with three (3) dial indicators to measure displacement at pre-selected locations (listed in test data sheet). The prepared test asembly is placed inside a pressure chamber capable of pressurizing to 30 psi. The chamber must allow for clear viewing of the dial indicators. Since the jacket is evaluated as indicated above, the test chamber is pressurized to 15 psi. This results in a total of 30 psi deferential pressure across the jacket. The chamber pressure shall be verified on a calibrated pressure gauge with an accuracy of no less than 1% (of full scale reading).

ACCEPTABLE TEST RESULTS:
The vessel will withstand the external pressure without evidence of collapse or loss of vacuum and no permanent deflection in excess of 0.01".

TEST DATA SHEET AND DISPOSITION OF TEST RESULTS:

§178.CC-12 (e) (1) Thermal Cycling Test

SCOPE:_To perform this test according to provisions of §178.CC-12 (e) (1) Design Qualification Tests as referenced in DOT-E 11739 dated Jan. 14, 1998.

ITEMS INCLUDED IN THIS REPORT:

Test Procedure

Test Data Sheets

Test Results

SUMMARY OF TEST RESULTS:

According to §178.CC-13 Acceptable Test Results included by reference in DOT-E 11739, there was no evidence of distortion, deterioration or failure after testing.

Thermal Cycling Test Procedure

Equipment To Be Used:

A Production Dewar
Pressure Control Hardware
Hot Fluid Bath (controlled to a temperature of 200°F)
Cold Fluid Bath (controlled to a temperature of -25°F)
Data Acquisition System - Computer
- Four (4) temperature sensors bonded to outer vessel
- One (1) cold bath temperature sensor
- One (1) hot bath temperature sensor
- One (1) vessel pressure sensor

Procedure:

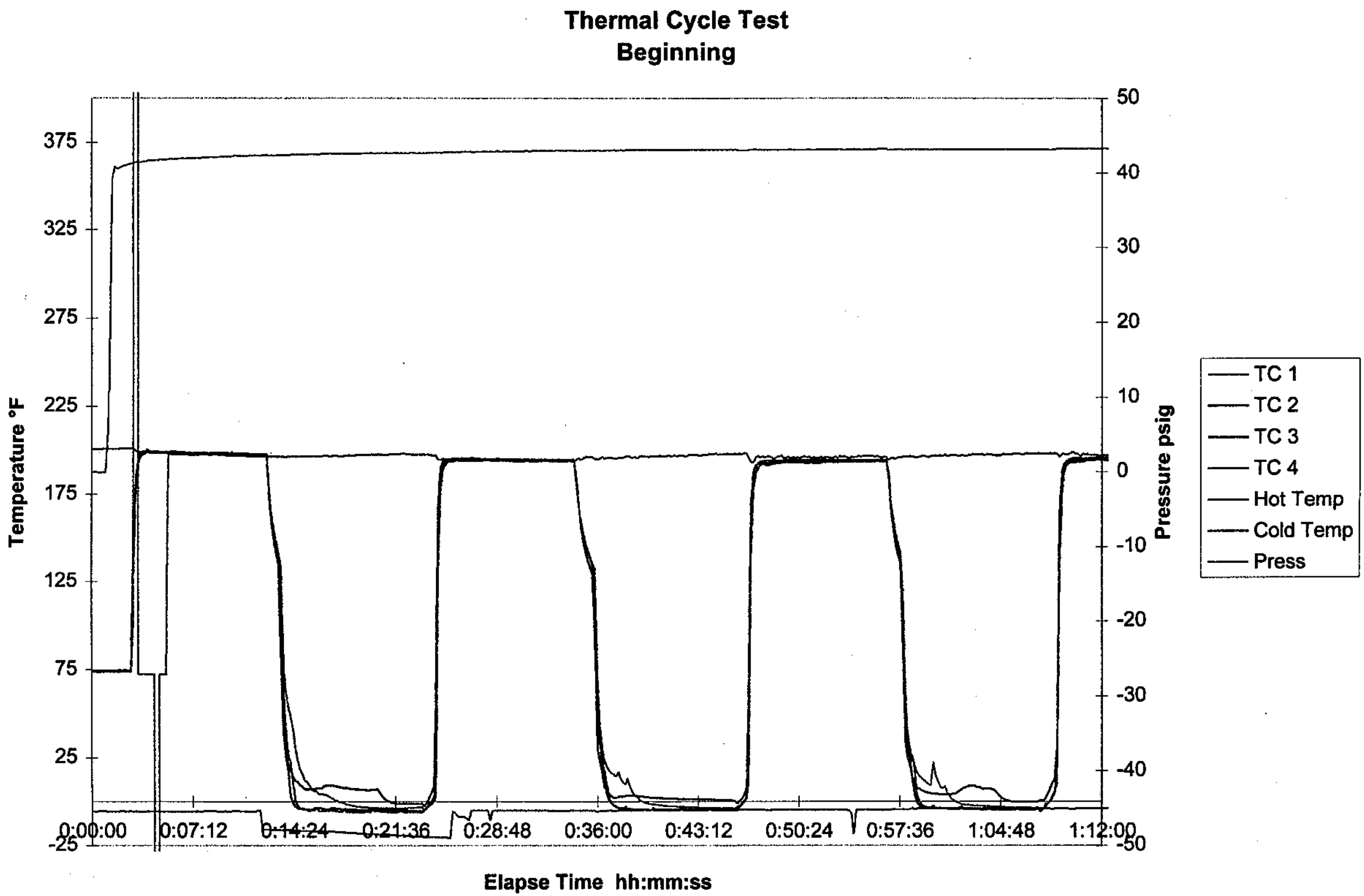
Stage 1: Initial Pump Down
1. Evacuate vessel down to a minimum 1 X 10^{-3} torr and allow to pump down until vacuum stabilizes when disconnected from vacuum pump.
2. Disconnect pump and leave overnight.
3. Recheck pressure (with vessel on pump).

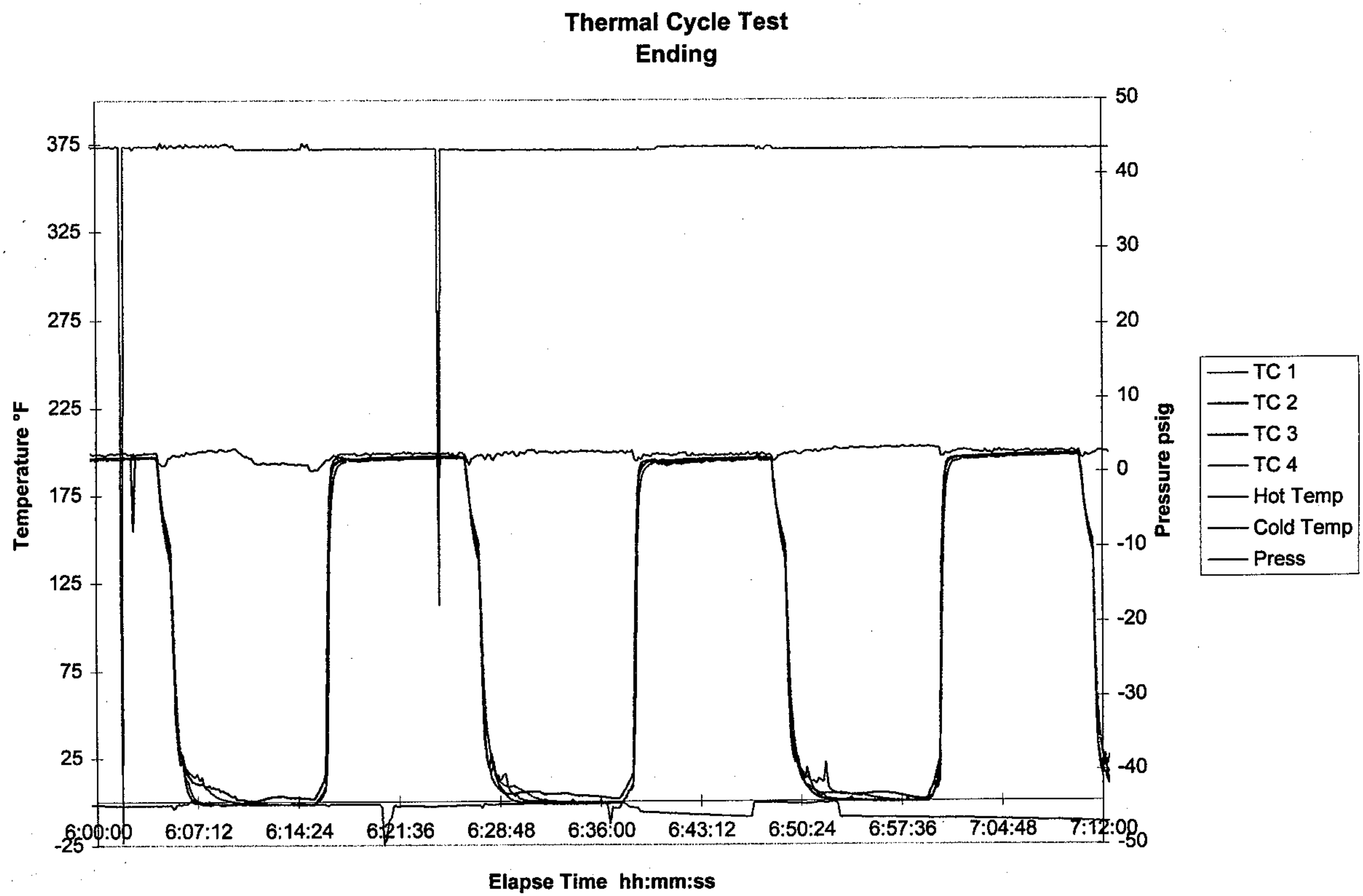
Stage 2: Equipmenmt set up
1. See schematic (vessel with instrumentation and pressure control hardware).
2. Set up tubes and wires from vessel to other components to minimize components in hot and cold environments.

Hot Fluid Bath
1. Set up specially prepared 55 gallon drum for hot bath (see picture).
2. Bath should be instrumented for temperature.
3. Bath should be brought up to temperature in advance of the test to allow the bath to stabilize.

Cold Fluid Bath
1. Set up specially prepared 55 gallon drum for cold bath (see picture).
2. Bath should be instrumented for temperature.
3. Bath should be brought down to temperature in advance of the test to allow the bath to stabilize.

Stage 3: Temperature Cycle Tests at Service Pressure
1. After vacuum is achieved in the vessel, connect vessel as specified in schematic and pressurize to service pressure (40 psig).
2. Start data acquisition system (at 1 sample per 10 seconds rate).
3. Submerge vessel in 200°F fluid bath, allow to soak for 10 minutes.


Thermal Cycle Test
Beginning
Temperature °F
375
325
275
225
175
125
75
25
-25
Pressure psig
50
40
30
20
10
0
-10
-20
-30
-40
-50
0:00:00
0:07:12
0:14:24
0:21:36
0:28:48
0:36:00
0:43:12
0:50:24
0:57:36
1:04:48
1:12:00
Elapse Time hh:mm:ss
TC 1
TC 2
TC 3
TC 4
Hot Temp
Cold Temp
Press


Thermal Cycle Test
Ending
Temperature °F
375
325
275
225
175
125
75
25
-25
Pressure psig
50
40
30
20
10
0
-10
-20
-30
-40
-50
6:00:00
6:07:12
6:14:24
6:21:36
6:28:48
6:36:00
6:43:12
6:50:24
6:57:36
7:04:48
7:12:00
Elapse Time hh:mm:ss
TC 1
TC 2
TC 3
TC 4
Hot Temp
Cold Temp
Press

STANDARDIZED LIQUID AIR PACK TEST FORM

This form allows for the standardized recording of basic test set-up data. Use one form for each test. Circle, cross out, or add appropriate data as required. It is important to provide details so that someone reading the logbook can tell what happened during this test. This form should be attached to the lab logbook. Actual test data and any additional pertinent information should be written in the lab logbook.

TEST DATE AND TIME 3/6/98
TEST CONDUCTOR Todd Upp
TEST ENGINEER John Fricker
PURPOSE OF TEST: *The engineer should fill out this section with enough detail to enable the test conductor to perform the test as desired. What are we trying to learn? (e.g., boil-off test, duration at NIOSH or NFPA, fill weight, capacitance gauge calibration, pressure control system evaluation, tilt test, manned test, deflection data, etc.) What data is being recorded? (e.g., cap gauge, breathing counts, duration, ullage pressure, check valve pressure, %O2, tilt, cryo weight, etc.) Provide a sketch if necessary.*

DOT Thermal Cycle Test, per written test plan. Dip dewar in 200°F bath. Then in -25°F bath for 20 cycles. Instrument dewar & bath with thermocouples, record once every 10 seconds.

more pics on back

3/6/98 DOT Thermal Cycle Test Set-up

1. Cold bath w/ dewar submerged
2. Data acquisition
3. Hot bath w/ foam lid

TEST DESCRIPTION: *Check box and record appropriate data.*
- ☐ 1 Hour/EG&G Dewar, s/n
- ☑ 2 Hour/AWPS Dewar, s/n Pack E
- ☑ Prototype Hardware
- ☐ Certified Hardware
- ☑ Vacuum condition ~~?~~ 6x10^-6 morning 3/6/98
- ☐ Pre-Chilled Vessel
- ☐ Hours Since Last Dewar Fill Days or weeks
- ☐ Breathing and Cooling
- ☐ Breathing Only
- ☐ Liquid Air Fill
- ☐ Liquid Nitrogen Fill
- ☐ PosiChek Breathing Machine s/n
- ☐ Other machine, describe
- ☐ Manned Test, name
- ☐ Engineer Sign-Off on Test Set-up JHF

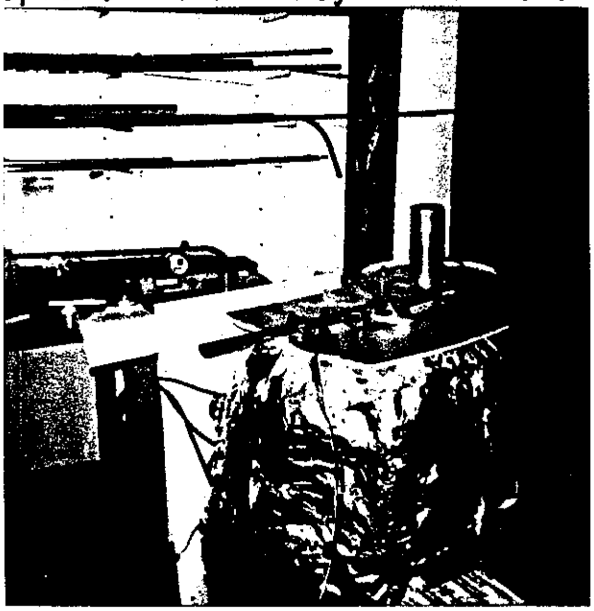
Other: *List serial numbers of components (IV, OV, tension rings, PCS), describe modifications to components, take a Polaroid or sketch setup, describe orientation of dewar, list any unusual aspects of the test, etc.*

~~See attached pages from DOT~~

Stage 3 ~~testing~~ temp. Cycle Tests at Service Pressure
1. After acceptable vaccum established take dewar to test setup
2. Pressurize dewar to 40 psig
3. Start data acquisition system set at 1 sample per 10 seconds
4. Submerge vessel in 200°F fluid bath, allow to soak for 10 min
5. Remove vessel from hot bath
6. transfer to cold bath, taking at least 1 min and less than 3 min
7. Submerge vessel in -25°F fluid bath, allow to soak 10 min
8. Remove vessel from cold bath
9. Transfer to hot bath taking at least 1 min and less than 3 min
10. Repeat steps 4-9 for a total of 20 cycles from hot bath to cold bath

[illegible]

3/6/98 DOT Thermal Cycle Hot Bath

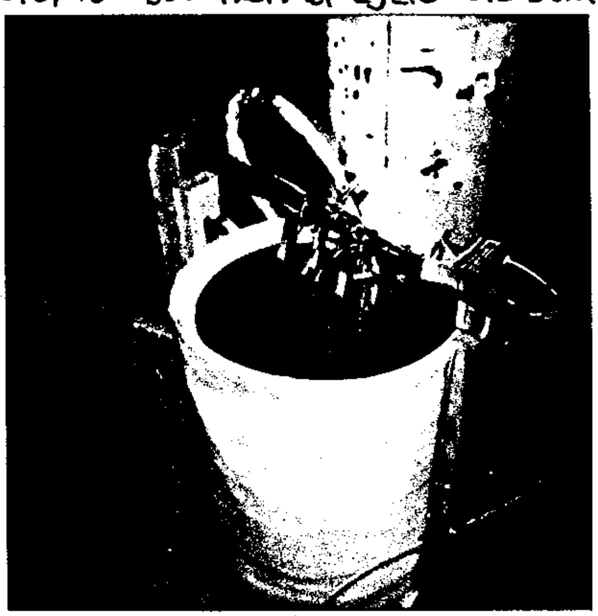


55 gal. drum filled with water plus ~1 gal anti freeze, Al. foil skirt to keep heat in, 3 band heaters around drum, foam lid.

3/6/98 DOT Thermal Cycle Hot Bath

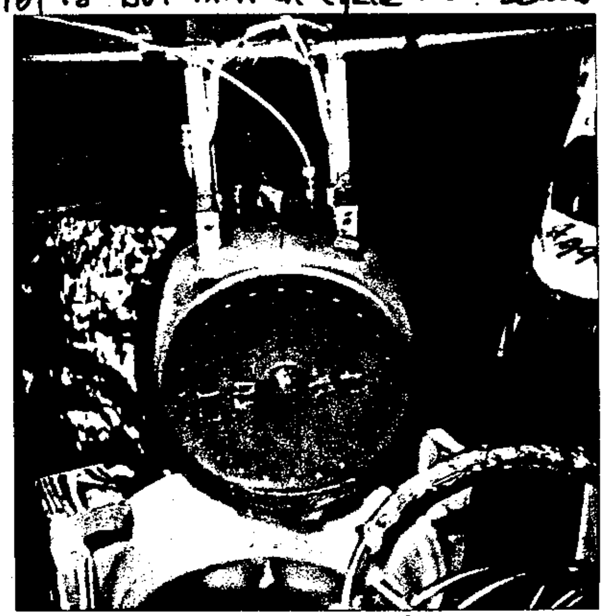
2hr. pack E bolted to T-bar handle, 40 psig operating press. instrumented with 4 Thermocouples. No P.S. system attached.

3/6/98 DOT Thermal Cycle Cold Bath



~30 gal drum filled w/ 50/50 antifreeze/water mix, insulated w/ wrapping foam. 15-30 lbs dry ice sunk in bath. Cryo heat exchanger in bath.

3/6/98 DOT Thermal Cycle Test Dewar



Pack E w/ Thermocouples

Test 3-6-1 .ASC

Thermal cycling Pack 'E' controller reads 203 200.7

1 12:20:36 place dewar in Hot tank ~~200~~ ~~cold~~ for 10 min
Punctured plate coil in cold bath. LN_2 causes bubbling in bath - still works

12:23:38 replugged in TC 4 which had become unplugged on initial immersion.

12:30:36 remove from Hot Bath let stand 1 min

12:31:36 place in cold Bath for 10 min

12:41:36 remove from cold let stand 1 min
2 12:42:36 Place in Hot Bath 10 min 197
12:52:36 remove from Hot Bath lets stand 1 min
12:54:00 place in cold Bath 10 min
1:04 remove from cold bath letstand 1 min
3 1:05 Place in hot Bath for 10 min
1:15 remove from ~~hot~~ Bath let stand 1 min
1:16 place in cold Bath F 10 min - 4.7°F
1:26 remove from cold Bath let stand 1 min
1:27 place in hot Bath for 10 min
1:37 remove from hot Bath let stand for 1 min
1:38 place in cold bath. For 10 min
1:48 remove from cold bath let stand for 1 min
1:49 Place in ~~cold~~ hot bath for 10 min
:59 remove from hot bath letstand for 1 min
:00 Place in cold bath for 10 min, temp -6.6
:10 remove from cold bath let stand 1 min
:11 place in hot bath for 10 mins
:21 remove from hot bath let stand for 1 min
:22 Place in cold bath for 10 mins
:32 remove from cold bath ~~for~~ letstand for 1 min
:33 Place in hot bath for 10 mins
12:43 remove from hot bath let stand for 1 min
2:44 place in cold bath for 10 min
:54 remove from cold bath letstand for 1 min
:55 Place in hot bath for 10 min

) 3:05 remove From hot bath let stand For 1 min
3:06 Place in cold bath for 10 min
3:16 remove from cold Bath let stand For 1 min
9 3:17 Place in hot bath for 10 min
3:27 remove From hot ~~cold~~ bath ~~let~~ stand For 1 min
3:28 Place in cold bath For 10 min
3:38 remove From cold bath ~~for~~ let stand For 1 min
10 3:39 Place in hot both For 10 min
3:49 remove from hot bath let stand for 1 min
3:50 Place in cold bath For 10 min
4:00 pm Remove From cold bath let stand for 1 min.
11 4:01 pm place in Hot Bath After Standing for 1 min.
4:11 pm Remove ~~R~~ From Hot Bath Let stand for 1 min
4:12 PM Place in cold bath for 10 mins
4:22 pm remove from cold bath let stand for min
12. 4:23 Place in hot bath for 10 min
4:33 remove from hot bath let stand for 1 min
) 4:34 Place in cold bath for 10 min
4:44 remove from cold bath let stand for 1 min
13 4:45 Place in hot bath For 10 min
4:55 remove from hot bath let stand for 1 min
4:56 Place in cold bath For 10 min.
5:06 remove from cold bath let stand for 1 min
14 5:07 Place in hot bath for 10 min
5:17 remove from hot bath let stand for 1 min
5:18 Place in cold bath for 10 min
5:28 remove from cold bath let stand for 1 min
15 5:29 Place in Hot Bath for 10 min.
5:39 remove from hot bath let stand for 1 min
5:40 Place in cold bath for 10 min
5:50 remove from cold bath let stand for 1 min
16 5:51 place in hot bath for 10 min.
6:01 remove from hot ~~bath~~ let stand for 1 min
6:02 place in Cold Bath for 10 min. After ~~ak~~ let stand for 1 min
) 6:12 Remove from Cold Bath let stand for 1 min
pressure (6:20) transducer was disconnected to change dewar
17 6:13 place in Hot Bath ~~for~~
6:23 Removed from Hot Bath let stand for 1 min
6:24 Placed in Cold Bath

6:34 Remove from Cold Bath let stand 1min.
18 6:35 Placed in Hot Bath for 10 min
6:45 remove from hot Bath let stand 1min
6:46 Place in cold Bath for 10 minutes
6:56 remove from cold Bath let stand for 1min
19 6:57 Place in hot Bath for 10 min
7:07 remove from hot Bath let stand for 1min
7:08 Place in cold Bath for 10 mins
7:18 remove from cold Bath let stand for 1min
20 7:19 Place in hot Bath for 10 min
7:29 remove from hot Bath let stand for 1min
7:30 Place in cold Bath for 10 min
7:40 remove from cold Bath end test.

Hot Bath was able to reach specified temperature & maintain. Cold Bath was only able to obtain -5.5 but was able to maintain this temp within 6° for the test duration

3-11-98 8:30 am put pack E back on vacuum pump vessel pressure was 3×10^{-3} torr. This pressure is ~~cons~~ consistant with normal vacuum loss of this vessel.

3/12/98 orientation test of pack E after thermal cycle.
vessel is plumbed w/no pcs only 2 valves fill & vent.
11:05 start Fill
11:15 Finish Fill close vent & Fill disconnect
1:00 start orientation test
1:01 open fill valve liquid out
rotate 180° pitch forward open fill valve liquid out
rotate 0° pitch open fill valve liquid out Both Fill & Vent
rotate 90° pitch forward open fill valve liquid out " " "
rotate 90° lt yaw open fill valve liquid out " " "
rotate 90° rt yaw open fill valve liquid out " " "
return to 0° pitch 0° yaw

~~[illegible]~~

drain for 20 sec repeat movements note any irregularities. ~~Functioned Normally in~~ liquid out vent & fill ~~all orientations.~~

drain for 20 sec repeat movements note any irregularities checked vent and found liquid at the same time as fill. will press to 40 psia and repeat. ~~As long as vessel is pressed to 25 psia and up unit functioned pickup mechanism~~ → vent & fill give liquid in all orientations. drain for 10 secs repeat

no cryo in vent at 0° pitch 0° yaw

rotate 180 pitch forward liquid at fill gas @ vent 25psi

Pitch 90° forward yaw 90° lt liquid at fill gas @ vent 25psi

" " " " rt " " " " " " "

~~drain for~~ rotate 0° pitch & 0° yaw drain for 10 sec

repeat movements. function Normal drain for 10 sec

repeat movements function normal drain for 10 sec

repeat movements function Normal drain for 10 sec

repeat movements function Normal

The results of the orientation test indicate that the pickup mechanism is functioning properly. But also indicate a broken or damaged vent belows. This belows is of the old design and have proved to be unreliable after continued use. The belows appear to fail during fill cycles.

4. Remove vessel from hot bath.
5. Transfer to cold bath, taking at least 1 minute and less than 3 minutes.
6. Submerge vessel in -25°F fluid bath, allow to soak for 10 minutes.
7. Remove vessel from cold bath.
8. Transfer to hot bath, taking 1 minute and less than 3 minutes.
9. Repeat steps steps 3-8 for a total of 20 cycles from hot bath to cold bath (each immersion in the hot bath starts a cycle).
10. Disconnect the vessel and check vacuum.

Thermal Cycle Test Results

<u>Discussion of Test results</u>:

Four temperature sensors were attached to the dewar in the locations indicated in the picture below.

TC 3
TC 4

TC 2
TC 1

Temperature Sensor Locations
Thermal Cycling Test

In order to be able to submerge the dewar into the fluids, it was necessary to attach the unit to a T-bar handle (see pictures) that was also used to transfer the vessel between the two baths.

A data acquisition system was used to collect the temperature readings at each second interval. That log is available for review, but due to the voluminous nature of that log, it is not included in this report; however the charts on the following pages reflect the actual data in graphic form (at the beginning of the test and at the end). It should also be noted that the cycling did not allow time for the recovery of the fluid baths so the temperatures in those baths gradually rose or fell whether the unit was placed in the cold or hot fluids respectively. A comparison of the beginning and end will illustrate this commentary.

Conclusion:

There was no visible deterioration or distortion of the dewar. It had the same vacuum throughout the thermal cycling test duration. It met the acceptance criteria established by the Acceptable Test Results, §178.CC-13 (e).

Pictures:

§178.CC-12 (e) (2) Bonfire Test

SCOPE: To perform this test according to the Bonfire Test established in §178.CC-12 (e) (2) Design Qualification Tests as referenced in DOT-E 11739 dated Jan 14, 1998.

Items Included in This Report:

Test Setup and Instrumentation

Test Data Sheet

Test Results

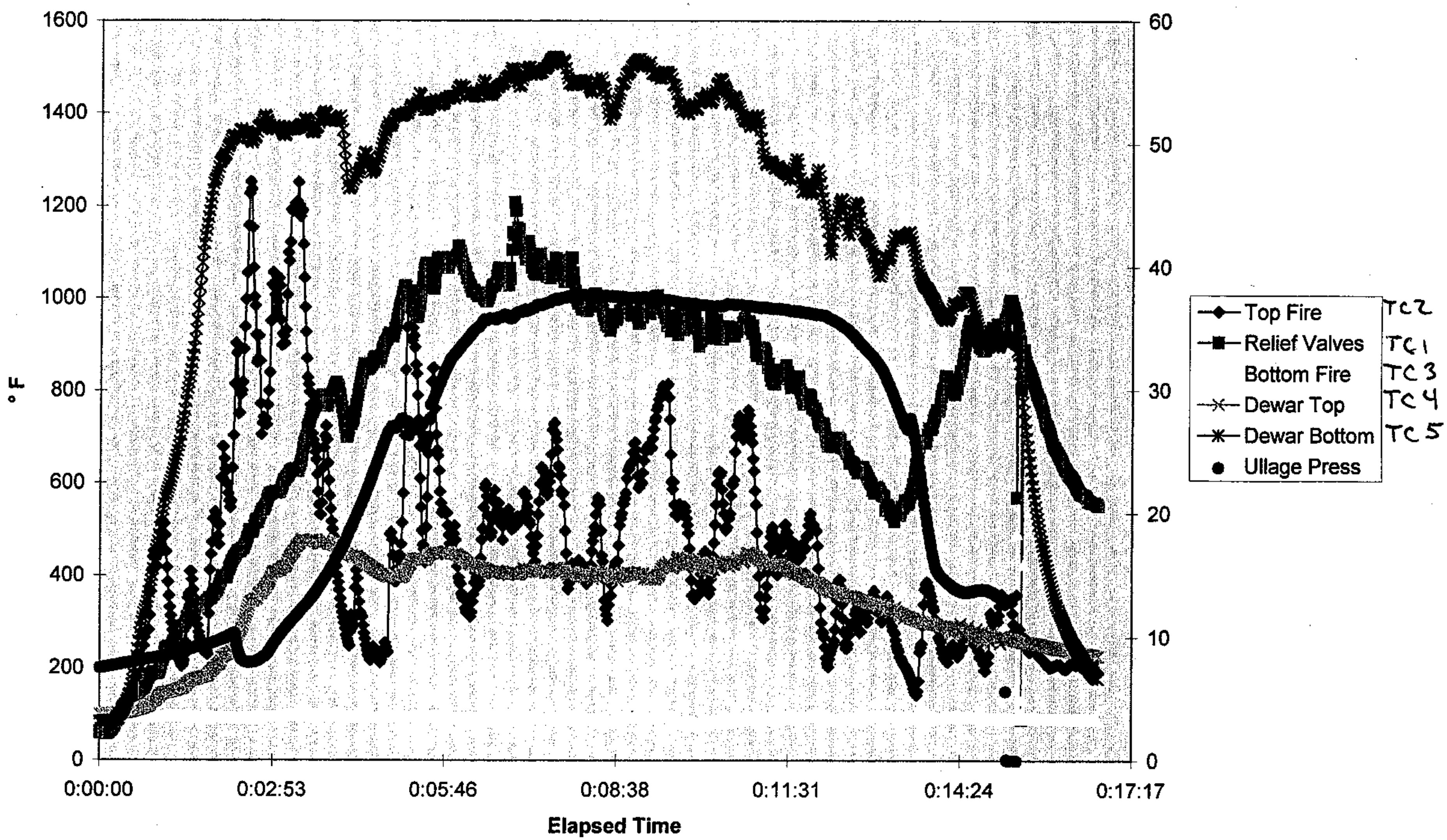
Summary of Test Results:

According to §178.CC-13 (f) Acceptable Test Results, the pressure relief valves functioned properly by preventing rupture of the dewar. There was secondary venting from the vacuum pump-out plug which was not unexpected once the vacuum was lost in the insulating jacket provided by the outer vessel and the heat leak affected the LCP (plastic) inner vessel; however, there was no rupture of the outer vessel. Pressure inside the inner vessel never rose above 52 psig. Secondary venting occurred about mid way in the burn.

A video tape of the actual burn at the Houston Fire Department Training Academy is included with this report as supplemental documentation.

There is also a series of pictures that were taken in the postmortem to document the containment of the inner vessel failure by the outer vessel.

Burn Test 2


1600
1400
1200
1000
800
600
400
200
0
°F
60
50
40
30
20
10
0
0:00:00
0:02:53
0:05:46
0:08:38
0:11:31
0:14:24
0:17:17
Elapsed Time
Top Fire TC2
Relief Valves TC1
Bottom Fire TC3
Dewar Top TC4
Dewar Bottom TC5
Ullage Press

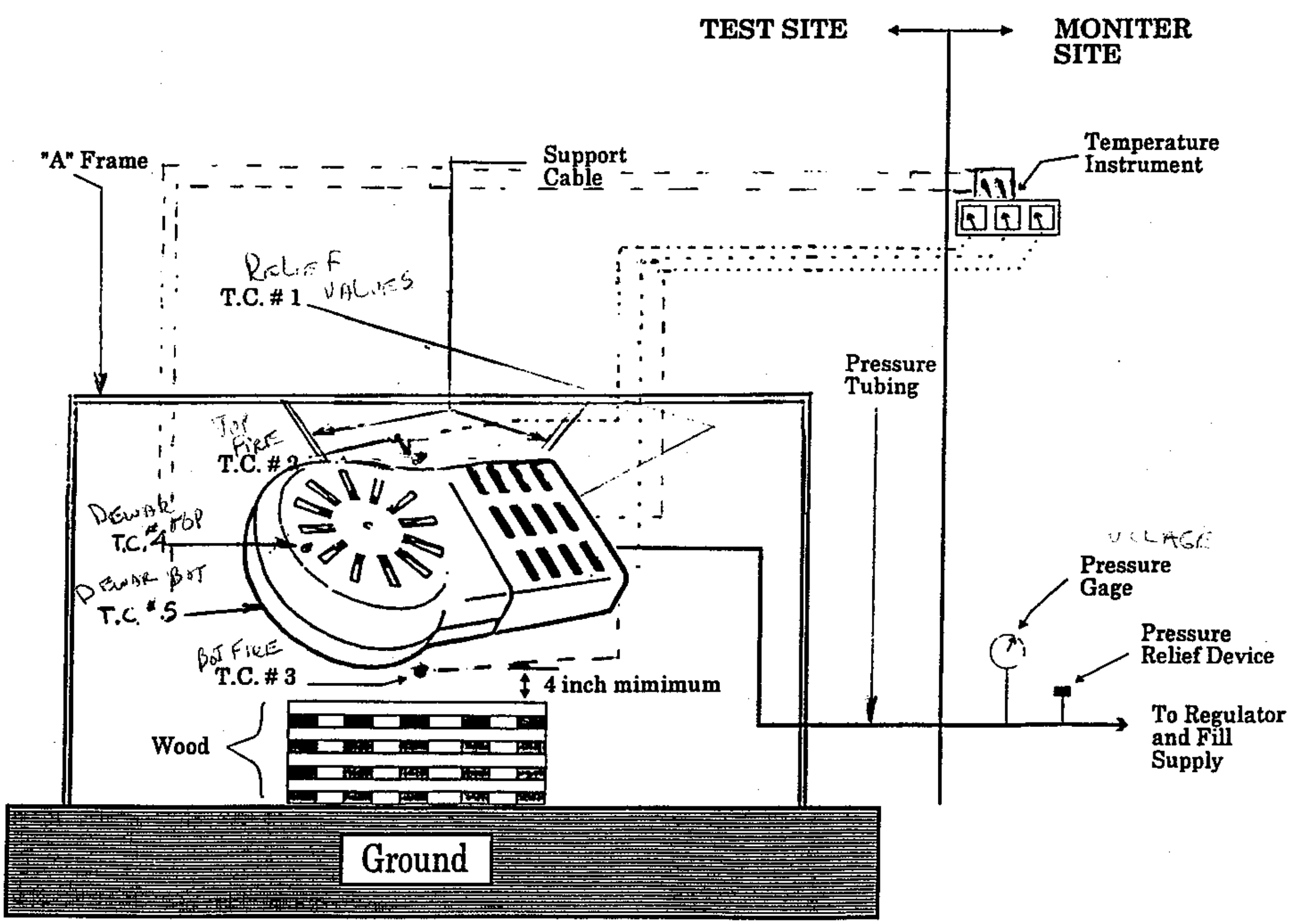
BONFIRE TEST PLAN & METHOD

Site Preparation:
At the Houston Fire Department Training Academy, located at 8030 Braniff.

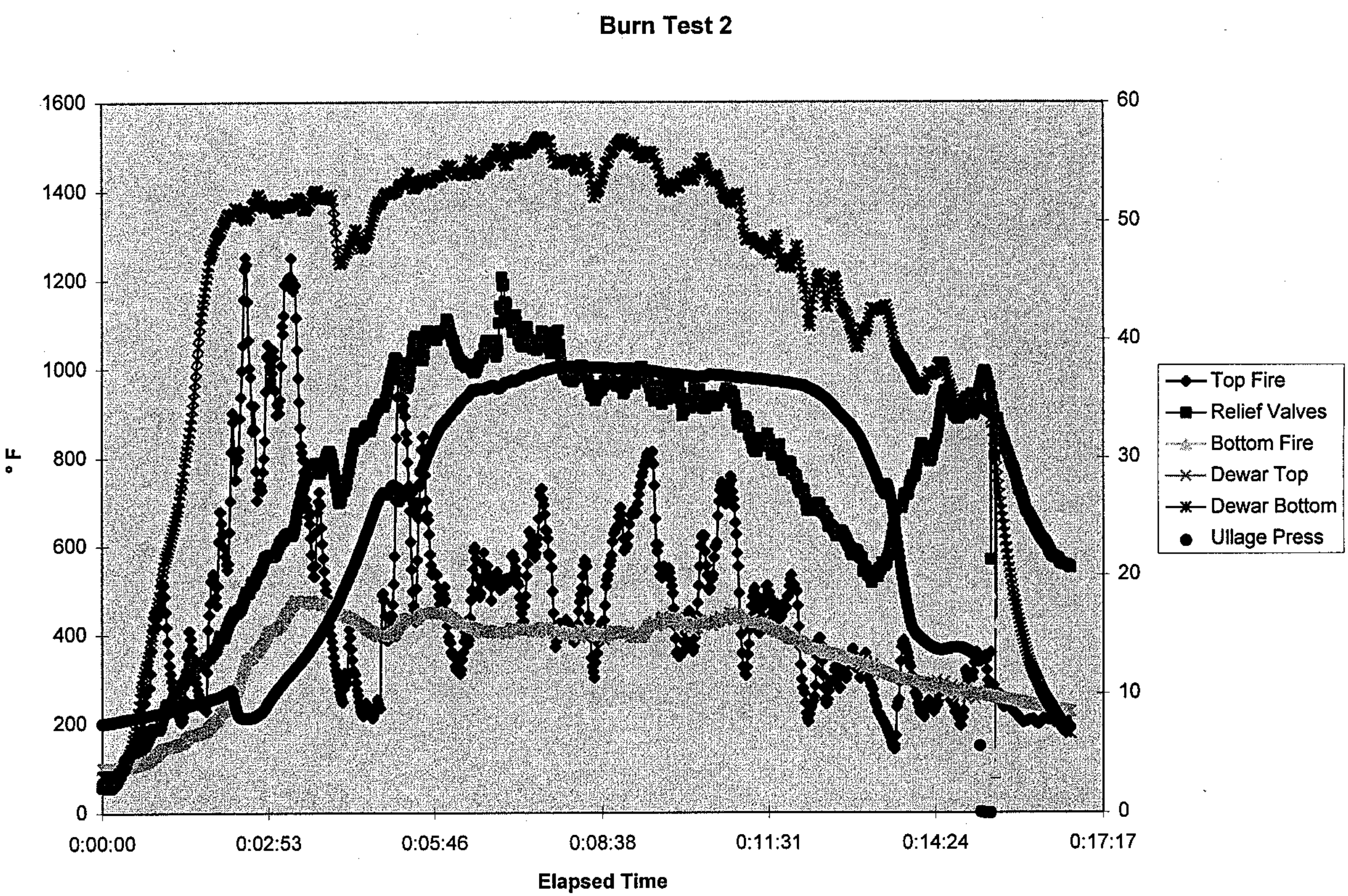
The *Wood:* it must be dry and sized approximately 1 in. X 2 in. X 30 inches for two (every other) layers and 1 in X 2 in. X 15 inches for the other two (every other) layers. It should be equally cross-stacked to comprise an approximate 4 in. high X 15 in. wide X 30 inches long rectangular shape which should be large enough to insure complete envelopment of the dewar and assure a burn time of at least 15 minutes. The unit must be located a minimum of 4 inches from the stack. The stack should weigh approximately 10 pounds.

The *Kerosene:* Two quarts should be applied to the wood stack in a uniform manner and allowed to absorb for approximately 2 minutes prior to ignition.

The *Test Setup:*



DRAWING OF WOOD BONFIRE TEST


Burn Test 2
1600
1400
1200
1000
800
600
400
200
0
° F
60
50
40
30
20
10
0
0:00:00
0:02:53
0:05:46
0:08:38
0:11:31
0:14:24
0:17:17
Elapsed Time
Top Fire
Relief Valves
Bottom Fire
Dewar Top
Dewar Bottom
Ullage Press

Bonfire Test Procedure

Site Preparation:
At the Houston Fire Department Training Academy, located at 8030 Braniff.

The *Wood:* it must be dry and sized approximately 1 in. X 2 in. X 30 inches for two (every other) layers and 1 in X 2 in. X 15 inches for the other two (every other) layers. It should be equally cross-stacked to comprise an approximate 4 in. high X 15 in. wide X 30 inches long rectangular shape which should be large enough to insure complete envelopment of the dewar and assure a burn time of at least 15 minutes. The unit must be located a minimum of 4 inches from the stack. The stack should weigh approximately 10 pounds.

The *Kerosene:* Two quarts should be applied to the wood stack in a uniform manner and allowed to absorb for approximately 2 minutes prior to ignition.

The Test Setup:

Schematic of Wood & Bonfire Test

The Test Equipment: the positioning of the five (5) thermocouples should be; one sensor at each side (top and bottom as pictured in the diagram) of the outer vessel and one near the pressure relief valve. Of the two (2) remaining sensors, one should be placed between the wood stack and the unit to measure the heat of the burn while the other should be above the unit to measure the flue affect of the burn surrounding the unit. T.C.#3 will insure that the fire has reached 1200°F in 5 minutes or less. T.C. #2 will indicate how well the burn is enveloping the outer vessel. T.C. #1 will indicate the temperature that the relief valve will see throughout the burn. T.C. #4 and #5 will be placed on the outside surfaces (top and bottom) of the outer vessel respectively.

The Thermocouples should be secured by heat resistant epoxy to insure proper insulation. They should also be connected to a suitable instrument capable of indicating temperatures attained during the testing.

A pressure indicating gauge shall be connected to the valve outlet via standard connections to permit remote monitoring and recording of attained pressure levels. A manual valve shall be installed into the pressure monitoring system to allow venting of the vessel contents in the event of test equipment or system malfunction.

*Note from C-14 §6.8: If required, relief device shields, valve caps, or other protective devices shall be installed.

The *Test:* make sure the following pertinent information is recorded as a minimum:

- Vessel information (size, material, serial number, etc.)
- Relief valve type and rating- location and orientation
- Date of test and location
- Type of cryogen
- Ambient conditions (temperature and RH)
- Charging information (pressure, etc.)
- Estimated wind conditions/direction
- Names of witnesses
- Pressure/temperature readings

Steps:

1.) Prepare test setup as per diagram

2.) Verify the proper installation and function of instrumentation

3.) Verify that all pertinent information (as described above) has been recorded

4.) Charge the dewar with cryogen to the maximum authorized limit ('normal charge")

5.) Note final pretest pressure in the dewar and starting temperatures at all sensor locations.

6.) Ignite fuel and record starting time

7.) Record ullage pressures and temperatures at specified locations at 30 second intervals for the duration of the test

8.) At the initial functioning of the relief valve, the pressure and temperatures shall be recorded. The fire shall be maintained for an additional 15 minutes or until the pressure in the ullage is approximately 0 psig, whichever occurs first

9.) Elapsed time to complete test shall be recorded

10.) In the event that the pressure relief valve does not function within a 10 minute period, and/or if the noted temperature and pressure readings indicate that the fire is waning, the test shall be aborted by safely venting the contents of the dewar. In this event, a retest must be conducted

The *Acceptance Criteria*: the pressure relief valve shall function preventing rupture of the dewar. Secondary venting from locations other than the pressure relief valve is not considered a failure, and retest is not required.

A localized split without propulsion is not considered a failure, but retest is required.

If the dewar becomes dislodged from its test position in a manner as to reduce its exposure to the fire, the test must be aborted and a retest initiated with a new dewar (if the original dewar has been compromised.

Discussion of Test Results:

The unit was fabricated according to the schematic that is made a part of this report to show the location of the relief valves. The two (2) 45 psig relief valves are located downstream of the Pressure Closing Valve (PCV) while the 80 psig relief valve is located upstream of the PCV to address potential abnormal pressure fluctuations in those respective configurations (possible over pressurization of the inner vessel ullage and possible over pressurization of the cryogen vaporizing upstream of the PCV).

Chart 1 on the following page has the results of the five thermocouples that were attached to the unit or located in the fire stream (see "key" for exact locations). The left hand "x" axis is in degrees F. The right hand axis is in "psig" that was used to measure pressure inside the inner vessel throughout the test.

The unit was charged with liquid nitrogen from a dewar that was delivered to the site prior to the test. The inner vessel was allowed to self pressurize for the test; that is why it started at approximately 22 psig instead of the operating pressure of 40 psig. Because of the heat involved, it was known that the inner vessel would get up to that pressure rather quickly in the sequence of events; this was borne out as the pressure achieved 40 psig within the first two minutes of the test. The pressure never went beyond approximately 52 psig when the inner vessel failed and the pressure dropped to zero at about 7 minutes into the test. The video bares this out, because it is at the time when the outer vessel expended and secondary venting occurred thought the pump-out plug. Prior to this <u>all</u> the venting occurred through the relief valves (which can be heard on the audio portion of the tape).

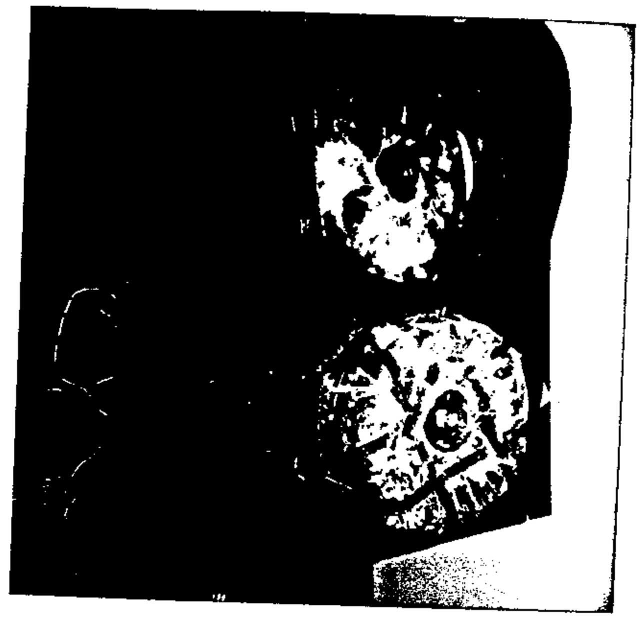
The temperature immediately below the unit reached 1375° F within the prescribed 5 minutes (actually within 2 minutes), while the top was somewhat controlled by the wind (SW at 14 mph) reaching a maximum temperature of 1300° F even though a three sided "A" frame was fabricated for the test. The maximum temperature reached in the fire approached 1600° F for almost 10 minutes of the prescribed fifteen minute burn.

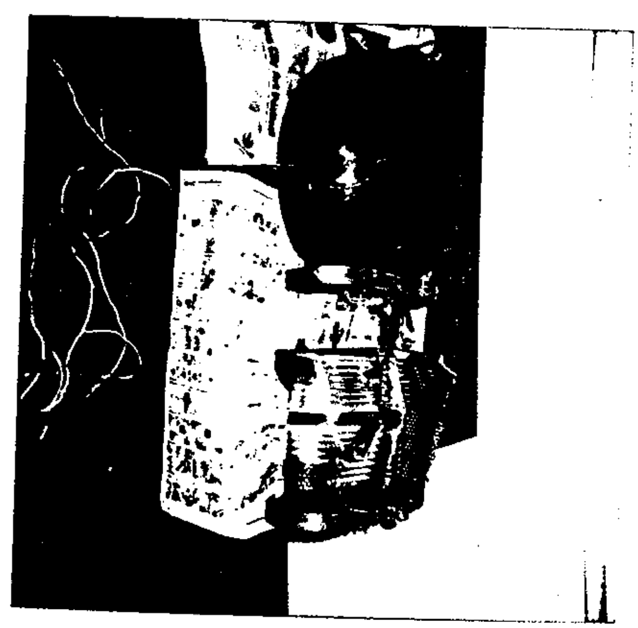
There is a series of pictures that are also included that demonstrate a postmortem on the burned unit. It seems to bear out the results that are seen in the video as well as those recorded from the computer data acquisition system that was used to log the thermocouples temperatures and pressure readings. The sequence of pictures shown the following:

- The total unit as exposed
- The dewar cut open to expose inside

<u>Conclusions</u>:

The test was deemed successful by the criteria established from the CGA Document C-14- 1992 for a Bonfire Test.





Appendix C: Bottom Box Components and Layout

Cryopack Transition Packet - Pressure Control System

Functional Description

The pressure control system for the Cryopack utilizes higher pressure air to supply the dewar when the ullage pressure drops below a set point (see attached functional schematic). As the users breathes, cryogen is withdrawn from the inner vessel through the vaporizer check valve. The withdrawn cryogen boils and the increasing pressure seats the vaporizer check valve, preventing back flow into the inner vessel (which would cause venting through the low pressure relief valve and a slow increase in oxygen percentage during us The higher pressure air goes through the vaporizer and ambient heat exchanger (AHX), where it is warmed to a breathable temperature. e). In the event that the vaporizer check valve fails closed, the bypass check valve allows cryogen to bypass the vaporizer and be provided directly to the AHX. The warmed air is delivered through the shutoff valve to the mask and regulator. Some of the air also is supplied from between the AHX and shutoff valve to the pressure control system

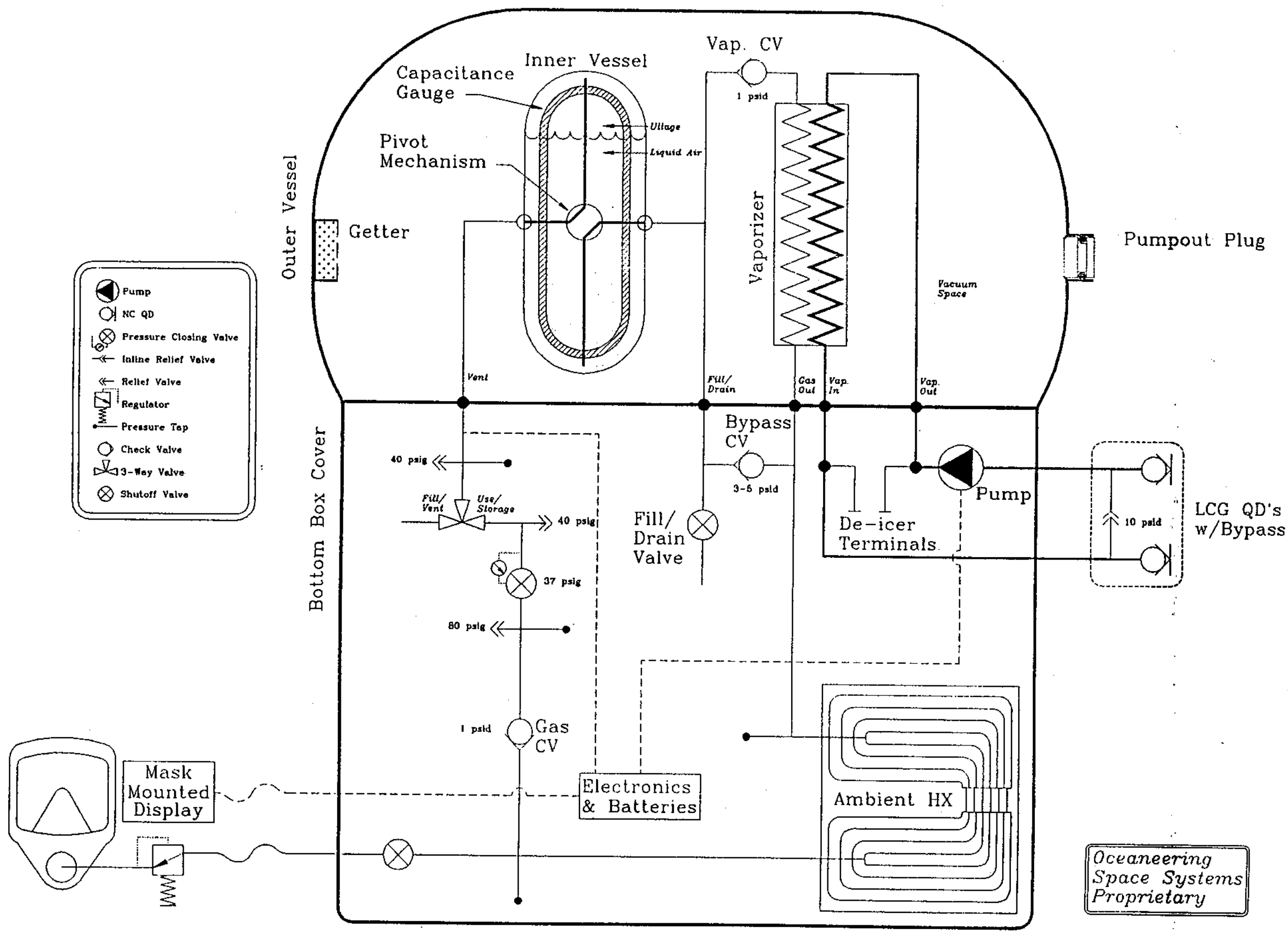
The vent line coming out of the dewar communicates with the ullage in the inner vessel via the pivot mechanism. Excess pressure is relieved through the low pressure relief valve. There is a secondary relief valve as well that may be replaced by a burst disc. The vent line goes to the inlet of a three-way valve. During recharge, the backpack is filled with liquid air though the fill/drain valve and vented though one side of the three-way valve. After filling is complete, the fill/drain valve is closed and the three-way valve is turned to "pressurize". The downstream side of the pressure control valve (PCV) communicates with the ullage through the three-way valve. When the ullage pressure drops below the set point, the pressure control valve opens allowing higher pressure air from the AHX to flow to the ullage. There is a gas check valve on the supply side of the pressure control valve to prevent ullage gas from being withdrawn backwards through the PCV when the AHX pressure is lower than the ullage pressure and the PCV opens. A high pressure relief valve is located between the gas check valve and the PCV to protect that section in the event it becomes a trapped cryogen section and also to protect the AHX from over pressurization.

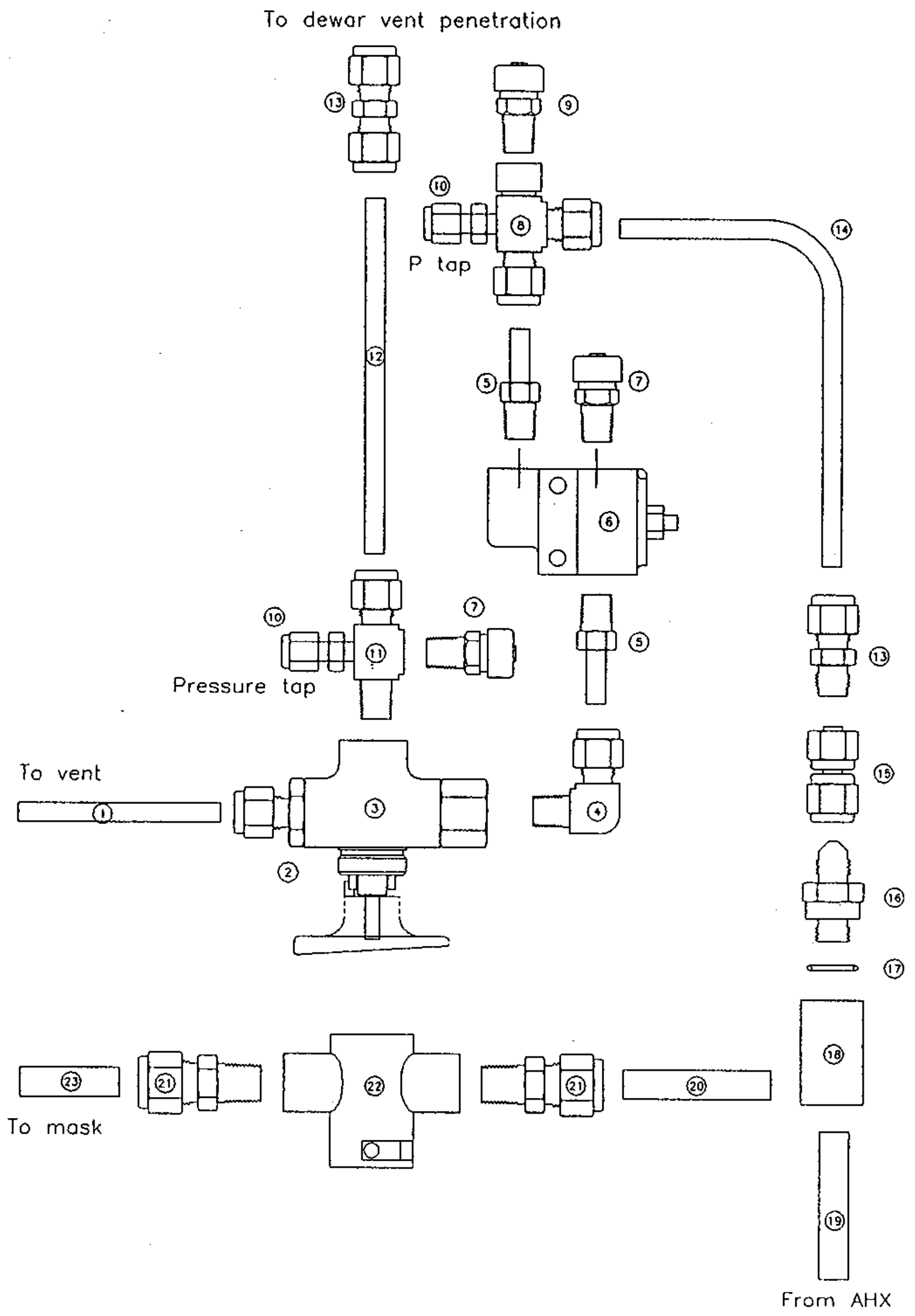
Summary

Currently the pressure control system has been tested without the bypass check valve and meets the NFPA and NIOSH performance requirements. Tests with the bypass check valve have shown some startup problems, but these are most likely due to valving in the system for the test and the associated pressure drop. The tests will be conducted again without the valving and the results are expected to be acceptable.

The issues still involved with the pressure control system are production and reliability-related. The components need to be redesigned for reduced weight and smaller packaging. The cost of some of the components is probably not suitable, even in production quantities. However, one of the bigger issues is to specify and design components that are reliable through the number of pressure and thermal cycles to which they will be subjected, particularly the relief valves, three-way valve, and fill/drain valve. Specifying components for these three functions should be the highest priority. These components should then be integrated into a package/manifold of the desired weight and size. The assembly needs to be designed and tested to ensure it achieves the current level of flow and pressure performance.

Liquid Air Backpack r/Vaporizer Bypass Functional Schematic – 5/21/96





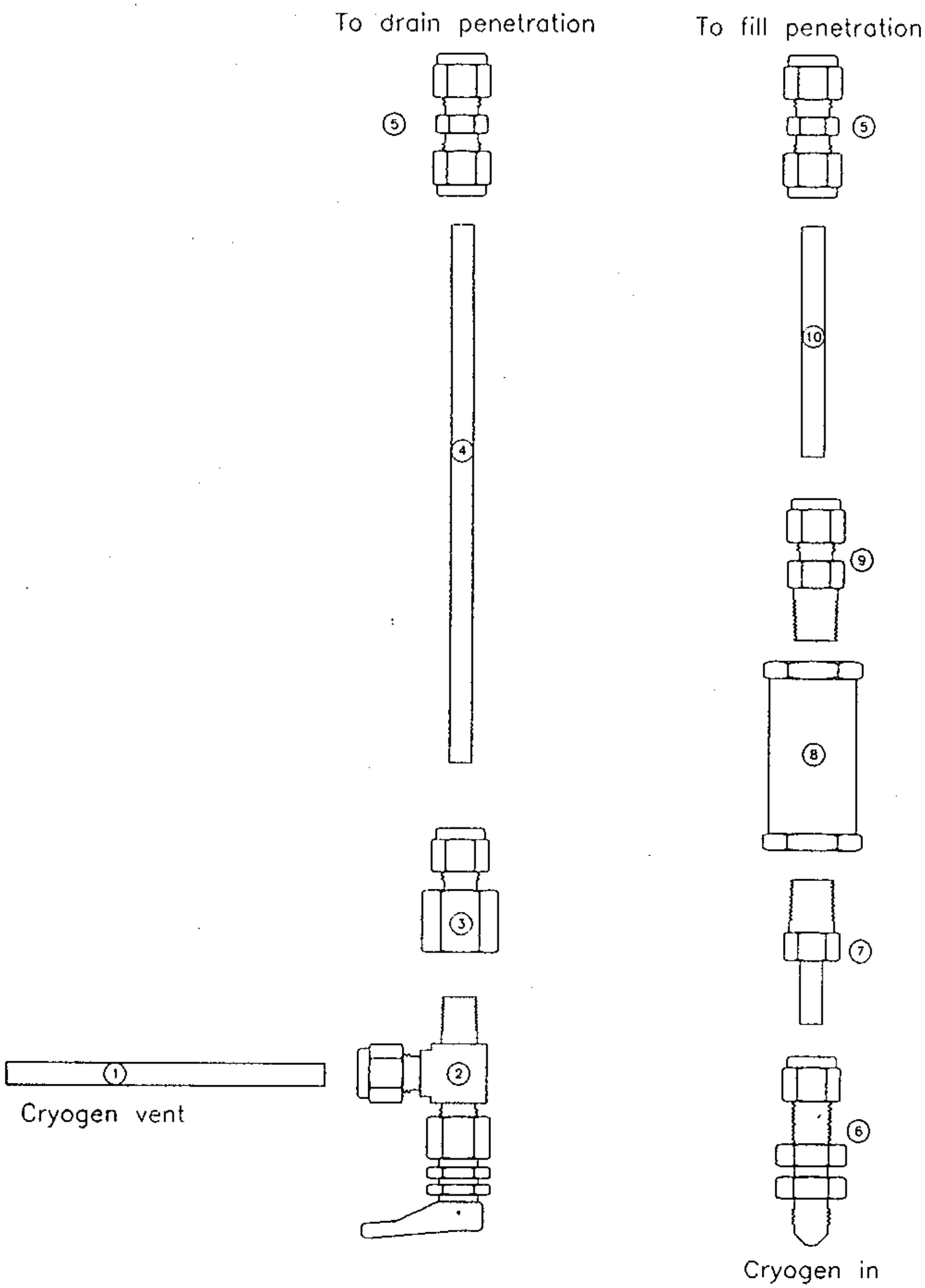
IUOE Pressure Control Part List and Assembly Diagram (6/11/96)

1. 1/4" Al tube, vent
2. Custom Al 3-way valve adapter
3. 3-way valve
4. 1/4" NPT to Swagelok elboe, A-400-2-4
5. 1/8" NPT to 1/4" tube adapter, A-4-TA-1-2
6. PCV
7. 45 psig relief valve, Circle Seal
8. Modified 1/8"NPT to 1/4" Swagelok female run tee, A-400-3TFT
9. 80 psig relief valve, Circle Seal
10. 1/8" Swagelok to 1/4" tube reducer, A-200-R-4
11. Modified 1/8" NPT to 1/4" Swagelok male run tee, A-400-3-4TMT
12. 1/4" Al tube, return to dewar
13. 1/4" Swagelok union, A-400-6
14. 1/4" plastic flex line to AHX
15. 1/4" AN to 1/4" Swagelok adapter, A-400-A-4ANF
16. Modified 3/8" AN Gas check valve, Precision Valve
17. 2-014 o-ring
18. Custom aluminum manifold block
19. 3/8" Al tube to AHX
20. 3/8" Al tube to shut off valve
21. 3/8" male connector, A-600-1-6
22. Shut off valve
23. 3/8" Al tube, gas out to mask

Special note: #11 in future will be a modified female branch tee with a male connector between it and the 3-way valve.

Fittings #8 and #11 are modified as follows:
#10 fittings are trimmed to 0.25" long stub after nut and then welded into 1/4" holes cut in #8 and #11.
Also, the branch on #11 is turned off and tapped w/ 1/8" NPT

IUOE Fill and Drain lines Part List and Assembly Diagram (6/7/96)

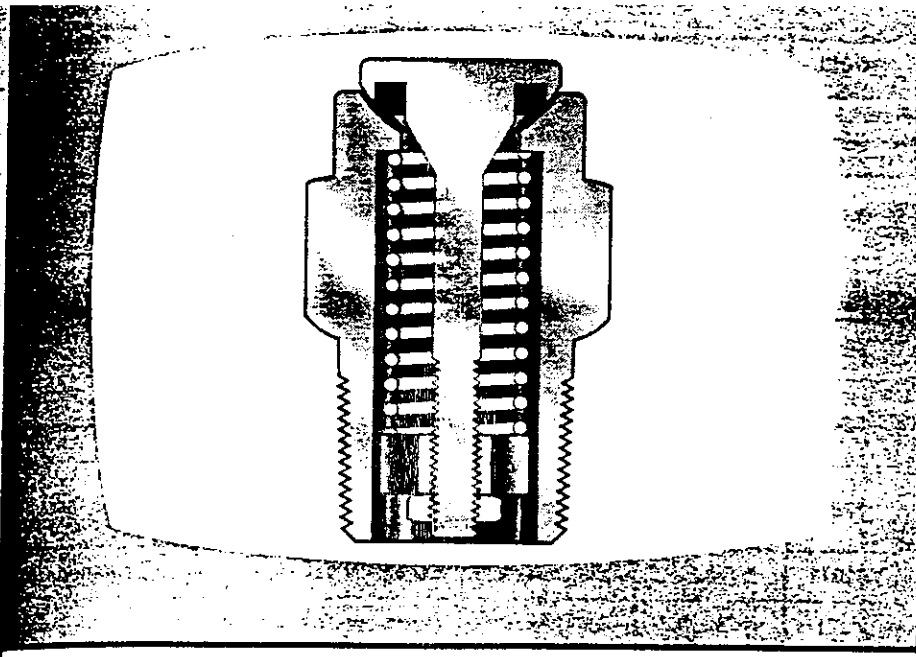


1. 1/4" Al tube, vent
2. Drain toggle valve, Macro technologies
3. 1/8" NPT to 1/4" Swagelok female connector, A-400-7-2
4. 1/4" Al tube, drain line
5. 1/4" Swagelok union, A-400-6
6. 1/4" AN bulkhead union, SS-400-61-4AN
7. 1/4" male adapter, A-4-TA-1-4
8. 1/4" check valve, Circle Seal
9. 1/4" male connector, A-400-1-4
10. 1/4" Al tube, fill line

Special note:
Entire fill line assembly covered with insulation.

1) Comp: Low Pressure Relief Valve (40 psig @ 60°F)
   Vendor: Circle Seal (& Macro Technology)
   Descript: This relief valve is the primary relief device for the dewar pressure. It is located between the 3-way valve and the PCV. It also serves to relieve that section in the event there is cryogen trapped there when the 3-way valve is turned to vent. Because this valve protects the dewar and can get cold during venting, it must operate consistently into the cryogenic temperature range.
   Issues: The Circle Seal relief valves (500 series, popoff) that have been in service in the backpack have not proven reliable. They are supposedly rated down to -320°F but they consistently fail in two common ways. The first is that once the relief valve begins to vent, the poppet "leans" to one side. Frost then builds up on the rest of the valve. Moisture and frost buildup between the poppet and seat then prevent the valve from reseating or cause it to open more, dropping the dewar pressure. This problem was worse when we using the versions with the domed deflection cap, but still occurred after they were removed. The other problem is that over time, the seal on the poppet deforms and begins to leak at pressures below the set point. Trying to reset the valve does not provide satisfactory results. I have talked to Jeff Zabrokrisky at Circle Seal, and his answer was basically 'of course they begin to leak over time, they were never designed to work at those low pressures.' It seems that they will work at higher pressures (90+ psig) because the spring force makes the Teflon seal. At lower pressures, there is not enough force on the seal once it begins to deform. As for the frost causing the valve to fail open, he suggested putting a cap around it to keep it dry, but the seal failure overshadows the frost problem. Macro Technology makes a relief valve almost identical to the Circle Seal one for about a quarter the cost, so we have basically been swapping them out as they fail.

   Essex Cryogenics makes a relief valve that has proven much more reliable for use at cryogenic temperatures but its lowest normal set point is 80 psig. We have had Essex deliver some to us with settings as low as 60 psig, but the valve will not work below that without redesign to a bellows component inside. The relief valve is larger and heavier than the circle seal ones, but we have never had a problem with them.



CIRCLE SEAL CONTROLS

RELIEF VALVES
500 Series

Popoff, inline
.5-150 PSI

OPERATING CHARACTERISTICS

ZERO LEAKAGE — to 95-98% of cracking pressure.

INCREASED SEALING EFFICIENCY — as pressure increases. Resilient "Q" ring seal is forced against metal seat as pressure increases up to set cracking pressure.

CRACKING PRESSURE ACCURACY — Valves can be preset to required cracking pressure.

WIDE RANGE — of cracking pressures, without sacrificing flow characteristics, provided through interchangeable springs and simple adjustment. (See replacement springs and adjusting information.)

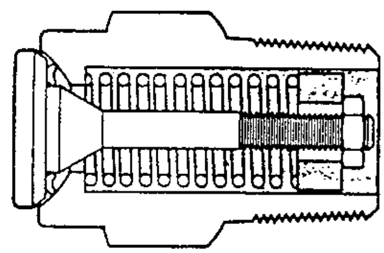
TAMPER-PROOF ADJUSTMENT — Adjustable only from inlet side for safety against tampering. Permits precise setting for the most exacting system requirements.

STICKING ELIMINATED — Poppet head provides metal seat on low pressure side of seal, limits squeeze on resilient seal ring. Prevents water and dirt from entering valve.

LONG, MAINTENANCE-FREE SERVICE — Parts will not wear out in normal service. Overhaul, if necessary, is quickly made by replacing resilient seal.

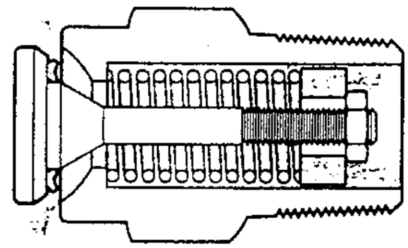
VARIATIONS — Vent to atmosphere or inline connections, various materials.

HOW IT WORKS



CLOSED

Resilient seal design prevents leakage. Sealing efficiency increases with increased pressure up to cracking pressure. Metal to metal seat on low pressure side supports spring load, prevents sticking.



OPEN

When system pressure overcomes spring force poppet opens momentarily exposing variable orifice between poppet and body to pass increasing flow with minimum pressure rise without blowdown.

RESEALING

Resilient seal automatically establishes line of contact with spherical seat. Seal provides dead tight reseal very close to cracking pressure.

CIRCLE SEAL CONTROLS, INC.
2301 WARDLOW CIRCLE
P.O. BOX 3300
CORONA, CALIFORNIA 91718

CIRCLE SEAL

CONTROLS

RELIEF VALVES
500 Series

Popoff, inline
.5-150 PSI

SERVICE RECOMMENDATIONS

MODEL NUMBER	O-RING MATERIAL	OPERATING TEMPERATURE	SUITABLE FOR
559	Buna N	-40° to +250°F	General Purpose, Air, Acetylene, Ammonia, Freon 12, Hydrogen, Inert Gases
532	Viton	-20° to +400°F	Aromatic Fuels, Synthetic Oils, Solvents, Carbon Tetrachloride, Toluene, Trichloroethylene, Steam
533	Neoprene	-40° to +250°F	Oxygen, Helium, Air, Hydrogen, Carbon Dioxide, Nitrogen, Acetylene
562	Ethylene Propylene	-65° to +300°F	Skydrol, Air, Steam
524	Silicone	-65° to +400°F	Air, Chlorinated Transformer Oil, Oxygen. Not available for cracking pressures above 74.9 PSI
520	Teflon	-100° to +400°F	Chemically inert. Suitable for nearly all fluids. Not available for cracking pressures below 2.5 PSI
K520T1	Teflon	-320° to +165°F	Especially assembled and LOX cleaned
580T1	Teflon	-320° to +165°F	No cryogenic processing

TECHNICAL DATA

MATERIAL................ Body and internal parts—bar stock

SPRING .... Stainless steel 302 or 17-7Ph

RESILIENT SEAL .... See service ommendations

OPERATING PRESSURE...0-200 PSI Satisfactory for vacuum applications

CRACKING PRESSURE....5-150 PSI Higher cracking pressures available—please check with factory. (Cracking pressure is defined as 5 cc/mi. with gas, except for 520 Series for which flow is 0.02 SCFM.) **NOTE:** See exceptions for Teflon and Silicone under Service Recommendations.

FOR INLINE VALVES:
PROOF PRESSURE ....400 PSI
BURST PRESSURE .. Above 500 PSI

ADJUSTMENT .... Adjustment is on inlet side, and cannot be tampered with after valve is installed.

†Alpha Code is for Circle Seal internal use only.

HOW TO ORDER

D 559 A-6MP-10

PART NUMBER DESIGNATION

VARIATION IDENTIFICATION
D— Prefixed Part Number is supplied with a cap which diverts high pressure blasts from personnel and instruments. Serves as a rain and dust shield. Increases flow capacity and facilitates manual override.
NOT RECOMMENDED FOR CRACKING PRESSURES BELOW 2 PSI
K—Cryogenic service (stainless steel valves only) (Specially manufactured, cleaned and tested for cryogenic temperatures)

BASIC MODEL NUMBER

MATERIAL
A—Aluminum **T1**—Stainless, 316
B—Brass

END CONNECTIONS—INLET/OUTLET
(size in 1/8")
M—Male pipe **P**—Female pipe

CRACKING PRESSURE—Specify setting in psi.

CRACKING PRESSURE INFORMATION

1M thru 2M & 2MP thru 3MP			3M thru 12M & 4MP thru 10MP		
CODE†	C.P. SETTING	C.P. RANGE	CODE†	C.P. SETTING	C.P. RANGE
A	0.5	.2-.9	A	1	.5-2.4
B	1	1.0-2.3	B	4	2.5-5.9
C	4	2.4-5.5	C	10	6.0-13.9
D	10	5.6-13.9	D	20	14.0-31.0
E	20	14.0-27.9	E	50	31.0-72.9
F	30	28.0-33.9	F	100	73.0-150.0
G	55	34.0-74.9			
H	90	75.0-104.9			
J	125	105.0-147.9			

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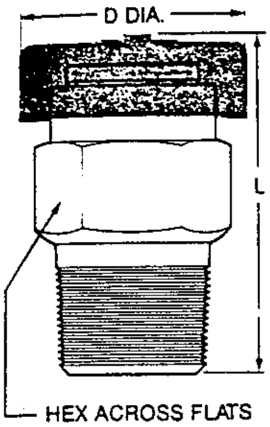
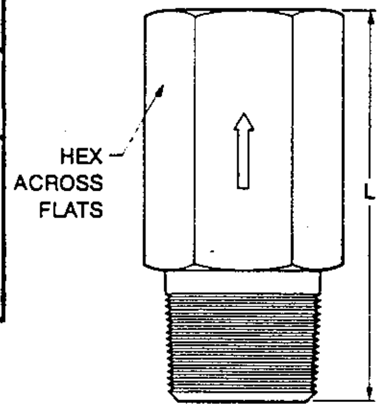


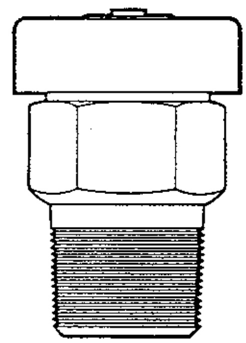
VENT TO ATMOSPHERE DIMENSIONS			
PIPE SIZE MALE	L	HEX	D DIA. MAX
⅛	1.14	½	.63
¼	1.38	⅝	.90
⅜	1.43	¾	1.21
½	1.98	1	1.45
¾	2.31	1⅛	1.45
1	3.16	1½	1.89



INLINE DIMENSIONS		
PIPE SIZE MALE & FEMALE	L	HEX
¼	1.62	¾
⅜	2.08	⅞
½	2.34	1⅛
¾	2.72	1¼
1	3.62	1½
1¼	4.67	1⅞

*Complete part number must include cracking pressure. See chart on previous page.

MATERIAL AND STYLE		SIZE	MODEL NUMBER			
			559	533	532	524
ALUMINUM	POPOFF	⅛	559A-1M-*	533A-1M-*	532A-1M-*	524A-1M-*
		¼	559A-2M-*	533A-2M-*	532A-2M-*	524A-2M-*
		⅜	559A-3M-*	533A-3M-*	532A-3M-*	524A-3M-*
		½	559A-4M-*	533A-4M-*	532A-4M-*	524A-4M-*
		¾	559A-6M-*	533A-6M-*	532A-6M-*	524A-6M-*
		1	559A-8M-*	533A-8M-*	532A-8M-*	524A-8M-*
	INLINE	¼	559A-2MP-*	533A-2MP-*	532A-2MP-*	524A-2MP-*
BRASS	POPOFF	⅛	559B-1M-*	533B-1M-*	532B-1M-*	524B-1M-*
		¼	559B-2M-*	533B-2M-*	532B-2M-*	524B-2M-*
		⅜	559B-3M-*	533B-3M-*	532B-3M-*	524B-3M-*
		½	559B-4M-*	533B-4M-*	532B-4M-*	524B-4M-*
		¾	559B-6M-*	533B-6M-*	532B-6M-*	524B-6M-*
		1	559B-8M-*	533B-8M-*	532B-8M-*	524B-8M-*
	INLINE	¼	559B-2MP-*	533B-2MP-*	532B-2MP-*	524B-2MP-*
		⅜	559B-3MP-*	533B-3MP-*	532B-3MP-*	524B-3MP-*
		½	559B-4MP-*	533B-4MP-*	532B-4MP-*	524B-4MP-*
		¾	559B-6MP-*	533B-6MP-*	532B-6MP-*	524B-6MP-*
		1	559B-8MP-*	533B-8MP-*	532B-8MP-*	524B-8MP-*
		1¼	559B-10MP-*	533B-10MP-*	532B-10MP-*	524B-10MP-*
316 S.S.	POPOFF	⅛	559T1-1M-*	533T1-1M-*	532T1-1M-*	524T1-1M-*
		¼	559T1-2M-*	533T1-2M-*	532T1-2M-*	524T1-2M-*
		⅜	559T1-3M-*	533T1-3M-*	532T1-3M-*	524T1-3M-*
		½	559T1-4M-*	533T1-4M-*	532T1-4M-*	524T1-4M-*
		¾	559T1-6M-*	533T1-6M-*	532T1-6M-*	524T1-6M-*
		1	559T1-8M-*	533T1-8M-*	532T1-8M-*	524T1-8M-*
	INLINE	¼	559T1-2MP-*	533T1-2MP-*	532T1-2MP-*	524T1-2MP-*
		½	559T1-4MP-*	533T1-4MP-*	532T1-4MP-*	524T1-4MP-*
		¾	559T1-6MP-*	533T1-6MP-*	532T1-6MP-*	524T1-6MP-*



For ASME code valve, available in ¼ inch size only. Add ASME after valve number. For operation details see ASME Valve catalog sheet, Form Number CSP-366L.

REPLACEMENT SPRINGS**

C.P. RANGE	1M/2MP	2M/3MP	C.P. RANGE	3M/4MP	4M/6MP	6M/8MP	8M/10MP
0.2-0.9	22335-0.5	22336-0.5	.5-2.4	10362-1	10462-1	10662-1	10845-1
1.0-2.3	22335-1	22336-1	2.5-5.9	10362-4	10462-4	10662-4	10845-4
2.4-5.5	22335-4	22336-4	6.0-13.9	10362-10	10462-10	10662-10	10845-10
5.6-13.9	22335-10	22336-10	14.0-31.0	10362-20	10462-20	10662-20	10845-20
14.0-27.9	22335-20	22336-20	31.1-72.9	10362-50	10462-50	10662-50	10845-50
28.0-33.9	22335-30	22336-30	73.0-150.0	10362-100PH	10462-100PH	10662-100PH	10845-100PH
34.0-74.9	22335-55	22336-55					
75.0-104.9	22335-90PH	22336-90PH					
105.0-147.9	22335-125PH	22336-125PH					

**Springs for each valve size are interchangeable. The Cracking Pressure range can be changed by replacing the spring with one covering the desired range.

CIRCLE SEAL CONTROLS, INC
2301 WARDLOW CIRCLE
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CORONA, CALIFORNIA 91718

HEX
¾
⅞
1
1¼
1½
1⅞

CIRCLE SEAL CONTROLS

RELIEF VALVES
500 Series
Popoff, inline
.5-150 PSI

ADJUSTING INFORMATION

Two tools for adjusting cracking pressure range are listed in the chart below; the adjusting tool, 10086 and nut driver, 10087. Use them as follows:

1. Remove Valve from service.
2. Fit proper size adjusting tool (see chart below) over the spring guide (3-fingered spider) in the inlet end.
3. Place nut driver (10087) inside the adjusting tool (10086) and loosen lock nut. Remove nut driver leaving adjusting tool engaged with spider nut. Press down on valve housing to compress spring, causing poppet to raise above housing seat. Turn poppet head with your fingers clockwise or counter clockwise to increase or decrease cracking pressure.
4. On inline models (500-*MP) proceed as in step 3 until it is necessary to turn poppet head. Insert screwdriver into slot in poppet head and turn screwdriver clockwise or counter clockwise to increase or decrease cracking pressure.

NOTE: Older models, which do not have a slot in the poppet head, require the use of a wood spacer, secured by a pipe plug, to hold poppet while adjusting.

5. Test for desired adjustment.
6. Hold spring seat spider nut stationary with adjusting tool and cinch lock nut against spider with nut driver after desired setting is obtained.
7. Retest to be sure adjustment is not changed.

ADJUSTMENT TOOLS

SIZE	1M/2MP	2M/3MP	3M/4MP	4M/6MP 6M/8MP	8M/10MP
ADJUSTING TOOL NUT DRIVER	10086-1 10087-1	10086-2 10087-2	10086-3 10087-3	10086-4 10087-4	10086-5 10087-5

REPLACEMENT PARTS

ORDER REPAIR KIT: GIVE COMPLETE MODEL NUMBER, SIZE & CRACKING PRESSURE

CRACKING PRESSURE — RESEAL CHARACTERISTICS

CRACKING PRESSURE
STANDARD SEALS AND SILICONE .... 5 cc/min.
TEFLON ....0.02 scfm
CRACKING PRESSURE TOLERANCE .... ±5%
Cracking pressure on initial crack may be higher than cracking pressure tolerance due to inherent characteristics of seals.

LEAKAGE Below Cracking Pressure:
STANDARD SEALS.............. 0 to lower limit of tolerance
SILICONE (524) & EPR (562) ..... 0 to 80% of cracking pressure
TEFLON (520) .... 1 cc/min. to reseal pressure
10 cc/min. max. with gas from reseal to cracking pressure

ch size
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MP

0
0
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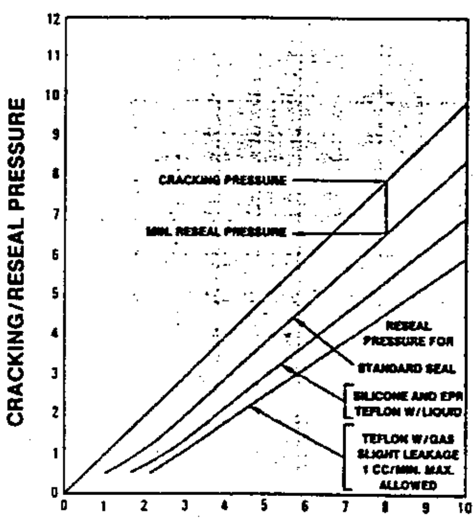
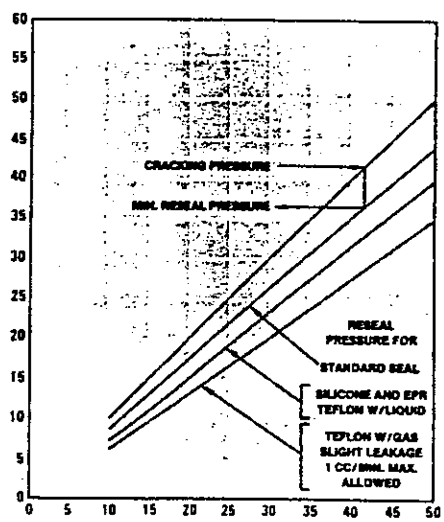
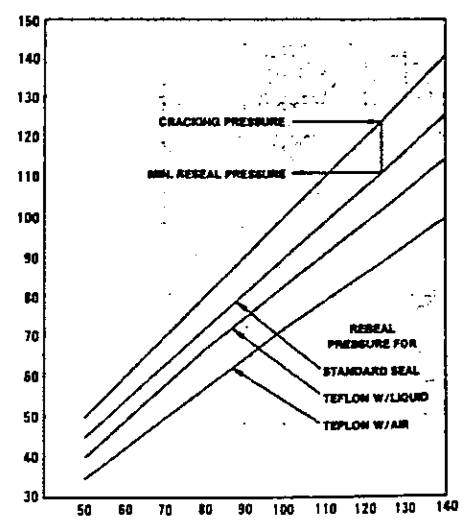


CRACKING PRESSURE—PSI



CRACKING PRESSURE—PSI



CRACKING PRESSURE—PSI

INC.

CIRCLE SEAL CONTROLS, INC.
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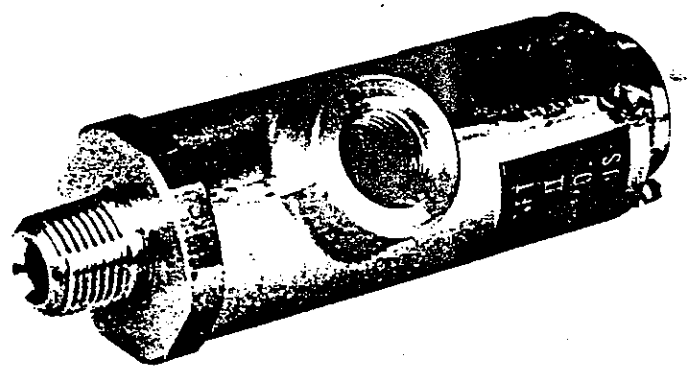
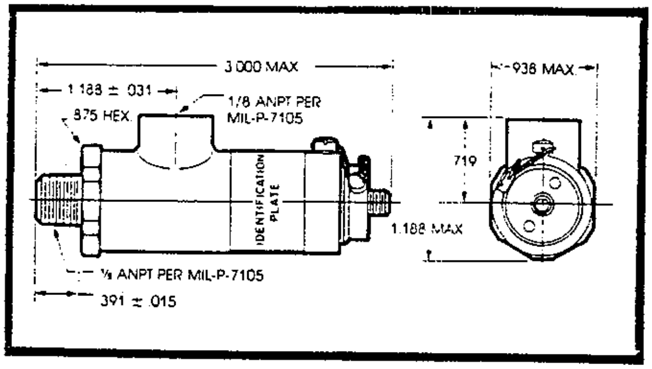
CORONA, CALIFORNIA 91718

CRYOGENIC VALVES



RELIEF VALVES

part no. 20C-0050 series



The 20C-0050 series Relief Valves are designed for use on Air Force and Navy liquid oxygen converters and other cryogenic systems.

The valves are manufactured to meet all the requirements of MIL-V-9050.

The relief valve construction features a stainless steel ball and a Teflon seat arrangement which provides zero leakage at re-seat pressures and ample area for flow in excess of 100 liters per minute at the high end of the operating range.

Other valve features include ANPT threaded inlet and outlet ports, internal filter and corrosion resistant steel construction.

The valves are available in a wide range of pressure settings to accommodate a variety of present system requirements.

Maximum weight in this series is approximately 2.50 ozs.

PART NO.	MIL SPEC. AND TYPE	OPERATING RANGE
20C-0050-1	MIL-V-9050, Type I	80-100 PSIG
20C-0050-2	MIL-V-9050, Type II	100-120 PSIG
20C-0050-3	MIL-V-9050, Type III	330-380 PSIG
20C-0050-4	MIL-V-9050, Type IV	380-430 PSIG
20C-0050-5	MIL-V-9050, Type V	120-140 PSIG

ESSEX CRYOGENICS OF MISSOURI, INC.
a subsidiary of Essex Industries, Inc.
8007 Chivvis Drive • St. Louis, MO 63123
PH (314) 832-8077
Telex 44-2310 • TWX 910-761-1165

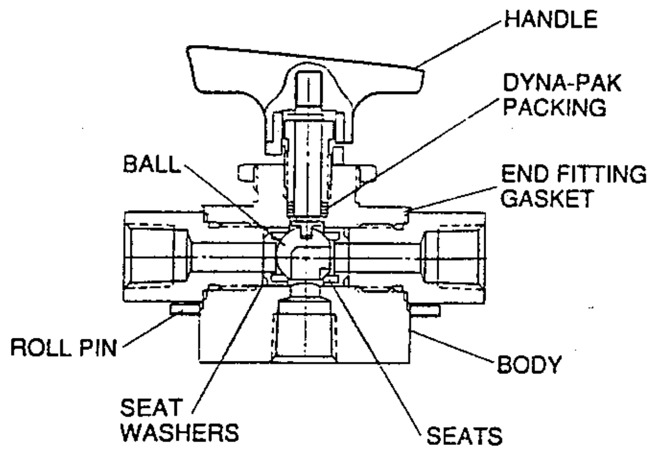
2) Comp: Three - Way Valve
Vendor: Hoke or Essex Cryogenics
Descript: This valve diverts flow to a vent during fill, and therefore will have liquid air flowing through it and must be cryogen compatible. When turned to vent, it also prevents the liquid from flowing through the vaporizer during fill. Basically, testing has shown that if the line from the pressure control system were not blocked during fill, liquid would flow into the vaporizer, venting through the pressure control system, in addition to filling the dewar. By using a 3-way valve, some of the cryogen flows into the vaporizer, boils, and prevents any more from entering. Also, the valve preferably has no "middle closed position." If the valve can be turned to a middle position where the inlet is deadheaded, a second relief valve is required between the dewar and the valve to protect the dewar.
Issues: There have been two three-way valves that have been used in the backpack. One is a Hoke 3-way ball valve that is not rated down to cryogenic temperatures but will work for a reasonable amount of time. The biggest problem with Hoke valve seems to be that during use, frost builds up on the valve and valve stem. Then the frost melts and seeps into the packing when the valve is not in use. When it has cryogen flowing through it again, the moisture freezes, seizing up the valve handle and damaging the packing. After repeated cycles, the packing begins to leak pressure. Also, the ball seat begins to wear after repeated thermal cycles and pressure will begin to leak around to ball to the vent.

The other is an Essex "shuttle" valve that is rated for liquid oxygen service but is not design to handle repetitive cycles with short down times. The valve utilizes a cam on the valve stem to move a shuttle along the valve body to seal one outlet or another. This valve has a similar problem to the Hoke valve. Frost and moisture buildup on the cam and freezes after repeated uses, seizing the cam or reducing its travel. This prevents the valve shuttle from moving into a sealing position.

HOKE Ultramite™ 7065 Series Ball Valves With Fixed End Connections

TECHNICAL DATA

Maximum operating pressure:	Moderate vacuum to 500 PSIG (3.4MPa)
Maximum operating temperature range:	0° to 350°F (-18° to 179°C)
Orifice:	.187 (5mm)
Cv range:	.15 to .66
End connections:	1/4", 1/8"- 3/8" Gyrolok

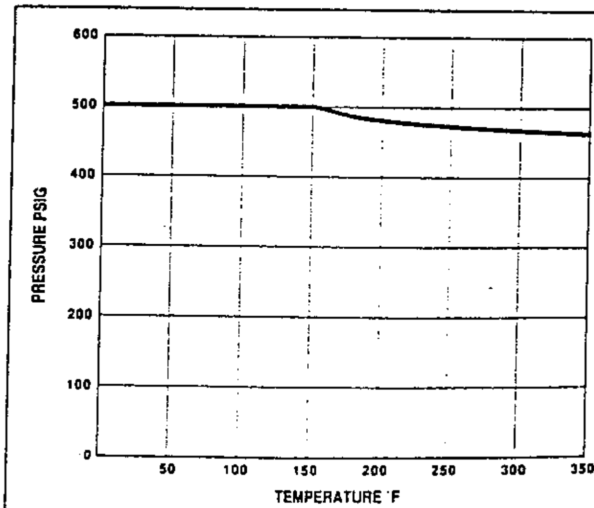


7065F4B

MATERIALS OF CONSTRUCTION	Brass	316SS
Body	Brass	316SS
Ball	316SS	316SS
Seats	Teflon	Teflon
Seat Retainers	Brass	316SS
Seat Washers	Teflon	Teflon
Stem Packing "Dyna-Pak"	Teflon & 316SS Wafers	Teflon & 316SS Wafers
End Fittings Gaskets	Teflon	Teflon
Handle	Nylon	Nylon

BENEFITS	FEATURES
Design	Roll pins secure end fittings
Compatibility	Teflon seats and washers for excellent corrosion resistance
Bi-directional Leaktight Sealing	Dual encapsulated Teflon seats and microfinished ball
Visual Flow Indication	Quarter-turn handle indicates on-off
Installation Variety	Gyrolok® tube fittings or pipe-ended models
Safety Handle	Oval trip-proof handle helps prevent accidental actuation
Remote Actuation	Electric and pneumatic actuators *See Hoke Actuated Valve Catalog for details.*
..dy Material Choice	Select from brass or 316SS

PRESSURE-TEMPERATURE CURVE



HOKE Ultramite™ 7065 Series Ball Valves With Fixed End Connections

VALVE ORDERING CHART

7065 SERIES FIXED ENDS — .187 ORIFICE

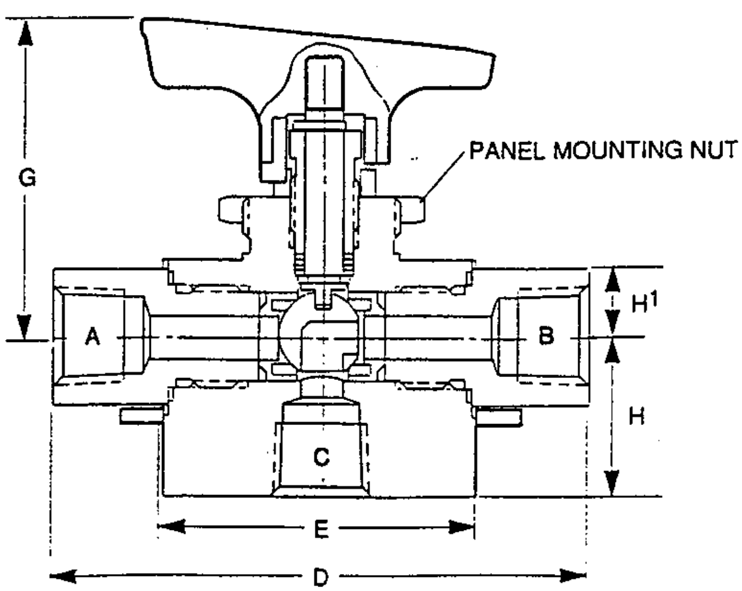
Moderate vacuum to 500 PSIG

End Connections	Order by Part Number			
Inlet & Outlet	Brass	316SS	Monel	Cv
1/4 NPT Female	7065F4B	7065F4Y	—	.66
1/8 Gyrolok	7065G2B	7065G2Y	—	.15
1/4 Gyrolok	7065G4B	7065G4Y	7065G4M	.53
3/8 Gyrolok	7065G6B	7065G6Y	—	.66

DIMENSIONS

End Connections A, B & C		D	E	G	H	H[1]	Panel Mounting Hole Size	Panel Mounting Max. Thickness
1/8 Gyrolok	inch	3 7/16**	1 3/4	1 15/16	2	7/16	57/64	3/16
	mm	87**	44	49	51	11	23	5
1/4 Gyrolok	inch	3 5/8**	1 3/4	1 15/16	2 1/16	7/16	57/64	3/16
	mm	92**	44	49	52	11	23	5
3/8 Gyrolok	inch	3 7/8**	1 3/4	1 15/16	2 3/16	7/16	57/64	3/16
	mm	98**	44	49	56	11	23	5
1/4 Female	inch	3	1 3/4	1 3/4	15/16	7/16	57/64	3/16
	mm	76	44	44	24	11	23	5

**Hand tight



7065 SERIES

Conval INC 265 Field Rd. Somers, CT 06071

FAX Transmission

From: C. A. Siver
To: Paul Duncan
Company: Oceaneering Space Center

Date: May 21, 1996
Time: 11:02 AM
FAX #: 1-713-286-2625
Number of Pages: 2

Message:

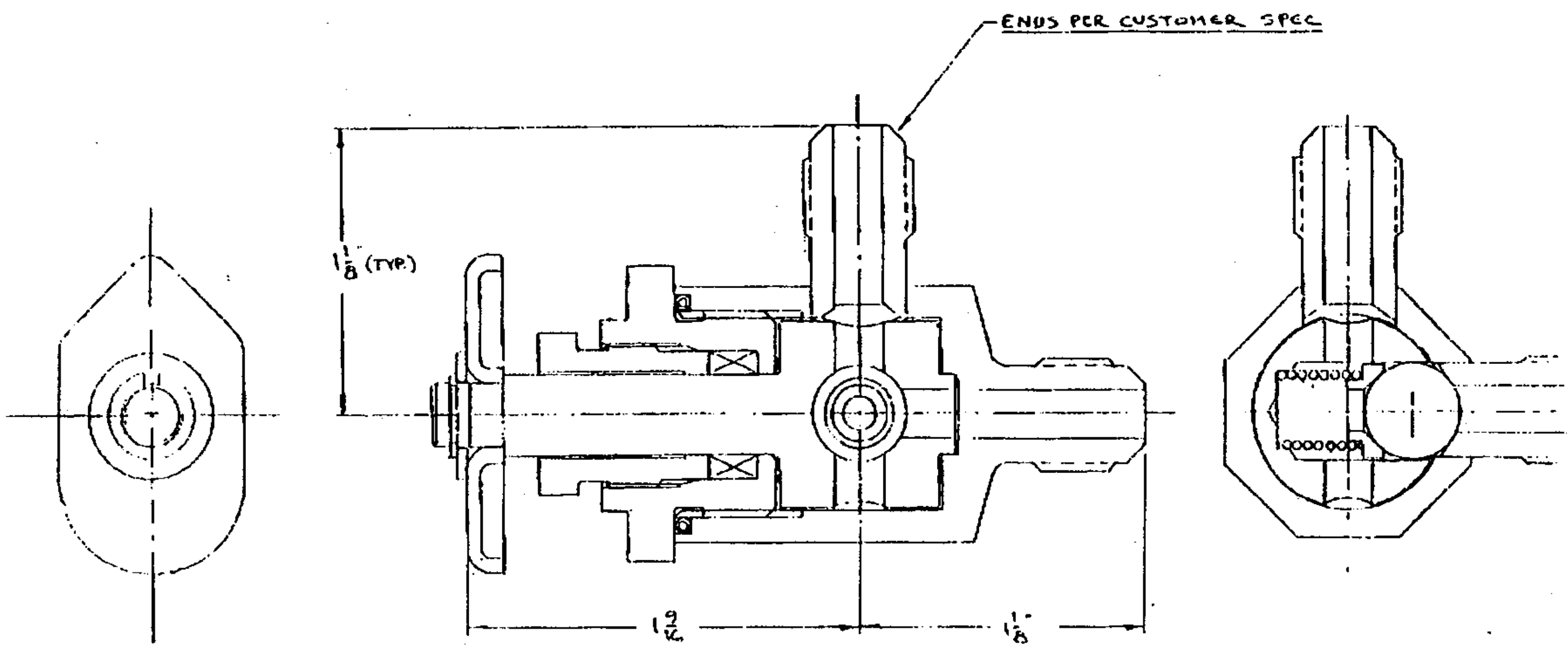
Sketch of our proposed 3-way diverter valve is attached. We assume that the objective is to take air from either of two tanks and deliver is to a mask. If tight shut-off of both tanks is a requirement, it would be necessary to modify this proposed design. The design shown would weigh about one-quater pound made out of aluminum.

Our pricing for an initial order would include a one-time charge for engineering and tooling.

I will call you this afternoon to inquire as to your interest in this valve.

C. A. Siver
Chrm & CEO

Voice: 860-749-0761 Fax: 860-763-3557



3 WAY VALVE ASSY

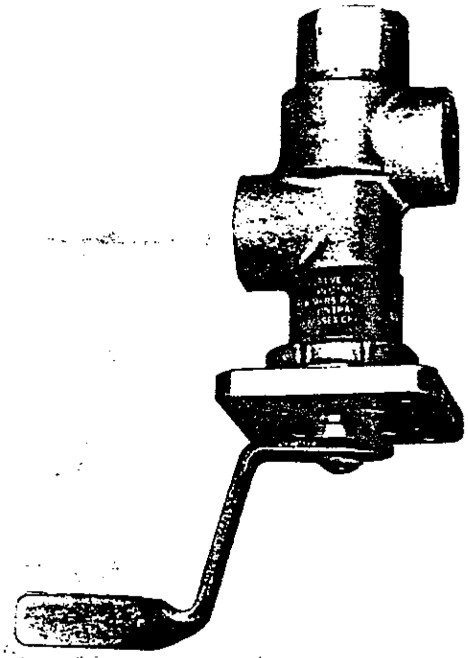
60 P.S.I. OPER. PRESSURE

SCALE 2/1

BUILD-UP AND VENT OXYGEN VALVE

part no. 20C-0023-4

Valve Body
6061-T6 AL Forging



The Oxygen build-up and vent valve is used with liquid oxygen converters on current military aircraft.

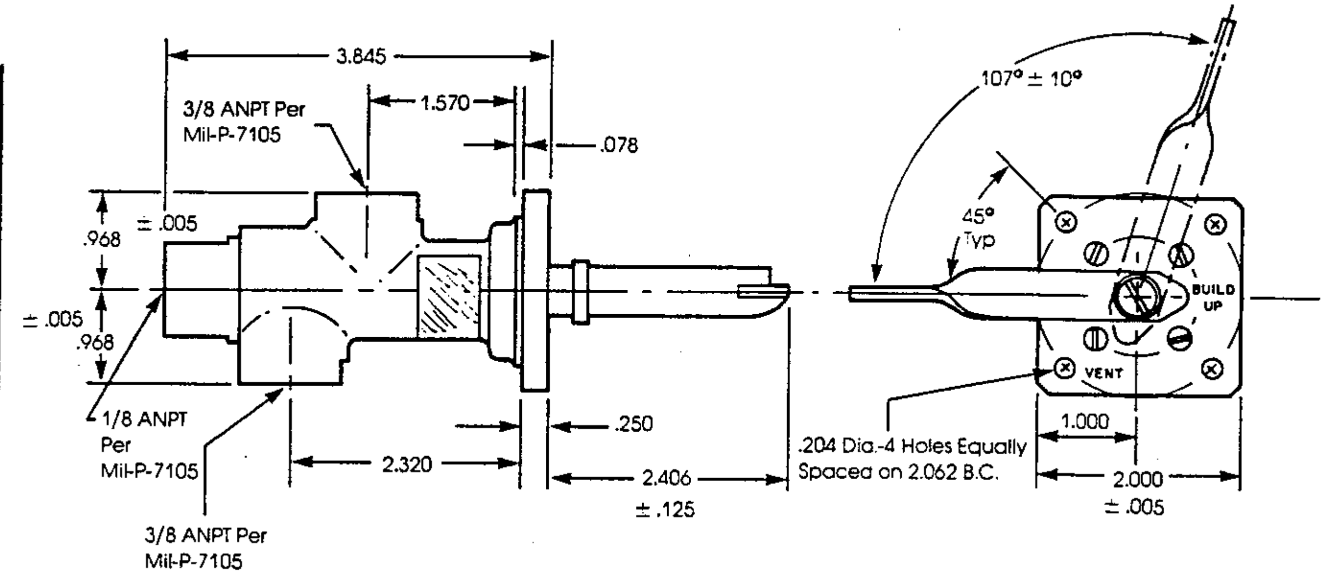
The valve conforms to MIL-V-8057.

Maximum weight is 0.85 pounds.

The valve is a three way, two position manually operated valve. In a crygogenic system, these features place the system in a vented or pressurized mode.

This valve is used with 70 or 300 psig systems.

ESSEX CRYOGENICS OF MISSOURI, INC.
a subsidiary of Essex Industries Inc.
8007 Chivvis Drive • St. Louis, MO 63123
PH(314) 832-8077
Telex 32618 • TWX 910-761-1165



SPECIFICATIONS

BUILD-UP AND VENT OXYGEN VALVE

part no. 20C-0023-4

Operating temperatures range from -320 F to +260 F.

Valve is fabricated from aluminum and stainless steel with teflon seat material.

The valve is used with oxygen, nitrogen and other cryogenic fluids.

Valve can be modified to meet specific customer requirements.

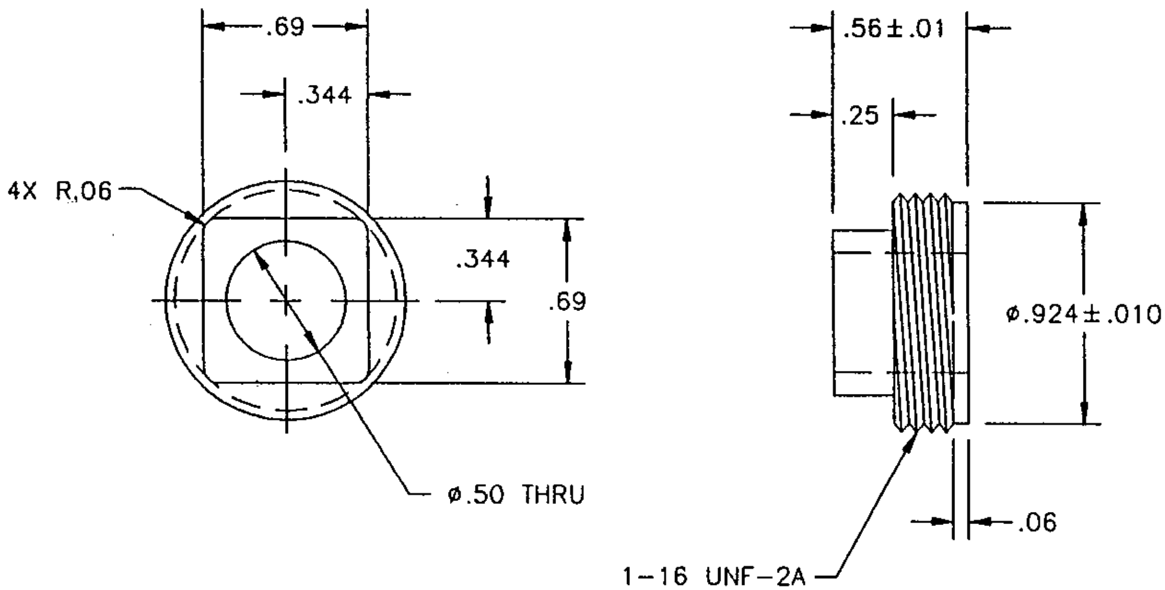
ESSEX CRYOGENICS OF MISSOURI, INC.
a subsidiary of Essex Industries Inc.
8007 Chivvis Drive • St. Louis, MO 63123
PH(314) 832-8077
Telex 32618 • TWX 910-761-1165

3) Comp: Secondary Relief Valve (40 psig) *or Burst Disc (80 psig)*
Vendor: Circle Seal (& Macro Technology) *or Pro Quip*
Descript: Same description as the previously mentioned 40 psig relief valve. This valve was installed primarily to protect the dewar if the 3-way valve were turned to the middle closed position. It also served as a redundant relief valve during operation. It is preferable to use a burst disc in place of this relief valve and have a 3-way valve with no middle closed position, as a burst disc should be less expensive and more reliable than a relief valve. According to CGA S-1.1, the burst disc set point should be .75-1 times the test pressure of the vessel. This burst disc will also be exposed to the cryogenic temperatures though that can be minimized through plumbing arrangements.
Issues: The secondary relief valve issues are the same as those for the aforementioned low pressure relief valve. If it is determined to used a burst disc instead of a relief valve to provide redundancy, the relief capacity of the primary low pressure valve will need to be increased.

A burst disc was originally used to provide redundancy for the low pressure relief valve. OSS conducted some subcomponent testing on the burst discs we have received from ProQuip and they bursted at a much lower pressure than expected when cold. Theoretically, the cryogenic temperatures should have caused them to rupture at a 10% higher pressure due to the inconel/teflon/inconel construction. Instead they were rupturing around 10% lower than design. ProQuip suggested that we pay them to research why this was happening, but we declined. OSS has looked into some other burst disc manufacturers but they all suggest a similar design for the thermal and pressure regime the pack operates in. It is possible to get an all metal construction burst disc for the low pressure, but the component would end up being relatively large.

DWG NO. SK01577 SH 1 REV IR

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
IR	ECO NO.		



NOTES:

1. THREADS SHALL BE IN ACCORDANCE WITH FED-STD-H28/2.
2. NON-FRACTURE CRITICAL.
3. CLEAN, PACKAGE AND IDENTIFY PER OSS DOCUMENT QOP 12.3.

QTY/ASSY	ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	NOTE OR REMARKS
		-001	CAP, BURST DISC	AL, ALY 2024	QQ-A-225/6

PARTS LIST

GENERAL TOLERANCES: .X±.1 X°±3° .XX±.02 X.X°±.5° .XXX±.005 $\frac{X}{X} \pm \frac{1}{8}$

APPLICABLE DOCUMENTS: MIL-STD-100 & ANSI Y14.5M-1982

UNLESS OTHERWISE SPECIFIED. ALL DIMENSIONS ARE INCHES. DEBURR AND BREAK EDGES R .015. CONCENTRICITY OF COAXIAL DIA'S: .006 FIM. ALL SURFACES 125 PER ANSI B46.1. DIMENSIONS AND SURFACE TEXTURES APPLY AFTER ANY FINISH, COATING, OR TREATMENT

THIRD ANGLE PROJECTION

CUSTOMER:

NEXT ASSY | USED ON | APPLICATIONS

DRAFT C. MICKENS 94/07/11
CHECK
DESIGN
PROJECT
PROGRAM
MFG
SR&QA
MAT'L
STRESS

OCEANEERING SPACE SYSTEMS
16665 SPACE CENTER BLVD., HOUSTON, TEXAS 77058

CAP, BURST DISC
AWPS, DESIGN

SIZE B | CAGE CODE 2F262 | DWG NO. SK01577 | REV IR

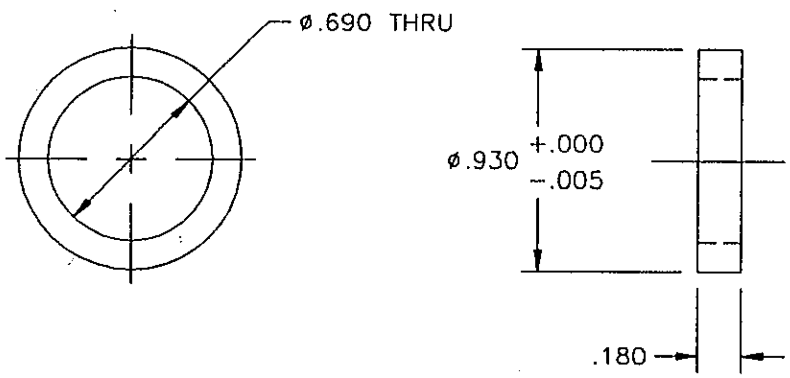
SCALE 2/1 | CONTRACT NO. | WT | SHEET 1 OF 1

OSSBI 04/06/15

OSSBI 94/06/15

DWG NO. SK01578 SH 1 REV IR

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
IR	ECO NO.		



NOTES:

1. NON-FRACTURE CRITICAL.
2. CLEAN, PACKAGE AND IDENTIFY PER OSS DOCUMENT QOP 12.3.

QTY/ASSY	ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	NOTE OR REMARKS
		-001	RETAINING RING, BURST DISC	AL, ALY 2024	QQ-A-225/6

PARTS LIST

GENERAL TOLERANCES: .X±.1 .XX±.02 .XXX±.005 X°±3° X.X°±.5° $\frac{X}{X}\pm\frac{1}{8}$

APPLICABLE DOCUMENTS: MIL-STD-100 & ANSI Y14.5M-1982

UNLESS OTHERWISE SPECIFIED.
ALL DIMENSIONS ARE INCHES
DEBURR AND BREAK EDGES R .015
CONCENTRICITY OF COAXIAL DIA'S: .006 FIM.
ALL SURFACES 125/ , PER ANSI B46.1
DIMENSIONS AND SURFACE TEXTURES APPLY AFTER ANY FINISH, COATING, OR TREATMENT

THIRD ANGLE PROJECTION

CUSTOMER:

NEXT ASSY | USED ON

APPLICATIONS

DRAFT C. MICKENS 94/07/11
CHECK
DESIGN
PROJECT
PROGRAM
MFG
SR&QA
MAT'L
STRESS

OCEANEERING SPACE SYSTEMS
OCEANEERING SPACE SYSTEMS 16665 SPACE CENTER BLVD., HOUSTON, TEXAS 77058

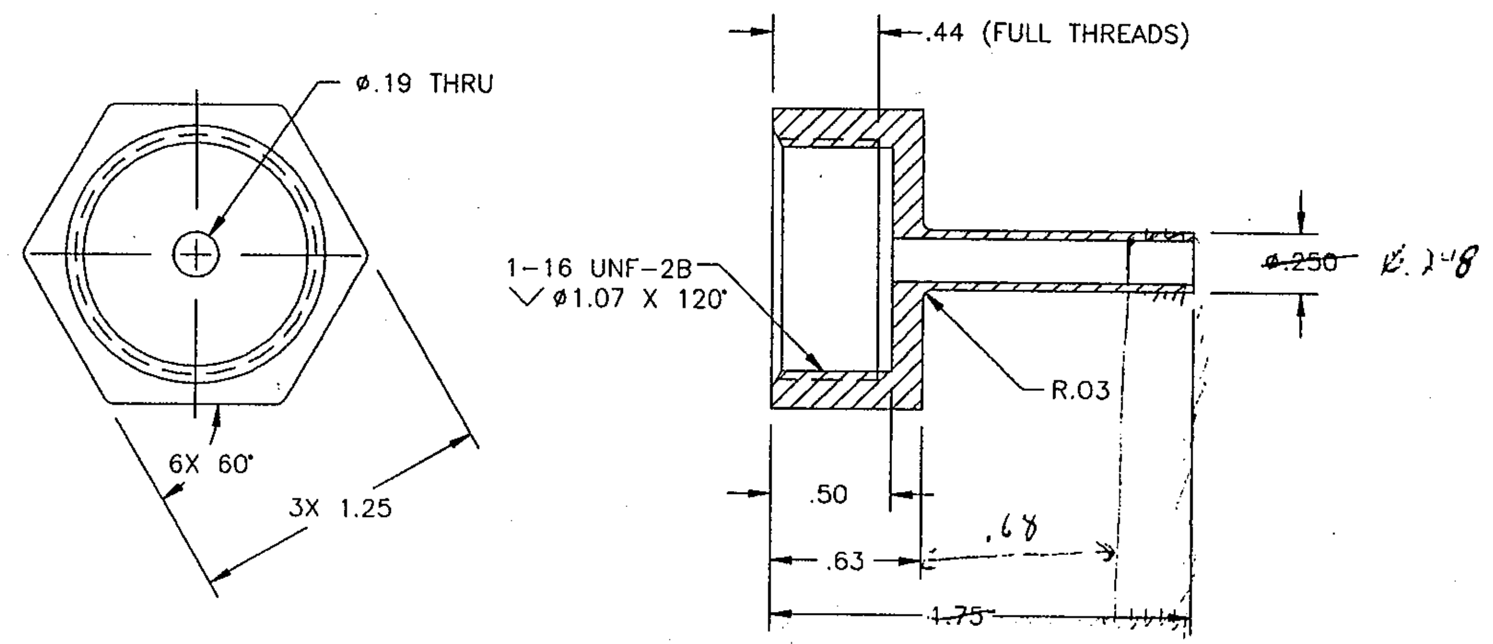
RETAINING RING, BURST DISC AWPS, DESIGN

SIZE B | CAGE CODE 2F262 | DWG NO. SK01578 | REV IR

SCALE 2 / 1 | CONTRACT NO | WT | SHEET 1 OF 1

DWG NO. SK01579 SH 1 REV IR

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
IR	ECO NO.		



NOTES:

1. THREADS SHALL BE IN ACCORDANCE WITH FED-STD-H28/2.
2. NON-FRACTURE CRITICAL.
3. CLEAN, PACKAGE AND IDENTIFY PER OSS DOCUMENT QOP 12.3.

QTY/ASSY	ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	NOTE OR REMARKS
		-001	HOLDER, BURST DISC	AL, ALY 2024 .	QQ-A-225/6

PARTS LIST

GENERAL TOLERANCES: .X±.1 X°±3° .XX±.02 X.X°±.5° .XXX±.005 $\frac{X}{X} \pm \frac{1}{8}$

APPLICABLE DOCUMENTS: MIL-STD-100 & ANSI Y14.5M-1982

UNLESS OTHERWISE SPECIFIED. ALL DIMENSIONS ARE INCHES. DEBURR AND BREAK EDGES R .015. CONCENTRICITY OF COAXIAL DIA'S: .006 FIM. ALL SURFACES 125⁄, PER ANSI B46.1. DIMENSIONS AND SURFACE TEXTURES APPLY AFTER ANY FINISH, COATING, OR TREATMENT.

THIRD ANGLE PROJECTION

CUSTOMER:

NEXT ASSY | USED ON — APPLICATIONS

DRAFT	C. MICKENS	94/07/11
CHECK		
DESIGN		
PROJECT		
PROGRAM		
MFC		
SR&QA		
MAT'L		
STRESS		

OCEANEERING SPACE SYSTEMS
OCEANEERING SPACE SYSTEMS, 16665 SPACE CENTER BLVD., HOUSTON, TEXAS 77058

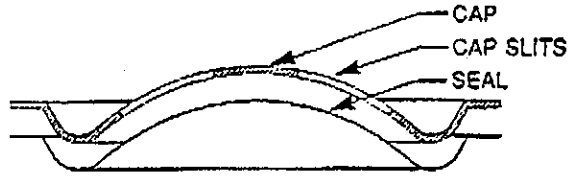
HOLDER, BURST DISC AWPS, DESIGN

SIZE B | CAGE CODE 2F262 | DWG NO. SK01579 | REV
SCALE 2 / 1 | CONTRACT NO. | WT | SHEET 1 OF 1

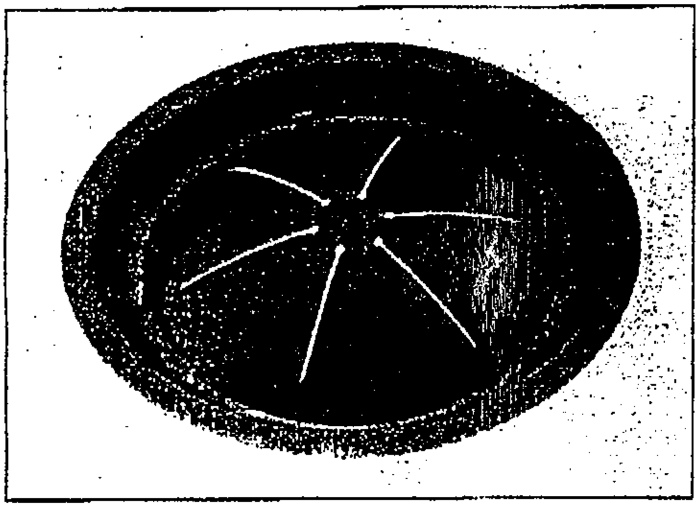
OSSB1 94/06/15

DESCRIPTION

ıe type D is a tension loaded, angle seated ıpture disc of composite (two part) construction. The two parts are called the cap and the seal. The cap is dome shaped with six radial slits that terminate in a "break away" circle at the top (see photo below). The seal may be metal foil or a film of plastic, usually Teflon.



Cross section of a Type "D" rupture disc.



Top view of the cap. Rupture begins when the aterial between adjacent holes tears.

The type D disc is installed with the concave side facing the system pressure. As the pressure rises, the tension in the cap material between the holes at the top of the slits increases. When the yield point of the material between adjacent holes is reached, the material tears, which initiates the complete rupture of the disc. The diameter of the circle of holes at the top of the slits determines the rupture pressure of the disc.

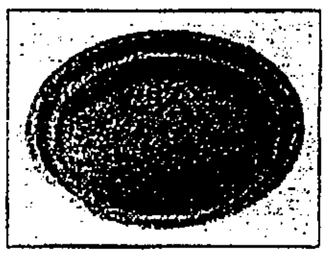
80% OPERATING RATIO

Working pressures up to 80% of the rupture pressure of the disc will not affect the service life of the disc. Accordingly, the "operating ratio" of the Type D disc is 80%.

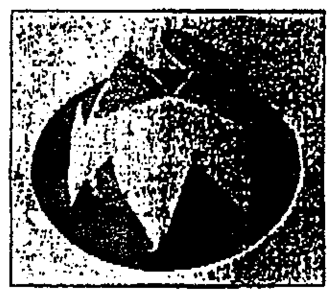
VACUUM AND REVERSE PRESSURE

If pressure is applied to the domed side of a type D disc, the seal will reverse and collapse. Accordingly, if it will be exposed to vacuum or back pressure, the seal must be supported. The support member is called a "Vacuum Support". A vacuum support will not hold pressure and, when the disc ruptures, will open fully. The PROQUIP vacuum support has 6 pie-shaped sections that open like the petals of a flower when the disc ruptures. When supplied with a vacuum support. the Type D is designated Type DV.

Although the shape of the vacuum support is very close to that of the seal, it is never identical. Consequently, when exposed to vacuum or back pressure, the seal will move slightly. This movement creates stress in the seal material and, repeated frequently, will cause the seal, and ence the disc, to fail pre-maturely. Accordingly, Type DV discs are not recommended for services where there is frequent positive-to-negative pressure cycling.



Vacuum Support before rupture



Vacuum Support after rupture

PROTECTIVE RING

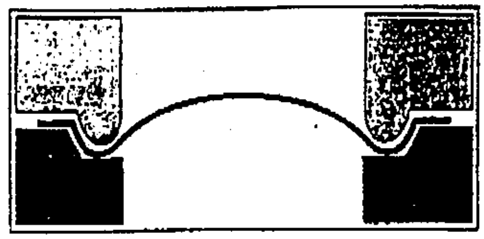
When the rupture pressure is very low, the cap and seal materials are very thin and extremely fragile. Also, when the seal is Teflon or some other soft material, it is very vulnerable. If there is no vacuum support, a protective ring is recommended to facilitate the handling of the disc and to prevent the holder from cutting through the seal material during installation. When supplied with a ring the disc is designated DR.

DISC HOLDER

Most type D discs are made with an angle seat for installation in standard 30 degree angle seat disc holders. When the male and female seats engage, a line contact is made around the circumference. This causes a concentrated "squeeze" on the disc which results in a very efficient seal. A GASKET IS NOT REQUIRED. Some low pressure Type D discs are made with flat seats and require gaskets. These are designated Type FD. Holders are available with threaded, weld or flat ends in bolted, union or screw types. The most popular is the model "7A" which fits inside the bolt circle of the companion flanges. Refer to catalog RD18 for more information and dimensions.

TYPE TMT AND TMTV

The type TMT (Teflon-Metal-Teflon) disc was developed for very corrosive environments. It is a type D disc with Teflon seal that also has a Teflon liner on the outlet side. As a result, all exposed parts are Teflon, which can withstand attack from most chemicals. The TMTV has reinforcing on the under side of the metal element that enables it to withstand vacuum or back pressure.



Cross section of a Model 7A Holder showing the angle seat.

SERVICE RECOMMENDATIONS

Type D and TMT rupture discs are recommended for liquid or gas pressure relief where the maximum operating pressure in the system being protected is constant and does not exceed 80% of the rupture pressure marked on the tag of the disc. When supplied with vacuum supports, they will also give satisfactory service if occasionally exposed to vacuum or back pressure.

Type D and TMT discs are not recommended where the working pressure exceeds 80% of their rupture pressure or where they may be exposed to positive-to-negative pressure cycling. They are also not recommended in services where fragmentation is not acceptable.

MANUFACTURING RANGE

Although it is possible to produce a Type D disc that will rupture at exactly the desired pressure and temperature, it takes a great deal of time and increases the cost considerably. Most applications do not require discs to rupture at precise pressures. Consequently,

DESIRED RUPTURE PRESSURE (PSIG)	MANUFACTURING RANGE*	
	MINUS	PLUS
2 ½ – 3 ½	1 psi	1 psi
4 – 6	1 psi	2 psi
7 – 10	1 ½ psi	2 ½ psi
11 – 16	2 psi	3 psi
17 – 25	2 psi	4 psi
26 – 40	3 psi	5 psi
41 – 65	4 psi	6 psi
66 – 100	5 psi	9 psi
101 – 150	6 psi	12 psi
151 – 200	9 psi	16 psi
201 – 350	12 psi	23 psi
351 – 500	15 psi	30 psi
Over 500	3%	6%

discs that burst within a known range of the desired pressure are usually acceptable. The Rupture Disc Manufacturing Industry has established a "Standard Manufacturing Range" that is normally acceptable to the users of rupture discs. The size of the range changes as the desired pressure increases and is shown in the table on the left.

Unless stated otherwise in the order, it is assumed that the Standard Manufacturing Range is acceptable to the buyer and discs that will rupture within this range will be shipped. If the standard range is not acceptable, it can usually be reduced by 50% or 75% and sometimes 100% on payment of a "Reduced Manufacturing Range" charge.

It is important to note that the Code states that a pressure relieving device set to relieve at a pressure higher than the design pressure of the system is UNACCEPTABLE. Consequently, if the desired rupture pressure is the same as the design pressure, it is extremely important to mark on the purchase order "MAXIMUM" rupture pressure. When this is done, the manufacturer will change the range to Plus Zero, Minus the total of the applicable plus and minus from the table.

MINIMUM/MAXIMUM RUPTURE PRESSURES
AT 72°F. (22°C.)

INCONEL 600 OR 316 STAINLESS STEEL CAP

Size	S E A L	M A T E R I A L					Maximum w/any seal
	Teflon	Aluminum	316 SS	Nickel	Monel	Inconel	
1″	25	60	400	185	240	300	2,500
25 mm	1.8	4.2	28	13	16.9	21	175
1 1/2″	20	35	275	125	155	200	2,000
40 mm	1.4	2.5	19	8.8	10.9	14	140
2″	15	25	165	80	90	120	1,500
50 mm	1.0	1.8	11.6	5.6	6.3	8.5	105
3″	10	15	125	55	70	95	1,000
80 mm	.7	1.	8.8	3.9	4.9	6.7	70
4″	8	12	90	40	50	75	900
100 mm	.6	.84	6.3	2.8	3.5	5.3	63
6″	6	10	75	35	40	60	700
150 mm	.4	.7	5.3	2.5	2.8	4.2	49
8″	5	8	60	25	35	40	600
200 mm	.35	.6	4.2	1.72	2.5	2.8	42
10″	4	7	45	22	30	30	500
250 mm	.3	.5	3.2	1.5	2.1	2.1	35
12″	3	7	40	19	25	25	400
300 mm	.2	.5	2.8	1.3	1.8	1.8	28
14″	3	7	35	17	20	25	300
350 mm	.2	.5	2.5	1.2	1.4	1.8	21
16″	3	7	30	15	18	25	275
400 mm	.2	.5	2.1	1	1.3	1.8	19
18″	3	6	25	15		35	250
450 mm	.2	.4	1.8	1		2.5	18
20″	3	6	2.5	20		50	225
500 mm	.2	.4	1.8	1.4		3.5	16
24″	3	5	45	60		60	200
600 mm	.2	.35	3.2	4.2		4.2	14

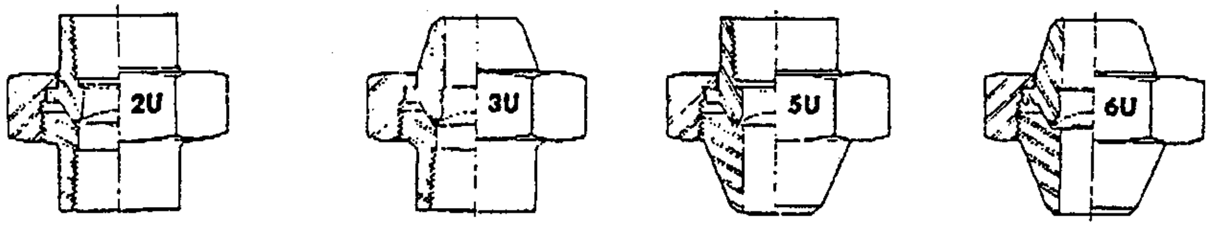
NOTE: CLEAR FIGURES ARE PSIG, SHADED FIGURES ARE kg/cm²

MAXIMUM SEAL OPERATING TEMPERATURES

FEP	400°F (204°C)	316 SS	900°F (482°C)
TFE or PFA	500°F (260°C)	Nickel	800°F (427°C)
Polyethylene	150°F (65°C)	Monel	900°F (482°C)
Aluminum	600°F (316°C)	Inconel	1000°F (538°C)

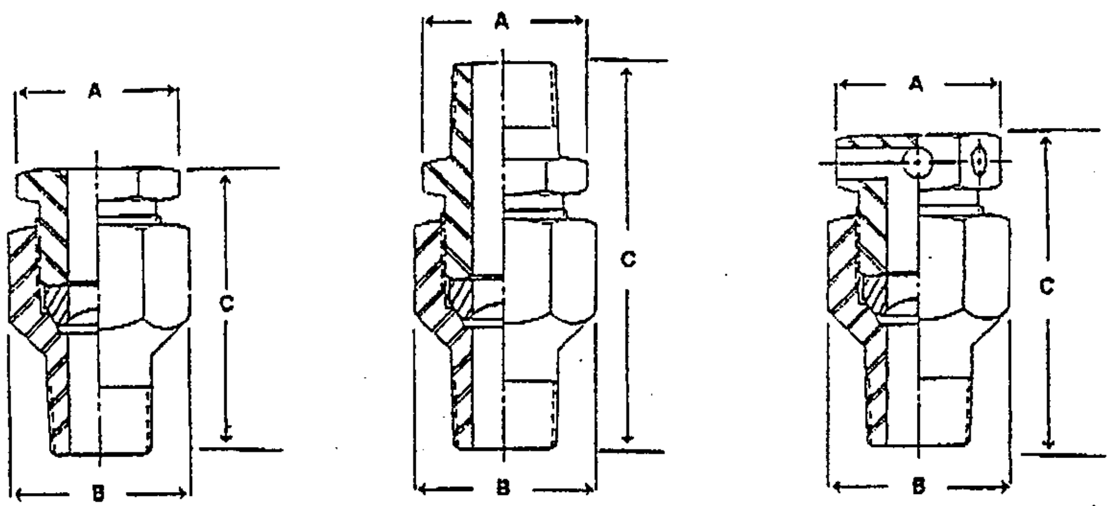
**USE TEMPERATURE CORRECTION TABLE TO DETERMINE MINIMUMS AT OTHER TEMPERATURES.*

UNION TYPE



SIZE	RATING	ACROSS FLATS	APPROXIMATE END-TO-END DIMENSION			
			2U	3U	5U	6U
½"	3000#	1¾	2¼	2¾	2¾	2½
	6000#	2¾	2¾	2¾	2¾	2⅞
1"	3000#	2½	2¾	2¾	2¾	2¾
	6000#	3⅛	3	3¼	3⅛	3¼
1½"	3000#	3½	3¼	3¾	3¾	2½
2"	1500#	4	3½	3⅝	3⅝	3½

SCREW TYPE



[redacted] [redacted] [redacted] STS-1

ASSEMBLY No.	CONNECTIONS		HEX SIZE		HEIGHT "C"	
	INLET	OUTLET	"A"	"B"	3000#	10,000#
[redacted]	¼	FREE	1¼	1¼	2¾	2½
[redacted]	½	FREE	1⅞	1¼	2⅞	2¼
[redacted]	¼	⅛	1⅛	1¼	3⅛	3
[redacted]	½	½	1⅛	1¼	3⅛	3
[redacted]	¼	MUFFLED	1⅛	1¼	2½	2⅝
[redacted]	½	MUFFLED	1⅛	1¼	2½	2⅝

STS-1

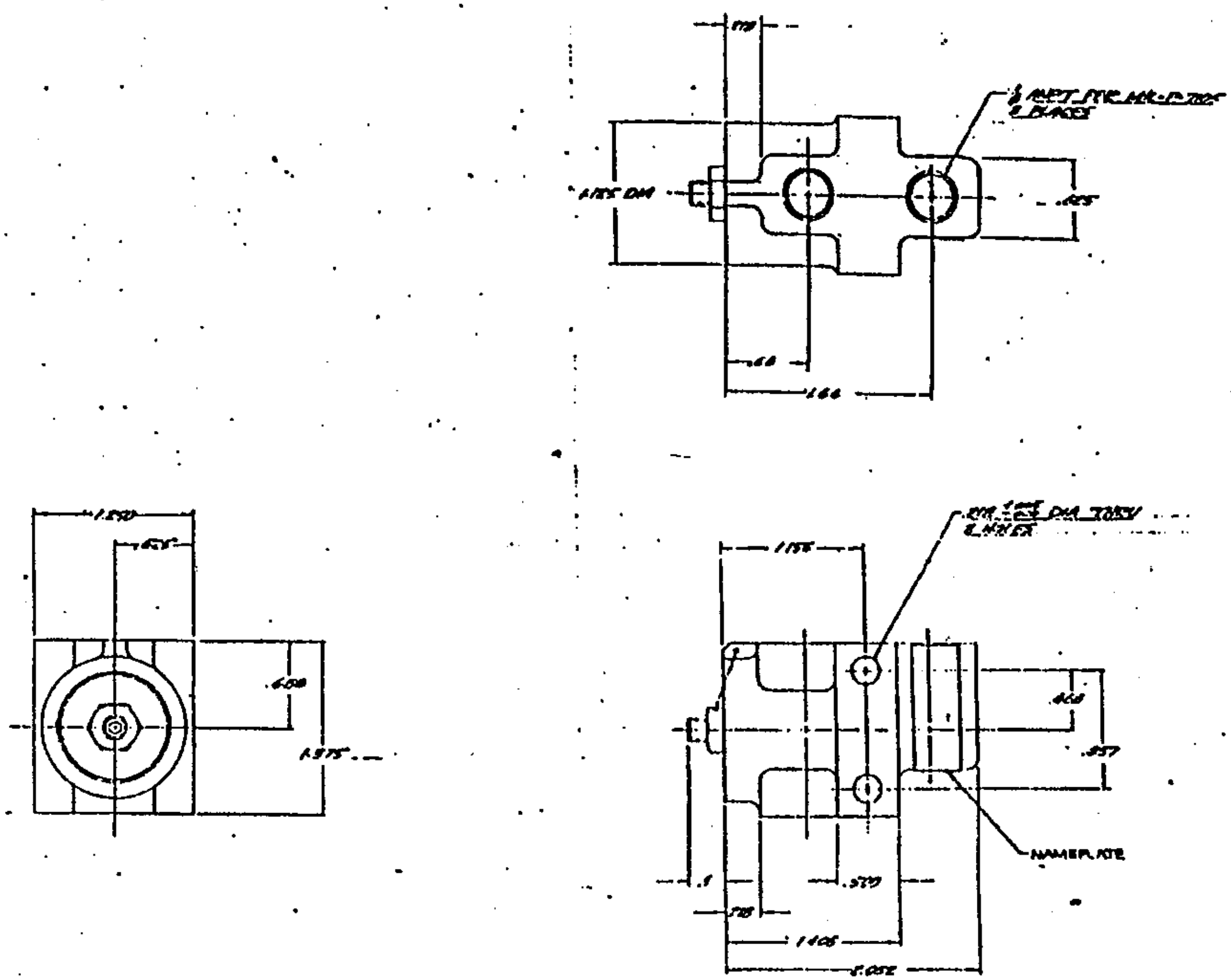
NOTE – An inexpensive, brass, disposable screw type with non-replaceable disc is also available for lower pressure applications. Ask the factory for details.

4) Comp: Pressure Control Valve (37 psig)

Vendor: Essex Cryogenics

Descript: The PCV is a valve made by Essex Cryogenics primarily for aircraft LOX converters. The valve opens when the downstream pressure drops below the set point, allowing the higher pressure air to flow into the ullage. High pressure air from the AHX is used to pressurize the dewar when the ullage pressure drops below ~37 psig. The valve does not act as a check valve however. If the ullage pressure drops below the set point and the PCV opens, it will flow gas from the ullage if the supply side pressure is lower.

Issues: There are no performance issues associated with the Essex PCV. This component has almost always performed exactly as required and expected. The only problems ever encountered with the PCV were a result of improper calibration. The valves are somewhat finicky to reset and, if not done properly, can be damaged. Components that have come from Essex preset have not had any problems.



FSN 1660-113-7191 TP (AF)

OXYGEN VALVE PRESSURE CLOSING

ESSEX CRYOGENICS INC.

3 OPERATING TEMPERATURE -320°F TO +260°F
2 OPERATING PRESSURE RANGE 50 TO 150 PSIG FOR USE WITH 75 PSIG LOX SYSTEMS
1 WEIGHT .9 LBS
NOTES:

5) Comp: High Pressure Relief Valve (80 psig)
Vendor: Circle Seal (& Macro Technology)
Descript: This relief valve is the same design as the aforementioned 40 psig RV's. It is used to protect the vaporizer from over pressurization. The most likely opportunity for this to occur is when the user takes off his mask or regulator. There will likely be some free flow of air and a large amount of cryogen can flow into the vaporizer/AHX. Then the user closes the donning switch, allow the cryogen to boiloff and build up pressure. The relief valve is located between the PCV and the Gas Check Valve. This also serves to relieve this section in the event that cryogen becomes trapped there.
Issues: See the issues described in Item 1 - Low Pressure Relief Valve for a summary of the problems. Additional information for this valve is that the frost is not as much of a problem and it takes longer for the seal wear to affect performance.

6) Comp: Gas Check Valve
   Vendor: Ausco
   Descript: This is a cryogen compatible check valve that prevents gas from back flowing through the PCV should it open when the ullage pressure is higher than the AHX pressure.
   Issues: We have used a variety of purchased metal-to-metal seal check valves for this component. Different vendors have been selected to get valves with reduced weight and size or desired material for modification. Once we began to use a purchased component we have not had any problems.

AUSCO INC.

PRECISION VALVES SINCE 1957

820 Port Washington Blvd., P.O. Box 1059
Port Washington, New York 11050
TEL. (516) 944-9882

TELEFAX TRANSMISSION

ATTENTION: Steve Hess

COMPANY: Oceaneering Space Systems

CITY, STATE: Houston, Tx 77058

FAX NUMBER: 1-713-286-2625

SUBJECT: Liquid Air Check Valve

REFERENCE: K2 & K3

DATE: Jan 19, 1996

TIME: 3:52 PM EST.

NO. OF PAGES 7
(including this cover)

FROM: Fran Martin

AUSCO FAX NUMBER 516-944-8522

If you do not receive all pages, please call 516-944-9882 immediately.

MESSAGE

Steve,

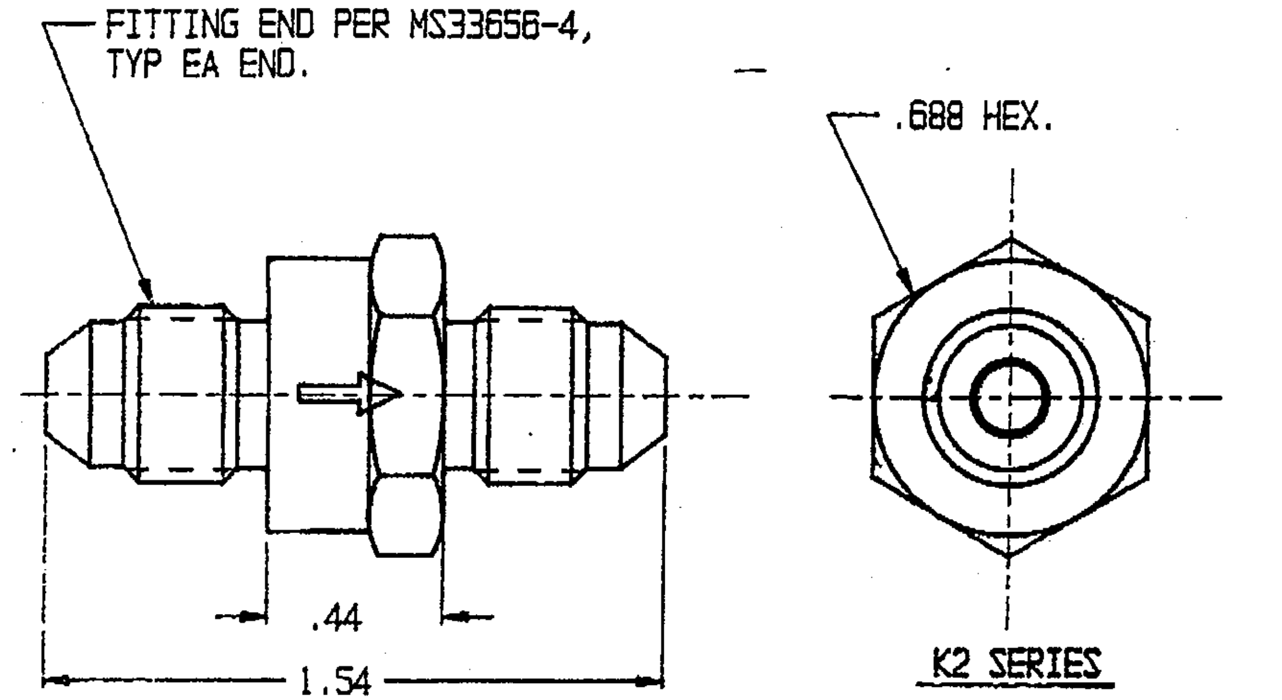
Enclosed is copy of 1/4 Check valve with two types of end fittings. Enclosed also are the applicable MS dwgs. The valves can be set to crack at 1.0 psid; and are all metal construction. Price for prototypes would be $50.00 each F.O.B Port Washington.

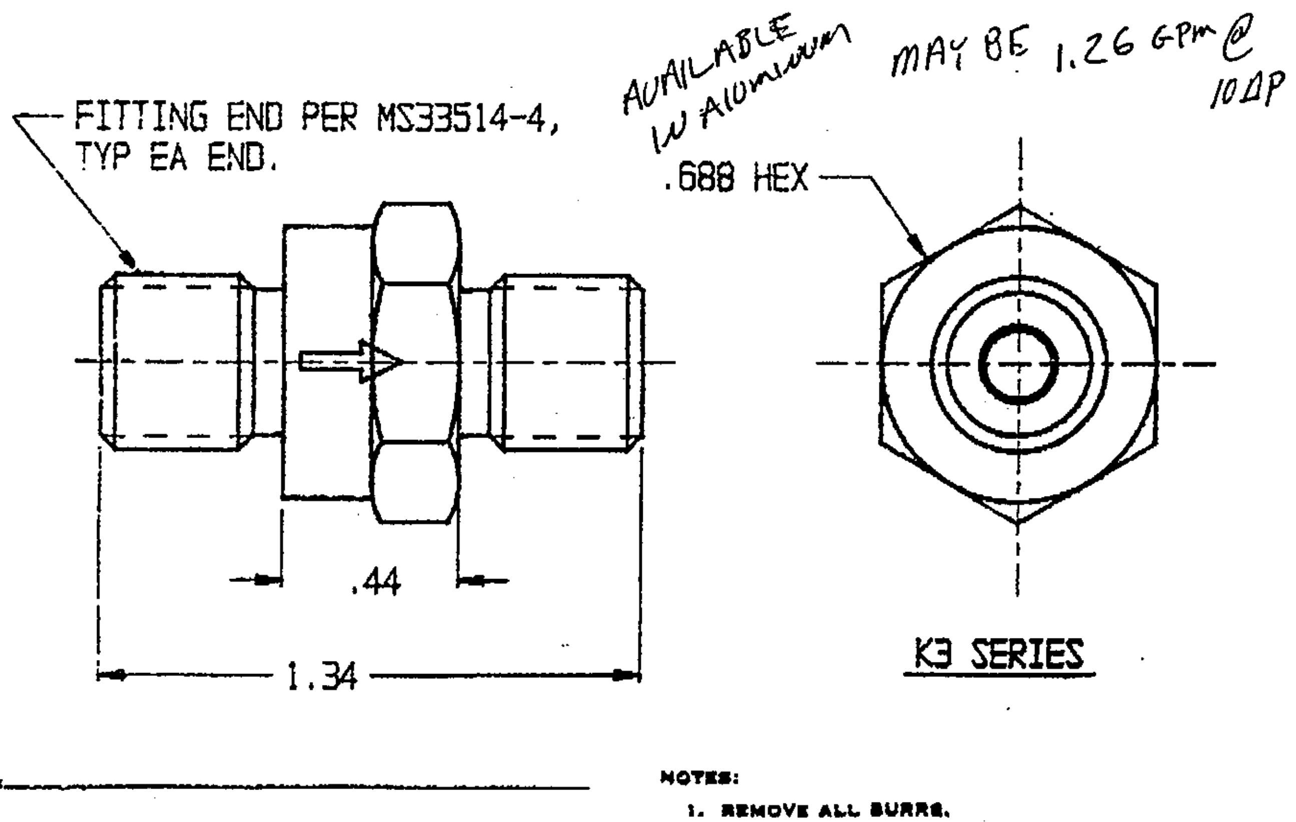
Please let me know your comments.

Regards,

Fran.

LET.	REVISION	DATE	BY





MATERIAL:

STOCK SIZE:

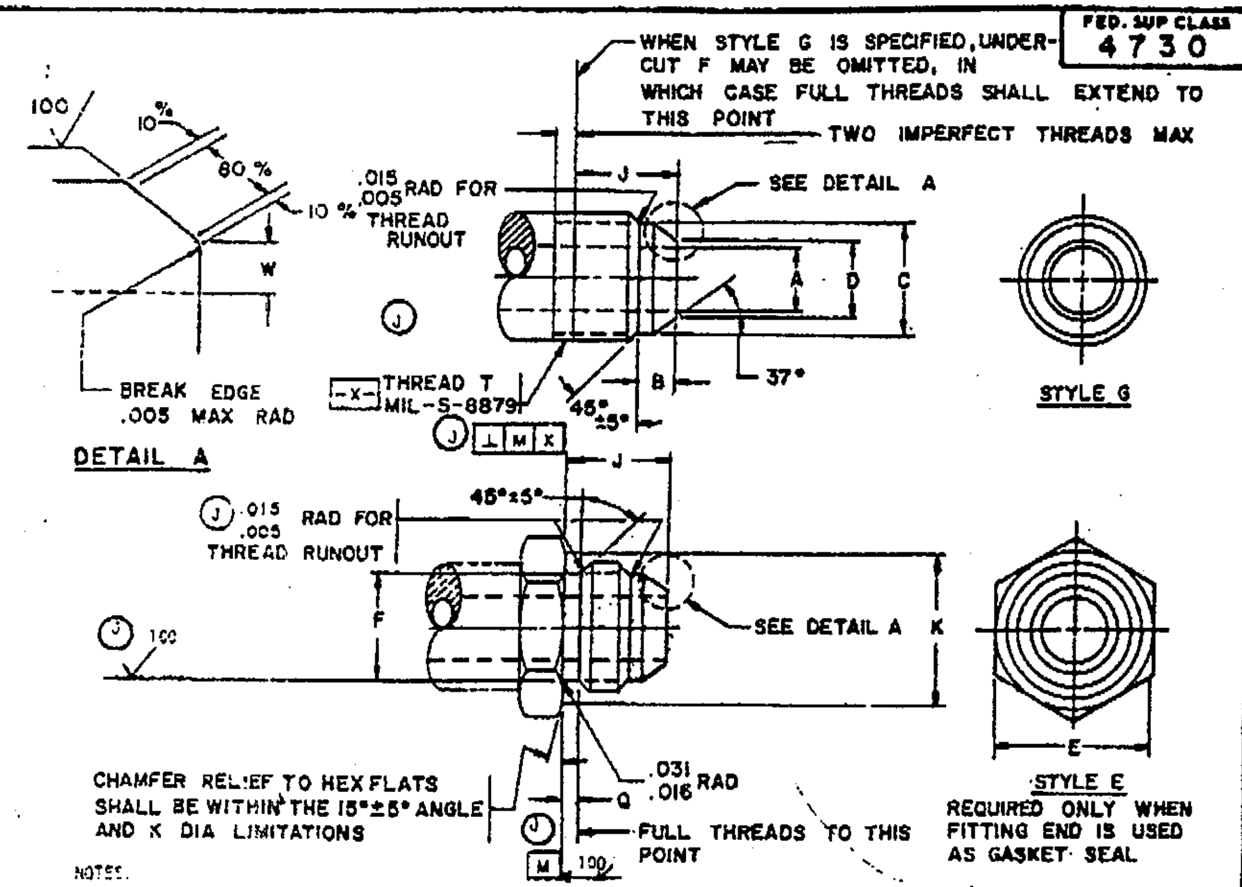
FINISH:

NOTES:

1. REMOVE ALL BURRS.
2. ✓ ALL MACHINED SURFACES EXCEPT AS NOTED.

DRAWN: J.M.	**AUSCO, Inc.** 820 PORT WASHINGTON BLVD.	SCALE: NONE	
CHECKED: F. MARTIN	PORT WASHINGTON, N.Y. 11050	DATE: 01-18-96	
TOLERANCES FRACTIONS ± 1/64 DECIMALS 2 PL. ± .01	CHECK VALVES	DWG. NO. K2K3	REV.

FED. SUP CLASS 4730



NOTES.

(J) 1. The conical seal surface shall be free of flaws, nicks and chatter marks when viewed with the unaided eye. The center 80% of the conical surface (see Detail A) shall also have no low spots and shall have an unbroken line of contact to show all around when rotated in contact with a 74° 0' ±1' included angle gage lightly coated by rubbing with carbon paper or by an equivalent blueing method.

EXAMPLE OF DESIGN IDENTIFICATION NUMBER: MS33656E8
- SIZE OF FITTING END IN 16THS
- E-STYLE E / G-STYLE G
- BASIC DESIGN NUMBER

2. Break all sharp edges and remove all hanging burrs and slivers.

3. Dimensions in inches: Unless otherwise specified, Tolerances: Angles $\pm\frac{1}{2}^\circ$, Decimals ±.016.

(J) 4. Dimensions D, C, F and T (pitch dia) shall be concentric to each other and with the 37° angle, measured and calculated as an included angle, within .005 total indicator reading. Other diameters shall be concentric within .010 TIR.

(J) 5. All machined surfaces shall be smooth to 125 microinches Ra maximum per ANSI B46.1 unless noted.

Certain provisions (screw threads, hexagon, and thread undercut) of this standard are the subject of international standardization agreement ASCC AIR STD 17/11 and STANAG 3315 and 3323. When revision or cancellation of this standard is proposed, the departmental custodians will inform their respective departmental standardization offices so that appropriate action may be taken respecting the international agreement concerned.

Referenced Government (or nongovernment) documents of the issue listed in that issue of the Department of Defense Index of Specifications and Standards (DODISS) specified in the solicitation form a part of this standard to the extent specified herein.

For design feature purposes, this standard takes precedence over acquisition documents referenced herein.

THIS IS A DESIGN STANDARD. NOT TO BE USED AS A PART NUMBER.

(J) DENOTES CHANGE

User activities: ARMY — ME — AT

Review activities: DLA — CS; ARMY — AV; AIR FORCE — 11

APPROVED 25 APRIL 57 REVISED (F) 11 OCT 74 (G) 15 OCT 82 (H) 1 MAR 84 (J) 12 MARCH 1987

P.A. AIR FORCE - 82 Other Cust ARMY - AS NAVY - AS AIR FORCE - 99	TITLE FITTING END, STANDARD DIMENSIONS FOR FLARED TUBE CONNECTION AND GASKET SEAL	MILITARY STANDARD MS 33656
PROCUREMENT SPECIFICATION NONE	SUPERSEDES: AND10056	SHEET 1 OF 2

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited. This military standard is approved for use by all departments and agencies of the Department of Defense. Selection, but all new engineering and design applications and for repetitive use shall be made from this document.

Review activities:
DLA-CS
ARMY-AV

User activities:
ARMY — ME — AT

FED. SUP CLASS
4730

TABLE I DIMENSIONS

SIZE NO	TUBING OD	THREAD T MIL-S-8879	A DIA	A tol.	G +.015 -.000	C +.000 -.005	D +.003 DIA	E	E tol.	F +.002 -.003	H MAX	J ±.015	K ±.010 DIA	Q +.016 -.000	M MIN
2	1/8	5/16-24UNJF-3A	.062		.177	.245	.083	.563	+.003 -.004	.250	.005	.448	.549	.063	.005
3	3/16	3/8-24UNJF-3A	.125	+.003 -.004		.307	.146	.625		.312		.479	.611		
4	1/4	7/16-20UNJF-3A	.172		.193	.359	.193	.688		.364		.550	.674	.075	
5	5/16	1/2-20UNJF-3A	.234			.421	.255	.750		.426			.736		
6	3/8	9/16-18UNJF-3A	.297		.198	.476	.318	.813		.481		.556	.799	.083	
8	1/2	3/4-16UNJF-3A	.391	±.004	.253	.654	.426	1.000		.660		.657	.966	.094	.012
10	5/8	7/8-14UNJF-3A	.484		.266	.767	.539	1.125		.773		.758	1.111	.107	.022
12	3/4	1-1/16-12UNJ-3A	.609	±.005	.315	.938	.664	1.375		.945		.864	1.361	.125	
16	1	1-5/16-12UNJ-3A	.844	+.007 -.005		1.188	.913	1.625	±.016	1.195	.008	.911	1.599		.029
20	1-1/4	1-5/8-12UNJ-3A	1.078	+.008 -.005	.367	1.501	1.147	1.875		1.507		.958	1.849		
24	1-1/2	1-7/8-12UNJ-3A	1.312		.378	1.750	1.381	2.125	±.020	1.756		1.083	2.095		
28	1-3/4	2-1/4-12UNJ-3A	1.547		.451	2.125	1.646	2.500		2.131		1.208	2.460		.044
32	2	2-1/2-12UNJ-3A	1.781		.461	2.375	1.880	2.750		2.381		1.333	2.718		
40	2-1/2	3 -12UNJ-3A	2.281	+.010 -.005	.495	2.882	2.380	3.250		2.881		1.109	3.210		
46	3	3-1/2-12UNJ-3A	2.781			3.382	2.880	3.750		3.381		1.187	3.718		

(J) DENOTES CHANGE

THIS IS A DESIGN STANDARD, NOT TO BE USED AS A PART NUMBER.

APPROVED 25 APR 57 REVISED (F) 11 OCT 74 (G) 13 OCT 82 (H) 1 MAR 84 (J) FOR CHANGES SEE PAGE 1

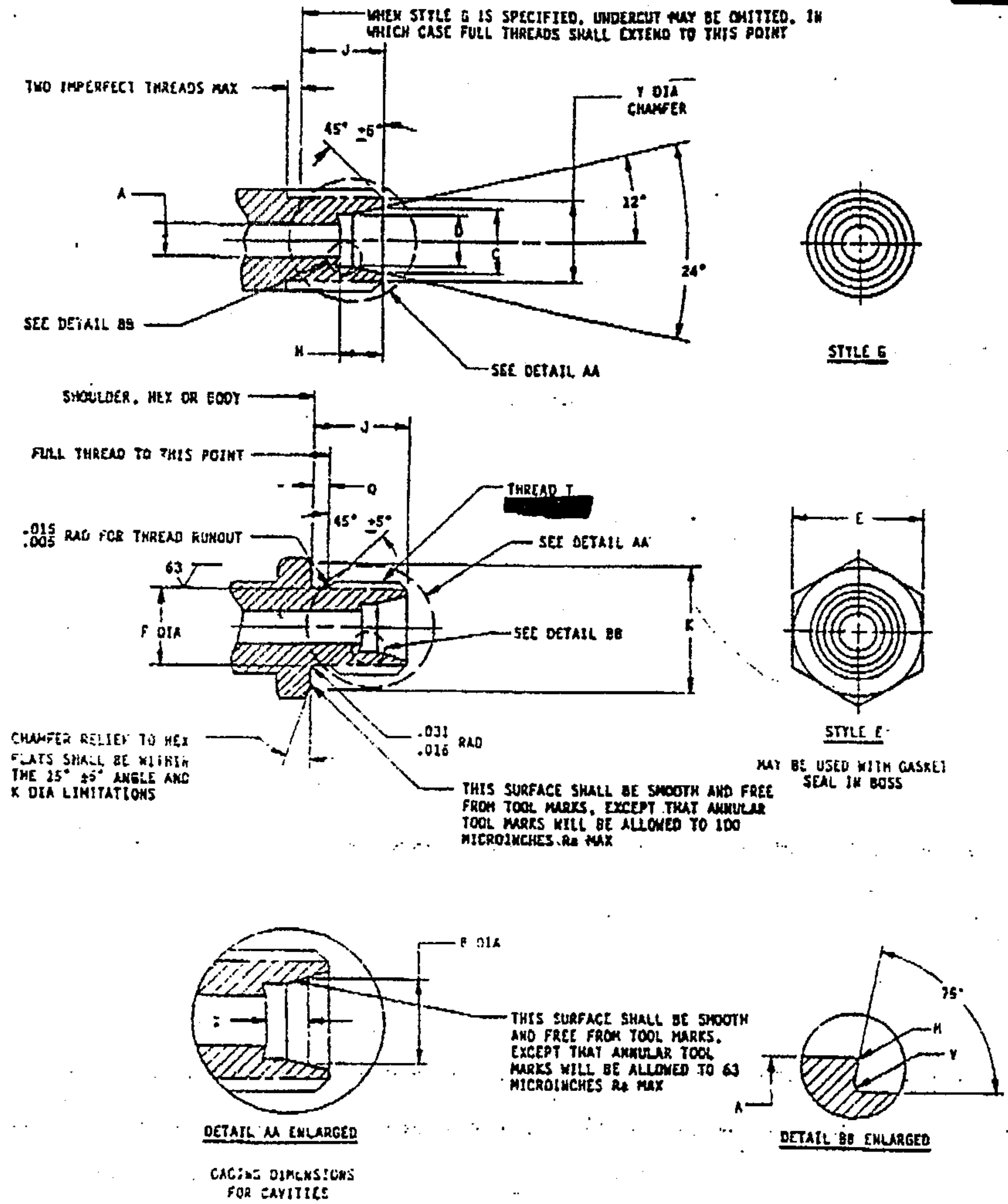
P.A. AIR FORCE-82	TITLE
Other Cust: ARMY-MC, NAVY-AS, AIR FORCE-99	FITTING END, STANDARD DIMENSIONS FOR FLARED TUBE CONNECTION AND GASKET SEAL
PROCUREMENT SPECIFICATION: NONE	SUPERSEDES: AND10056

MILITARY STANDARD

MS 33656

DD FORM 672-1 (Coordinated)

FORM APPROVED
OMB NO. 0704-0188



(G) DENOTES CHANGE

DESIGN STANDARD

PREPARING ACTIVITY: NAVY — AS CUSTODIANS ARMY — AV NAVY — AS AIR FORCE — 99 DLA — REVIEW: USAF-71,82,DLA-CS,ARMY-MI USER: ARMY-GL,MC,AT,MARINE CORPS-MC PROJECT NUMBER: 4730-0021	MILITARY SPECIFICATION SHEET TITLE FITTING END, STANDARD DIMENSIONS FOR FLARELESS TUBE CONNECTION AND GASKET SEAL	SPECIFICATION SHEET NUMBER MS33514G 21 MAY 90 SUPERSEDING MS33514F 27 JAN 69 AMSC — N/A FSC 4730

DISTRIBUTION STATEMENT
A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

FORM APPROVED
OMB NO. 0704-0188

TABLE I. DIMENSIONS DATA

SIZE NO.	TUBE OD	THREAD T [redacted]	A ±.003	B GAGE	C REF	D +.004 -.000	E		F +.002 -.003	H ±.003	J ±.010	K ±.010 DIA	M MAX RAD
2	.125	.3125-24 UNJF-3A	.093	.1630	.189	.135	.563	+.003 -.004	.250	.188	.375	.549	.005
3	.188	.3750-24 UNJF-3A	.125	.2340	.267	.196	.625		.312	.234	.422	.611	
[redacted]									.364		.453	.674	
5	.313	.5000-20 UNJF-3A	.234	.3560	.382	.324	.750		.426	.250		.736	.010
6	.375	.5625-18 UNJF-3A	.297	.4160	.441	.386	.813		.481		.469	.799	
8	.500	.7500-16 UNJF-3A	.422	.5600	.601	.514	1.000		.660	.305	.562	.986	
10	.625	.8750-14 UNJF-3A	.500	.6860	.727	.641	1.125		.773	.350	.625	1.111	
12	.750	1.0625-12 UNJ -3A	.656	.8100	.852	.766	1.375		.945		.688	1.361	
16	1.000	1.3125-12 UNJ -3A	.875	1.0620	1.102	1.016	1.625	±.016	1.195	.415		1.599	
20	1.250	1.6250-12 UNJ -3A	1.093	1.3160	1.355	1.270	1.875		1.507			1.849	.015
24	1.500	1.8750-12 UNJ -3A	1.344	1.5650	1.604	1.520	2.125	±.020	1.756	.485		2.095	
32	2.000	2.5000-12 UNJ -3A	1.813	2.0680	2.108	2.022	2.750		2.381			2.720	

SIZE NO.	Q +.015 -.000	V RAD		W MAX	X ±.005	Y ±.010
		MAX	MIN			
2	.063	.010	.005	.002	.128	.250
3		.015	.010		.158	.310
4	.075				.174	.365
5					.190	.425
6	.083				.193	.480
8	.094				.210	.660
10	.107				.255	.775
12	.125			.003	.253	.945
16					.322	1.195
20		.030	.020		.325	1.505
24					.390	1.755
32					.395	2.380

PREPARING ACTIVITY: NAVY — AS

CUSTODIANS: ARMY — AV NAVY — AS
AIR FORCE — 99 DLA —

REVIEW: USAF-71, 82, DLA-CS, ARMY-MI
USER: ARMY-CL, ME, AT, MARINE CORPS-MC
PROJECT NUMBER: 4730-0021

MILITARY SPECIFICATION SHEET

TITLE

FITTING END, STANDARD DIMENSIONS FOR FLARELESS TUBE CONNECTION AND GASKET SEAL

SPECIFICATION SHEET NUMBER
MS33514G 21 MAY 90

SUPERSEDING
MS33514F 27 JAN 69

AMSC — N/A FSC 4730

DISTRIBUTION STATEMENT
A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

FORM APPROVED
OMB NO. 0704-0188

(C) NOTES:

1. CONCENTRICITY: D, C, AND T (PITCH DIA) SHALL BE CONCENTRIC TO EACH OTHER WITHIN .008 FULL INDICATOR MOVEMENT (F.I.M.).F AND T (PITCH DIA) SHALL BE CONCENTRIC TO EACH OTHER WITHIN .005 F.I.M.
2. SQUARENESS BETWEEN THREAD AND FACE OF HEX SHALL NOT EXCEED N WHEN MEASURED AT DIA K.
3. SURFCE ROUGHNESS IN ACCORDANCE WITH ANSI/ASME B46.1.
4. REMOVE ALL BURRS, SLIVERS AND SHARP EDGES.
5. DIMENSIONS IN INCHES, UNLESS OTHERWISE SPECIFIED. TOLERANCES: ANGLES 0.5°.
6. EXAMPLE OF DESIGN IDENTIFICATION NUMBERS: MS33514 E 8
   - 8 — SIZE OF FITTING END IN 16THS
   - E — E - STYLE E / G - STYLE G
   - MS33514 — BASIC DESIGN NUMBER
7. IN THE EVENT OF CONFLICT BETWEEN THE TEXT OF THIS STANDARD AND THE REFERENCES CITED HEREIN, THE TEXT OF THIS STANDARD SHALL TAKE PRECEDENCE.
8. REFERENCED GOVERNMENT (OR NON-GOVERNMENT) DOCUMENTS OF THE ISSUE LISTED IN THAT ISSUE OF THE DEPARTMENT OF DEFENSE INDEX OF SPECIFICATIONS AND STANDARDS (DoDISS) SPECIFIED IN THE SOLICITATION FORM A PART OF THIS STANDARD TO THE EXTENT SPECIFIED HEREIN.

PREPARING ACTIVITY: NAVY — AS

CUSTODIANS: ARMY — AV NAVY — AS AIR FORCE — 99 DLA —

REVIEW: USAF-71,82, DLA-CS, ARMY-MI
USER: ARMY-CL, ME, AT, MARINE CORPS-MC
PROJECT NUMBER: 4730-0021

MILITARY SPECIFICATION SHEET

TITLE
FITTING END, STANDARD DIMENSIONS FOR FLARELESS TUBE CONNECTION AND GASKET SEAL

SPECIFICATION SHEET NUMBER
MS33514G 21 MAY 90

SUPERSEDING
MS33514F 27 JAN 69

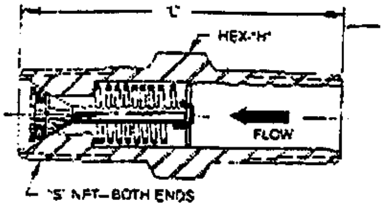
AMSC — N/A FSC 4730

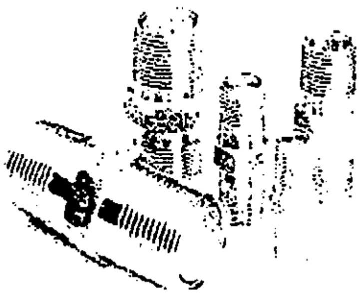
DISTRIBUTION STATEMENT
A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

7) Comp: Bypass Check Valve
   Vendor: Stewart
   Descript: This is a cryogen compatible check valve that bypasses the vaporizer if the vaporizer check valve were to fail close. It has a high enough cracking pressure that the pressure drop through the vaporizer will not cause it to open during peak flows.
   Issues: As with the previous component, we are utilizing a metal-to-metal seal check valve to provide a vaporizer bypass and it performs acceptably at the cryogenic temperatures. Different cracking pressures still have to be investigated to determine effect on system performance.

STEWART

Stainless Steel Check Valves

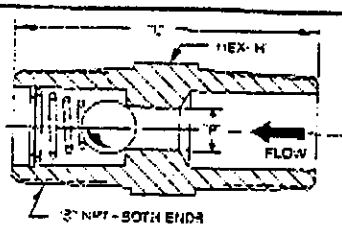


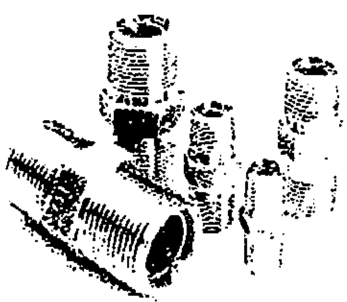


VALVE SIZE	CRACK'G PRESS	PART NUMBER	SIZE "S"	HEX "H"	"L"	CV
1/4	2 LB	A00101-01	1/4 - 18	5/8	1 7/8	.46
	10 LB	A00101-02				
3/8	2 LB	A00102-01	3/8 - 18	3/4	2 1/8	1.42
	10 LB	A00102-02				
1/2	2 LB	A00103-01	1/2 - 14	7/8	2 1/2	1.82
	10 LB	A00103-02				
3/4	2 LB	A00104-01	3/4 - 14	1 1/8	2 5/8	6.02
	10 LB	A00104-02				
1	2 LB	A00105-01	1 - 11 1/2	1 1/2	3 1/8	12.80
	10 LB	A00105-02				

O RING POPPET VALVES

- COMPACT LENGTH
- SPRING LOADED 2 OR 10 PSI
- FULL RANGE OF SIZES 1/4 TO 1" IPS
- ALL STAINLESS STEEL CONSTRUCTION
- VITON O-RINGS AS STANDARD
- OTHER O-RING MATERIALS AVAILABLE
- PRESSURES TO 2500 PSI
- TEMPERATURES -15°F TO +400°F
- CUSTOM VALVE INQUIRIES INVITED
VITON-TM-DUPONT





VALVE SIZE	CRACK'G PRESS	PART NUMBER	"L"	HEX "H"	"S" NPT	BALL SIZE	"P"	CV
[redacted]	[redacted]	[redacted]	1 1/2	5/8	1/4 - 18	.250	.200	.56
	10 LB	A00031-02						
3/8	2 LB	A00032-01	1 3/4	3/4	3/8 - 18	.312	.250	.83
	10 LB	A00032-02						
1/2	2 LB	A00033-01	2 1/4	7/8	1/2 - 14	.437	.335	1.49
	10 LB	A00033-02						
3/4	2 LB	A00034-01	2 1/2	1 1/8	3/4 - 14	.562	.442	2.98
	10 LB	A00034-02						
1	2 LB	A00035-01	2 3/4	1 3/8	1 - 11 1/2	.750	.530	5.65
	10 LB	A00035-02						

BALL CHECK VALVES

- COMPACT LENGTH
- SPRING LOADED 2 OR 10 PSI
- FULL RANGE OF SIZES 1/4 TO 1" IPS
- ALL STAINLESS STEEL CONSTRUCTION
- OTHER BALL MATERIALS AVAILABLE
- EASILY DISASSEMBLED FOR INSPECTION OR CLEANING
- PRESSURES TO 2500 PSI
- TEMPERATURES -20°F TO +650°F
- CUSTOM VALVE INQUIRIES INVITED

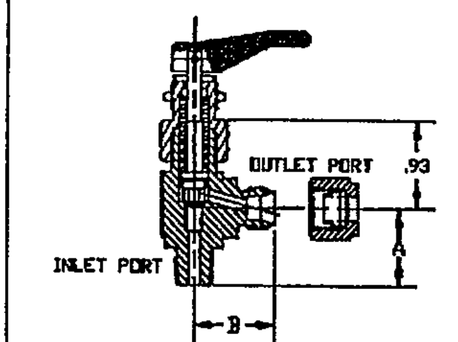
JAECO-STEWART, INC.
23 F.J. Clarke Circle / Bethel, CT 06801 / TEL: 1-800-897-6916 / FAX: 203/743-4362

8) Comp: Shutoff Valve
Vendor: Cole Palmer
Descript: The shutoff valve being used is not compatible with the temperature ranges we expect it to see but it has been used in the prototype because of its low pressure drop and light weight. It is a plug valve so that once open, the air flow basically goes straight through a tube, as opposed to using a multi-turn stem valve that has a higher C_v.
Issues: There has been discussion about removing this valve entirely or replacing it with a QD. The main problem with this is that as far as I have been able to determine, the donning switches on regulators doe not create a leak tight seal. SCBA's left open in trucks by firefighters that have forgotten to close them will slowly drain there contents. This would create a problem with our boiloff rate requirements and could also cause the vaporizer to freeze before use.
Req't: A low pressure drop shutoff valve that can meet the thermal and flow requirements is desired. A plug valve type design is appropriate but the potential for accidental closure with a quarter turn valve would require some sort of locking mechanism.

9) Comp: Fill/Drain Valve
   Vendor: Macro Technology
   Descript: The fill/drain valve is an aluminum toggle valve made by Macro Technology for cryogenic service. It is teed off of the liquid line between the bypass check valve and the inner vessel. During recharge, the vent stays closed and the remaining liquid air, if any, is drained from the dewar using the pivot mechanism. Then the vent valve is opened, the fill line connected to the fill/drain valve and the pack is filled with liquid air.
   Issues: This valve has problems similar to those encountered with the 3-way valve where the valve can freeze in a fail open position after draining the system. This valve has not been used as a fill valve yet, but the same problems would be expected. Macro Technology also manufactures a fill/drain QD. OSS has done preliminary tests on the component and it seems to work well but it is necessary to put it into service and cycle it. The component is used on home LOX medical units successfully.

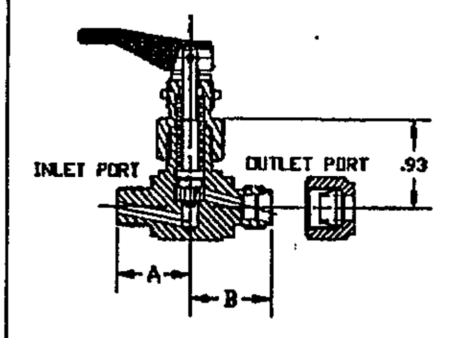
REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED

DEAD TIGHT SHUTOFF SEPARATES THIS UNIQUE DESIGN FROM MOST OF THE OTHER VALVES OFFERED BY OUR COMPETITORS. A RESILIENT STEM SEAL PACKING PREVENTS EXTERNAL STEM LEAKAGE, WHILE THE STEM SEAL PROVIDES BUBBLE TIGHT SEALING OVER THE FULL OPERATING RANGE. THE TOGGLE DESIGN PROVIDES QUICK OPENING AND CLOSING WITH A FLIP OF THE LEVER. THIS VALVE IS SUITABLE FOR SERVICE FROM VACUUM TO 250 PSIG. PANEL MOUNTING IS PROVIDED AS A STANDARD FEATURE. A PLASTIC HANDLE POSITIONER CAN BE ORDERED AS AN OPTION.



PART NUMBER: ATV04

ANGLE VALVE, ATV04



PART NUMBER: STV04

INLINE VALVE, STV04

GENERAL SPECIFICATIONS:

MAXIMUM OPERATING PRESSURE: 250 PSIG @ 70°F.
MAXIMUM OPERATING TEMPERATURE: 200°F. CONTINOUS
ORIFICE SIZE: ø.078 TO ø.176

PORT TYPE DASH NUMBER	PORT STYLE AND SIZE	INLET PORT 'A' DIMENSION	OUTLET PORT 'B' DIMENSION
NPT02	1/8 MALE NPTF	.81	.81
MPT04	1/4 MALE NPTF	.94	.94
FPT02	1/8 FEMALE NPTF	.81	.81
CPI02	1/8 FLARELESS TUBE		
CPI04	1/4 FLARELESS TUBE	.86	.86
SWG02	1/8 FLARELESS TUBE		
SWG04	1/4 FLARELESS TUBE	.86	.86

STANDARD MATERIALS OF CONSTRUCTION:

PANEL JAM NUT	BRASS, NICKEL PLATE
STEM	316 CRES
STEM TIP SEAL	KEL-F
SPRING	17-7 CRES
STEM PACKING	VITON
WASHER	316 CRES
HANDLE & WASHER	NYLON
HINGE PIN	300 SERIES CRES

HOUSING BODY AND STEM CAP:	MATERIAL CODE
2024-T351 ALUM / ANODIZE	AL
BRASS, QQ-B-626	BR
316 CRES, QQ-S-763 / ELEC-POL	SS

ORDER PART NUMBER INFORMATION:

BASIC PART NUMBER: ATV04 OR STV04 - OOOXX - OOOXX - OO

- OO — MATERIAL CODE
- OOOXX (second) — OUTLET PORT TYPE DASH NUMBER
- OOOXX (first) — INLET PORT TYPE DASH NUMBER

EXAMPLE:
DESIRED VALVE, INLINE PATTERN
1/8 FEMALE NPTF INLET PORT
1/4 MALE NPTF OUTLET PORT
ALUMINUM HOUSING
ORDER PART NUMBER: STV04-FPT02-MPT04-AL

CPI - REG. TM. PARKER HANNIFIN CORP.
SWG - "SWAGELOK" - REG. TM. SWAGELOK COMPANIES
KEL-F - REG. TM. 3M COMPANY
VITON - REG. TM. DUPONT
TEFLON - REG. TM. DUPONT

DRILLED HOLES: .0135 TO .125 = +.004 -.001 / .126 TO .250 = +.005 -.001 / .250 TO .500 = +.006 -.001 / .500 TO .750 = +.008 -.001 / .750 TO 1.000 = +.010 -.001

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND ARE TO BE MET BEFORE PLATING
TOLERANCES ARE: DECIMALS .XX = ±.02 .XXX = ±.010 ANGULAR ±1/2° FRACT ±

BREAK SHARP EDGES .005-.015 & REMOVE BURRS. MACHINED FILLETS TO BE .010-.020 RADIUS. CONC. =.005 TIR. SQUARENESS=.005 PER INCH. GENERAL FINISH TO BE 125 RMS PER ASA B46.1

DASH NO	NEXT ASSY	USED ON	N	P
APPLICATION			QUAN REQD	

-2	-1	UNC	FSCM No.	PART No.	DESCRIPTION	MATERIAL / SPECIFICATION	ITEM
QUAN REQD					PARTS LIST		

MATERIAL / SPEC.
HEAT TREAT / SPEC.
FINISH / SPEC.
CONTRACT No.
CUST. SPEC.
CUSTOMER
CHECKED — DATE
ENGR
DRAWN BY

Macro Technologies
Redmond - Washington - 98052

TOGGLE VALVE

SIZE	CODE IDENT No.	DRAWING No.
B	62529	S-11250

SCALE — RELEASE DATE — SHEET — OF

Appendix D: Backpack Electronics Information

LIQUID AIR BACKPACK ELECTRONICS

June 19, 1996

Technical contacts: Andrew Dawson (Project lead) 713-488-9080 Ext. 3205
Bill Robertson 713-488-9080 Ext. 3448

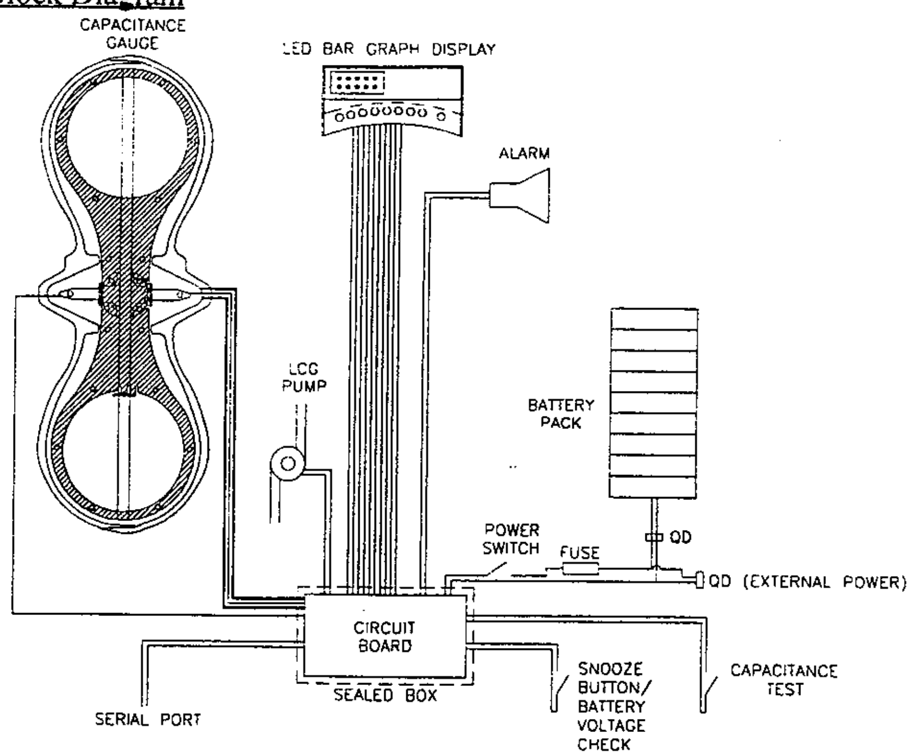
Description

The liquid air backpack electronics is an integrated microcontroller based capacitance gauge, battery monitor, caution & warning, failure detection, and liquid cooling garment (LCG) pump power supply circuit. The circuit is designed to operate from a +12V power supply or battery. For breathing-only backpacks, the LCG pump power supply circuit can be removed without interfering with the other electronic systems.

The microcontroller allows complete flexibility of the electronic design. Changes to the electronic logic and LED sequences can easily be changed by modifying the software. In the current Oceaneering Space Systems design, approximately 30% of the programming space and 10% of the RAM is used on the microcontroller chip (Microchip PIC16C73).

A prototype LED mask display is also provided in this package to provide liquid volume and electronic failure detect warning to the user. An eight green LED bar graph display is used to display liquid air volume in 1/8 increments. One red LED, when enabled, signals the user that a failure has occurred in the electronics package. If a failure occurs, it is intended that a technician will be used to trouble shoot the problem back at the repair shop.

Electronics Block Diagram



Electronics Package Features

- Main ON/OFF switch
  - Used to turn electronics ON or OFF
  - Both the capacitance gauge and LCG pump are toggle ON/OFF
  - Switch is in-line between the battery supply and electronics circuit
- LCG pump power supply
  - Switch mode voltage regulator design. 90% efficiency is achieved over linear regulator designs
  - Potentiometer (R11) sets pump speed
  - Pump typically draws 1 to 1.5 A (about 94% of the total current used)
- Capacitance gauge circuitry
  - Capacitance gauge oscillator
  - Coax cable voltage driven shield circuit: Prevents capacitance leakage to capacitance gauge circuit. Ensures that circuit is reading only capacitance gauge capacitance.
  - Capacitance gauge is connected to electronics by two wires. One plate of the capacitance gauge is connected to the center lead of the coax wire. The other capacitance gauge plate is grounded to the backpack. A ground wire connects the electronics to the backpack.
- Microcontroller
  - Using Microchip PIC16C73 microcontroller.
    - 4K programming space
    - 192 bytes of RAM
    - 4 A/Ds
    - 13 digital I/Os
    - Serial input/output
    - 3 counters
  - All logic of the electronics board is coded in an assembly language program.
  - Program features:
    - LED mask display driver
      - 8 green LEDs: Liquid air volume in 1/8 increments
      - 1 red LED: Failure detected
    - Alarm (triggered at ~20% liquid air volume)
    - Battery monitor and conservation modes:
      - Voltage detection
      - Voltage display driver (activated by holding snooze button or secondary button)
      - Conservation modes:
        - Shutdown LCG pump (i.e. < 10 V)
        - The capacitance gauge circuit and LED display functions as usual. The liquid volume display will blink alerting the user that the pump has been shut off.
        - Shutdown LED display (i.e. < 8 V)

- Failure detection & warning
  - If failure detected, red LED is enabled

  - Failures detected:
    - Capacitance gauge
      - Break in capacitance gauge wire: Under range display
      - Capacitance leak (i.e. human touch): Over range display
    - LCG pump
      - Broken wire or electronic failure in pump
      - High current load (i.e. frozen vaporizer)
- Filling Station toggle (next program upgrade)
  - Detects pack is connected to filling station
  - Disables alarm
- Serial output to PC computer (Calibration and data acquisition purposes)
  - Capacitance gauge frequency (Need to calibrate capacitance gauge)
  - Battery voltage
- Optional features built in to circuit
  - Snooze button: Sleep alarm for 5 min. when alarm is active
  - Secondary role: Press and hold to activate battery voltage display
    - Notes:
    - Snooze timer cannot be tripped when alarm is off
    - Snooze timer cannot be reset when alarm is in sleep mode
  - Electronic pressure transducer input (4-20 mA)
  - Second push-button switch
    - Separate switch for battery voltage display

- Connectors:
  - LED mask: 10 pin (8 green LEDs = liquid level, 1 red LED = Failure, ground)
  - Capacitance gauge: 4 pin (Coax center, Coax shield, ground, not used)
  - Battery: 2 pin (+12V, ground)
  - Snooze push-button: 2 pin
  - Secondary push-button: 2 pin (not used in prototype)
  - Alarm: 2 pin (+V, ground)
  - Serial output: 2 pin (Tx = transmitter, ground)
  - Pressure transducer: 4 pin (+12V, transducer output, ground, not used)
  - Pump circuit power: 2 pin (+12 V, ground)
  - Pump circuit power supply output: 2 pin (+V, ground)

Liquid Air Volume LED Mask Display (8 segment green LEDs)

OVER RANGE	●○○○○●○●
FULL	●●●●●●●●
7/8	●●●●●●●○
3/4	●●●●●●○○
5/8	●●●●●○○○
1/2	●●●●○○○○
3/8	●●●○○○○○
1/4	●●○○○○○○
1/8	●○○○○○○○
EMPTY	○○○○○○○○
UNDER RANGE	●○●○○○○●

- Over range display: Indicates a capacitance leak or added capacitance into the circuit. The voltage driven shield on the coax wire is designed to prevent this situation. This is a failure mode check. The red LED (failure detect) is also turned ON.

- Under range display: Indicates a loss of capacitance. This is caused by a break of either of the two wires to the capacitance gauge. This is a failure mode check. The red LED (failure detect) is also turned ON.

- Blinking display: If the pump is turned OFF by the microcontroller to conserve battery power (see Battery Conservation modes), the liquid volume LED display will blink at about 3 Hz. This alerts the user that the pump has been turned OFF.

Voltage Check Display

- Enabled when the user presses and holds the snooze button
- Display sequence (Note: Sequence is mirror of liquid volume display to prevent user confusion)

V > 12.5 Volts	●●●●●●●●
V > 12 Volts	○●●●●●●●
V > 11.5 Volts	○○●●●●●●
V > 11 Volts	○○○●●●●●
V > 10.5 Volts	○○○○●●●●
V > 10 Volts	○○○○○●●●
V > 9.5 Volts	○○○○○○●●
V > 9 Volts	○○○○○○○●
LOW BATTERY POWER	●○○●●○○●

- Notes:
  - For V < 10 V: LCG pump is turned OFF
  - For V < 8 V: Display is disabled (Battery power near complete discharge)
  -These settings are all software controlled. OSS is investigating preferred operational settings.

Additional Notes

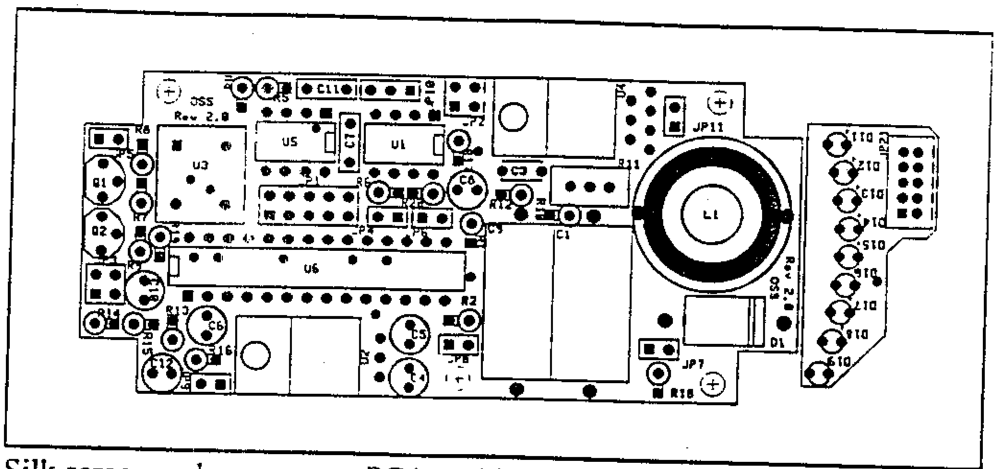
The microcontroller will require a programmer to assemble and download the object code to the chip. OSS has been using a programmer by Parallax (916-624-8333):

- Parallax programmer: PC16CXX-PGM (Part #35100)
- Parallax programmer software (Requires DOS based computer):
  - Assembler: SPASM EXE
  - Programmer: SPEP.EXE

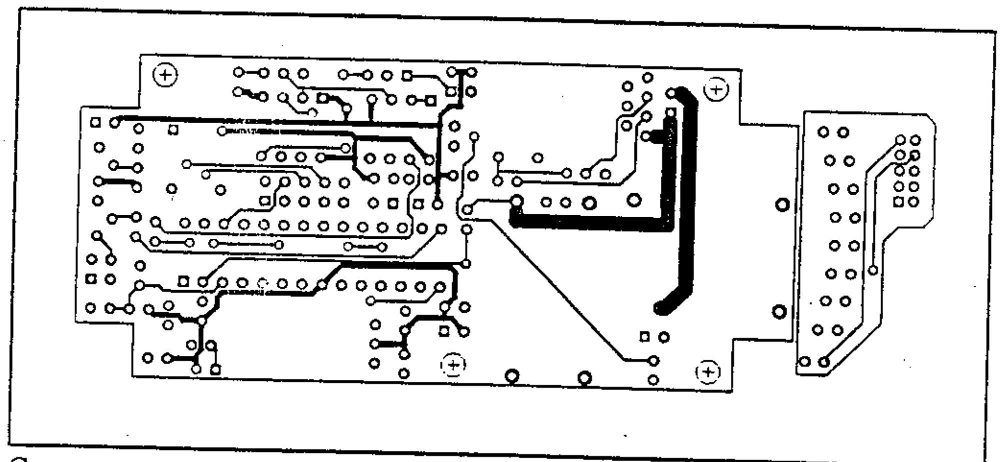
Parts List

Item	Qty	Part No.	Description	Ea.	Per Total	Pg Ref	Supplier/Notes	Part #
1	1		Printed circuit board	$45.00	$45.00			
Electronic Box								
1	1	HM114-ND	ABS Flame retardant plastic enclosure (Black)	$5.29	$5.29	343		
1b		HM126-ND	ABS Flame retardant plastic enclosure (Blue)	$5.29				
1c		HM139-ND	ABS Flame retardant plastic enclosure (Grey)	$5.29				
2		HM193-ND	Aluminum cover	$1.19				
Circuit Board								
1	1	P1317-ND	470 µF 16 V axial lead electrolytic capacitor	$2.10	$2.10	204		
2	2	P4582-ND	0.01 µF 16 V tantalum capacitor	$0.11	$0.23	227	$1.14 PER 10	
3	1	P2026-ND	10 µF 10V tantalum capacitor	$0.51	$0.51	224		
4	1	P2049-ND	10 µF 25V tantalum capacitor	$1.12	$1.12	224		
5	3	P2105-ND	1 µF 16V tantalum capacitor	$0.30	$0.90	224		
6	1	P1327-ND	220 µF 25V axial lead electrolytic capacitor	$1.10	$1.10	204		
7	1	1315PH-ND	150 pF capacitor (Cap gauge range: ~117-157 pF)	$0.06	$0.06	242	$0.63 per 10	
8	1	1N5821CT-ND	1N5821 Schottky barrier rectifier	$1.05	$1.05			
9	8	LT1049-ND	T-1 resistor LED (Green)	$0.23	$1.84	401	$1.88 per 10	
10			T-1 resistor LED (Green)				$15.00 per 100	
11			T-1 resistor LED (Green)					
12			T-1 resistor LED (Green)					
13			T-1 resistor LED (Green)					
14			T-1 resistor LED (Green)					
15			T-1 resistor LED (Green)					
16			T-1 resistor LED (Green)					
17	1	LT1045-ND	T-1 resistor LED (Red)	$0.23	$0.23	401		
18	2	*518-1020*	Header 5x2: Straight dual row gold solder tail header	$0.72	$1.44	197	Allied Electronics (No. 900): 72 position header	
19	2	*518-1020*	Header 2x2: (Same part stock as above)	$0.29	$0.58	197	Allied Electronics (No. 900): 72 position header	
20	7	*518-1046*	Header 2: Straight single row gold solder tail header	$0.15	$1.02	197	Allied Electronics (No. 900): 36 position header	
21	1	*518-1046*	Header 3 (Same part stock as above)	$0.22	$0.22	197	Allied Electronics (No. 900): 36 position header	
22	1	*PE-92402*	100 µH Inductor	$4.46	$4.46		Norvell Electronics	PE-92402
23	1	PN2907-ND	PNP EBC transistor (TO-92)	$0.18	$0.18	142	$1.79 per 10	
24	1	PN2222-ND	NPN EBC transistor (TO-92)	$0.18	$0.18	142	$1.79 per 10	
25	1	3299W-103-ND	10K Potentiometer	$3.30	$3.30	269	$28.29 per 10	
26	6	10KQBK-ND	10 K resistor	$0.12	$0.70	252	Box of 200	
27	1	22KQBK-ND	22 K resistor	$0.02	$0.02	252	Box of 200	
28	1	82KQBK-ND	82 K resistor	$0.02	$0.02	252	Box of 200	
29	1	180KQBK-ND	180 K resistor	$0.02	$0.02	252	Box of 200	
30	1	47KQBK-ND	47 K resistor	$0.02	$0.02	252	Box of 200	
31	1	4.7KQBK-ND	4.7 K resistor	$0.02	$0.02	252	Box of 200	
32	1	2.2KQBK-ND	2.2 K resistor	$0.02	$0.02	252	Box of 200	
33	1	2.7KQBK-ND	2.7 K resistor	$0.02	$0.02	252	Box of 200	
34	1		R	$0.02	$0.02	252	Box of 200	
35	1	14.0KXBK-ND	14.0 K 1% resistor	$0.11	$0.11	253	$0.54 per 5	
36	1	30.9KXBK-ND	30.9 K 1% resistor	$0.11	$0.11	253	$0.54 per 5	
37	1	SC1A0.1-ND	0.1 ohm 1W resistor	$1.93	$1.93	255		
38	1	LM158J	Dual Op Amp (8-Dip)	$3.57	$3.57	32	Newark	
39	1	NJM78M05FA-ND	LM7805 +5V regulator	$0.54	$0.54	122		
40	1	CXT152-ND	2 MHz clock oscillator	$4.08	$4.08	171		
41	1	*LT1074CY*	LM1074CY regulator	$7.17	$7.17		Marshall Electronics	LT1074CY
42	1	LM555CN-ND	LM555 timer	$0.81	$0.81	112		
43	1	PIC16C73/JW-ND	PIC1673 8-bit microcontroller (28-pin) (EEPROM)	$25.80	$25.80	99		
			PIC1673 8-bit microcontroller (28-pin) (OTP)	$18.15				
44	1	ED5328-ND	28-pin low profile socket	$2.27	$2.27	83		
45	2	ED5308-ND	8-pin low profile socket	$0.70	$1.40	83		
Other								
1	1	P9928-ND	Piezoelectric buzzer	$7.56	$7.56			
2	1	MPE-106D	Main power switch (SPST)	$8.33	$8.33	410	Newark	MPE-106D
3	1	61F768	Power switch cap (Type C-23, RED)	$0.67	$0.67	410	Newark	61F768
4	1	P7900060-1	Snooze: Otto Controls P7 Dome Switch (Momentary)	$9.50	$9.50			
5								
6								
7								
8	1	RG178B/U	Teflon Coaxial cable (3 ft @ $0.32/ft)	$0.96	$0.96	65	Pasternack Enterprises	
9	1	PE4202	SMC Plug, Clamp Attachment (Fits RG-178 cable)	$6.50	$6.50	38	Pasternack Enterprises	
10	1	PE4271	SMC Jack, Clamp Attachment (Fits RG-178 cable)	$6.95	$6.95	38	Pasternack Enterprises	
11	1	518-0173	Dual row mini-latch PV Housing (10 pin)	$1.17	$1.17	243	Allied Electronics (No. 956)	
12	2	518-0170	Dual row mini-latch PV Housing (4 pin)	$0.87	$1.74	243	Allied Electronics (No. 956)	

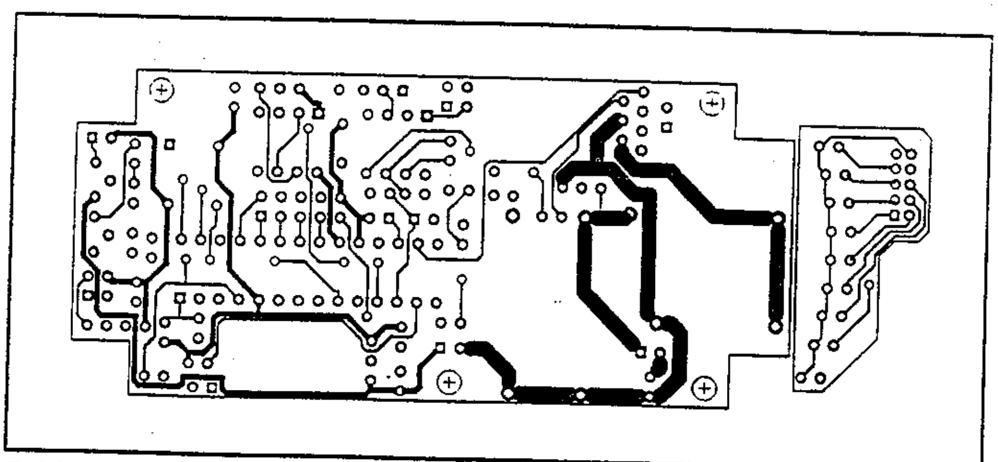
PC Board Layout:



Silk screen and component PC board layout of electronics and LED display



Component copper PC board layout of electronics and LED display



Solder copper PC board layout of electronics and LED display

<u>Attachments</u>

- Electronic parts ID list for circuit components
- Electronic circuit schematic
- Hard copy of PIC16C73 assembly source code
- PC disk containing:
  - OrCAD schematic
  - OrCAD PC Layout of current electronics board and LED display board
  - Assembly language source code for PIC16C73 microcontroller

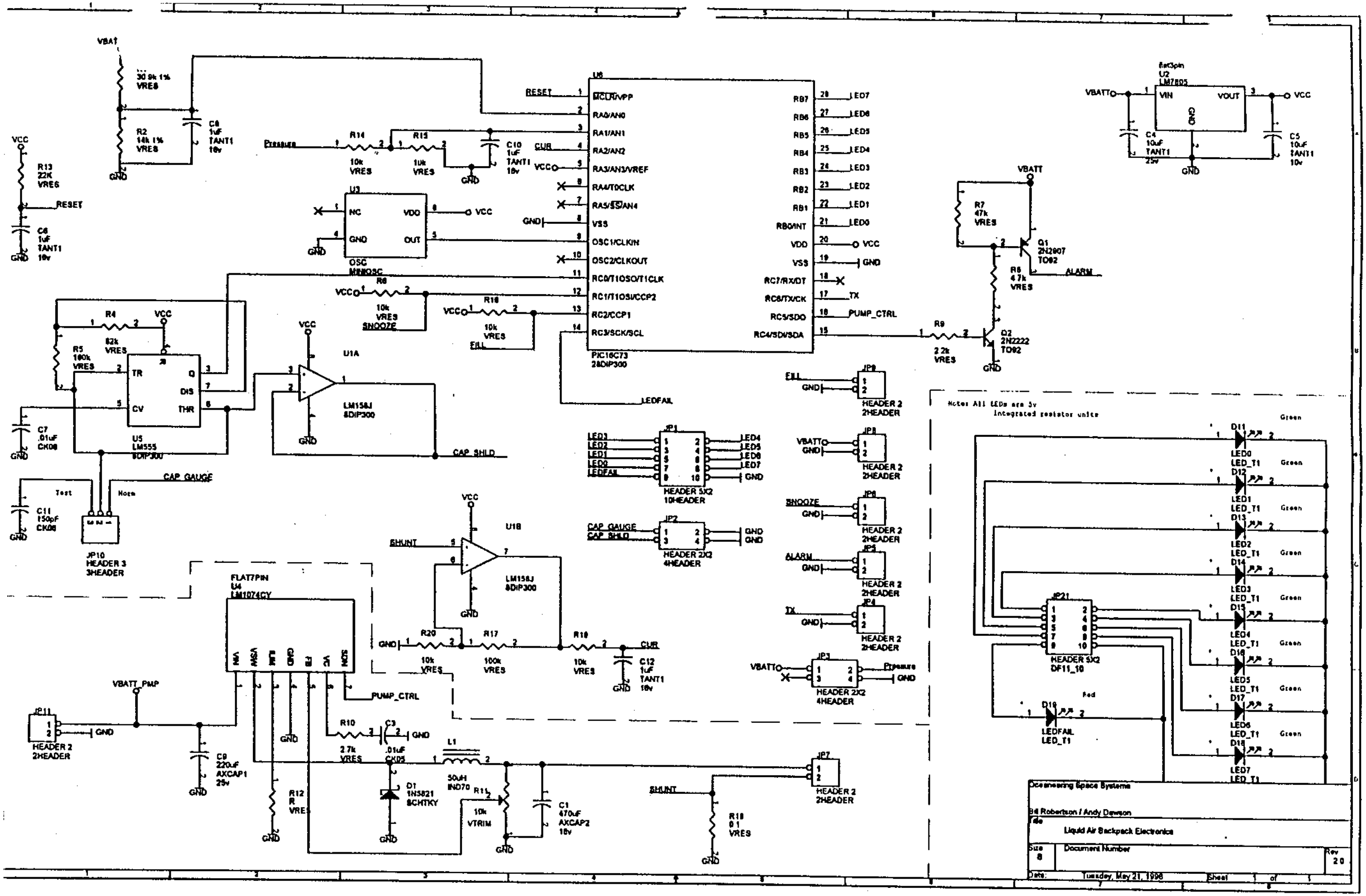
Liquid Air Backpack Electronics
1996

Revised: June 19,

Revision: 2.0

Bill Of Materials

Item	Quantity	Reference	Part
1	1	C1	470uF
2	2	C7.C3	.01uF
3	2	C4,C5	10uF
4	4	C6,C8,C10,C12	1uF
5	1	C9	220uF
6	1	C11	150pF
7	1	D1	1N5821
8	1	D11	LED0
9	1	D12	LED1
10	1	D13	LED2
11	1	D14	LED3
12	1	D15	LED4
13	1	D16	LED5
14	1	D17	LED6
15	1	D18	LED7
16	1	D19	LEDFAIL
17	2	JP1,JP21	HEADER 5X2
18	2	JP2,JP3	HEADER 2X2
19	7	JP4,JP5,JP6,JP7,JP8,JP9, JP11	HEADER 2
20	1	JP10	HEADER 3
21	1	L1	50uH
22	1	Q1	2N2907
23	1	Q2	2N2222
24	1	R1	30.9k 1%
25	1	R2	14k 1%
26	1	R4	82k
27	1	R5	180k
28	7	R6,R11,R14,R15,R16,R19, R20	10k
29	1	R7	47k
30	1	R8	4.7k
31	1	R9	2.2k
32	1	R10	2.7k
33	1	R12	R
34	1	R13	22K
35	1	R17	100k
36	1	R18	0.1
37	1	U1	LM158J
38	1	U2	LM7805
39	1	U3	OSC
40	1	U4	LT1074CY
41	1	U5	LM555
42	1	U6	PIC16C73



Oceaneering Space Systems
Bill Robertson / Andy Dawson
Title
Liquid Air Backpack Electronics
Size B
Document Number
Rev 2.0
Date: Tuesday, May 21, 1996
Sheet 1 of 1
Note: All LEDs are 5v integrated resistor units
U6 PIC16C73 28DIP300
U2 LM7805
U3 OSC MINIOSC
U5 LM555 8DIP300
U1A LM158J 8DIP300
U1B LM158J 8DIP300
U4 LM1074CY FLAT7PIN
JP21 HEADER 5X2 DF11_10
JP1 HEADER 5X2 10HEADER
JP2 HEADER 2X2 4HEADER
JP3 HEADER 2X2 4HEADER
JP10 HEADER 3 3HEADER
Q1 2N2907 TO92
Q2 2N2222 TO92
D1 1N5821 SCHTKY
L1 50uH IND70

Appendix E: Results of Human Testing of AWPS Prototype

Planned Manned Testing for AWPS Phase II

Part 1

Testing conducted during Part 1 is intended to compare four possible configurations of LCG's and target the cause of observed problems. Possible configurations include the IUOE LCG, a sized patch IUOE LCG, a shorty IUOE LCG, and a single connection LCG. All tests will be conducted on a common test subject in a highly controlled setting. Data collected will be utilized to create an optimized LCG.

1. Equipment
    a. Backpack
    b. LCG's
        I. IUOE garment
        ii. "sized patch" IUOE garment
        iii. "shorty" IUOE garment
        iv. single connection garment
2. Known problems
    a. Flow restrictions on LCG caused by equipment interface.
    b. Cracking pressure on LCG bypass.
3. Tests
    a. Fit (all 4 garments)
        i. Range of motion.
        ii. Interface locations and overlap areas.
        iii. Comfort
        iv. Patch and tube location.
    b. LCG flow restrictions (all 4 garments)
        i. Restrictions by movement.
        ii. Restrictions by backpack and harness.
        iii. Restrictions by confined space harness.
        iv. Restrictions by coveralls.
        v. Restrictions by splash suit.
        vi. Restriction by combination of i - v.
    c. LCG function (all 4 garments)
        i. Pressure drop.
            1) static
            2) typical positions and motions
        ii. Heat transfer.
        iii. Comfort scale
    d. Maximum pressure (representative garment)
        i. Garment burst test.
    e. LCG bypass function
        i. pressure setting
        ii. flow
    f. Weight
        i. Empty
        ii. Full

Manned Testing Part 1 Summary

Questions/Issues	Solutions
1. Is a shorty LCG viable?	A shorty version of an IUOE LCG was compared to an IUOE LCG and the difference in heat transfer was about a 20-25 watt decrease. The shorty concept seems viable for lower work rates or where having less garment interferences is more important than the loss in cooling effectiveness.
2. Do we need to size patches proportionately with the garment?	The sized patch LCG was compared to an IUOE LCG and the difference in heat transfer was about 50 watts. However, the garment was less comfortable. What was previously considered to be a small/medium patch size is more appropriate for a large/x-large garment. Sizing patches is not practical from a manufacturing standpoint. At this time it is not recommended that patches be sized. If it ever becomes necessary to size the patches, the current size should become a large/x-large size and the other size sets should be generated from it.
3. Is a single QD garment feasible? Did the rearrangement of the coat manifolds have any benefit?	The single QD garment was fairly successful although some fine tuning is needed. It does simplify the garment connection to the backpack and reduces the amount of external hoses. It also seems to have helped the balance of flow/cooling between the coat and pant. The different flow arrangement helped boost the coat performance. Overall there was a 100 watt increase in cooling when compared to an IUOE LCG. The rearrangement of the inlet and outlet locations for the front patches and the manifolds allowed the garment to bleed more effectively. By moving the patch outlet to the top of the patch the airtraps in those patches were eliminated.

4. Do the garments provide adequate cooling?	The heat transfer ranged from 176 to 312 watts during the treadmill portions of the tests. Although the work rate was higher, the KSU data had a heat transfer range of 175 to 400. Based on the Part 1 test results the cooling capacity of the garments seems to be in the right range.
5. What are the proper settings for the bypass and pump cut-off? What is the normal operating pressure drop across the garment?	The LCG bypass should open at 8-10 psi. The pump should shut-off at 10 psi. The garment should never be operated at over 12 psi. The garment should burst at 22 psi. The operating range for the garment (over a full range of motions and positions) is 3-7 psi with an average of 5 psi.
6. Where is the garment most susceptible to pinch-offs and restrictions?	The garment is most susceptible at the coat supply and return tubes. The pant supply and return tubes are the second worst problem. The other problems are in the top of the thigh patch, the bottom of the pant return patch, and the top of the calf patch.
7. How does using production patches affect the garment?	Using production patches raises the inflation pressure. The production patches raised the weight of the garment due to the fact that different transition and patch to patch tubing was used. Due to the increased pressure drop through the ribs of the patches the headers tend to overinflate and the patches fill unevenly. The addition of sealed dots raised the system pressure drop slightly over undotted production patches, but it prevents the overfilling and uneven flow.

8. Is pressure drop testing of individual patches beneficial? Can it predict the system pressure drop?	Pressure drop testing of individual patches is beneficial to compare and rank patch performance only. The results of an individual patch test cannot predict the system pressure drop. It is recommended that individual patches be tested to narrow the design possibilities and then system testing be performed on the best candidates. System testing is most beneficial in the proper orientation (on a mannequin) and with the proper length and type of tubing installed. Patch system tested does not predict the range of pressures associated with the wearer moving and changing positions in the garment.
9. How much does a garment weigh?	The current IUOE LCG weighs about 8.1 pounds full. The optimized LCG is expected to weigh about 7 pounds full. The weight reduction is due to the addition of sealed dots in the patch header which prevent ballooning and overfilling.
10. How important is the "fullness" of the garment?	There seems to be an optimum fullness for the garments. When properly filled they are less susceptible to pinch-offs and flow at a lower pressure drop. The bleeding of the garments is important to prevent air locked patches and dead areas. Dotted patches bleed and fill better than undotted patches. A fool-proof method for filling the garments properly has not been finalized.

11. Does the garment run effectively closed loop? What happens when the loop is opened for a period of time?	If a garment is filled on an open loop system, disconnected with the pump running, connected to a closed loop system, and then turned on, it runs closed loop without problems. If the loop is opened after the garment is filled, parts of the garment will drain and parts will overfill. Typically the coat drains and the pants overfill. When filling the pressure must be maintained to prevent the water from draining back into the bucket. When hooking the garment to the pack it cannot be partially connected while an open loop bypass is still connected to the pack. (i.e. Hooking up the coat while the pack is running with tubes connected to the pant QD's and flowing into a bucket. That scenario lets the coat drain into the bucket and when the pants are connected the total system volume is low.) A full garment can be connected to a running closed loop system, but turning it off first seemed preferable.

To Do List for New LCG's

Patch improvements

1. Dot headers.
2. Leave space in patches for transition tubing to be inserted about 3/4" beyond the tube sealing edge.
3. Refine single QD LCG coat manifold patches and revise for production sealing dimensions.
4. Improve the interface between the garment supply and return tubes and the manifold patches.

Pant improvements

1. Refine single QD pant design.
2. Change pant pattern to accommodate patch upgrades.
3. Shorten thigh patch to avoid top header pinch-offs and behind knee interference.
4. Lower calf patch to avoid behind knee interference.
5. Relocate/redesign pant return patch to avoid pinch-offs.
6. Build in strain relief along the back tubes between the return patch and the thigh and calf patches.
7. Improve pant to coat QD location and interface with coat.

Coat improvements

1. Refine single QD coat design.
2. Change coat pattern to accommodate patch upgrades.
3. Raise garment supply/return tubes to avoid waistbelt.
4. Lower supply/return tubes to the pant to avoid waistbelt.
5. Build in strain relief across shoulder blades and sleeves.
6. Improve coat to pant QD location and interface with pant.

LCG Flow Restriction Test

Test Summary

Each test consisted of five parts which tested one LCG with several pieces of equipment. The five parts were: LCG only, LCG and confined space harness, LCG and coveralls, LCG and splash suit pants and boots, LCG and splash suit pants and boots and backpack. The following LCG's were each run through all five parts: IUOE LCG, IUOE LCG2, Single QD LCG, Shorty LCG. Flow and pressure drop were recorded over all the standard motions. When a low flow or high pressure was observed the probable cause was recorded. All tests were run closed loop.

Observed Problems

During the first test the water loop was opened to add cold water. This allowed the "fullness" of the coat and pant to change and subsequently the flow balance changed. On all remaining tests a heat exchanger was placed in the water bucket to allow the loop to remain closed and keep the water chilled.

The instrumentation was designed for a garment with separate connections for the coat and pant. This made the single QD LCG very hard to instrument. The pant instrumentation was connected inline between the coat and pant. The coat instrumentation was connected to the single supply and return lines for the entire garment. This set-up included the pressure drop across the pant instrumentation in the garment pressure drop. It also required extra tubing that had to be looped around the waist to reach the instrumentation connections. This tubing did not interface well with the other equipment and possibly caused additional flow problems. This garment was run alone without the instrumentation in line to verify that it functioned better without the interferences.

The sized patch IUOE LCG was to be used but it developed an unrepairable leak after another test. A second IUOE LCG was substituted on the basis that interferences and restrictions would be the same between the two garments.

Results

IUOE LCG

The total flow was fairly stable but the pants consistently flowed higher than the coat. The pressure drop was the lowest but it also had the lowest percentage of Jasco patches. The most problematic pinch-offs were associated with the coat supply and return tubes. See "11/15 Restriction Test".

IUOE LCG2

The total flow was reasonably stable but slightly low. The shirt flowed better than the pants this test, probably due to the fact that the pant patches were all Jasco and had a higher pressure drop but the coat had some OSS patches, most importantly the supply patch, which have a lower pressure drop. The total garment had a higher percentage of Jasco patches but the pressure drop was not significantly higher than the previous IUOE LCG. However, the flow was lower and theoretically if the flows were matched the pressure drop would be higher. The restrictions were the same as with the previous IUOE LCG. See "1/3 Restriction Test".

Single QD LCG

The total flow was stable and average. The pressure drop was high and the flow in the pants was low, probably due to the problems associated with the instrumentation connection. The supply and return tubes were still the most susceptible to pinch-offs, but they were improved over the IUOE LCG's. See "11/26 Restriction Test". The garment was rerun without the instrumentation in line and with the tubes trimmed and connected properly. The flow was still stable, but the pressure drop was reduced. The pressure drop was still higher than the IUOE LCG, but the garment has a higher percentage of Jasco patches and an extra set of QD's in line. See "12/31 Restriction Test".

Shorty LCG

The total flow was stable but a little low. The pressure drop was slightly higher than the IUOE LCG but at comparable flow rates the pressure drop should be higher. The supply and return tubes were the most susceptible to pinch-offs. See "12/31 Restriction Test".

Conclusions

Through all of the tests the garment pressure drop followed the trends observed in the patch system testing. The more Jasco patches a garment had the higher the pressure drop was. Where the Jasco patches were located also affected the flow balance between coat and pant. If a pant was all Jasco patches and the jacket had some OSS patches, the jacket would flow better than the pant. Also, the make of the manifold patches made more of a difference in the garment than an individual patch did.

The most problematic pinch-offs were consistent throughout the tests. The supply and return tubes on the jacket were the biggest problem. These tubes got caught on the waistbelt of the backpack and the waistline of the splash suit pant. Once these tubes were caught on something or pushed up they would fold over the patch they supplied and cut off the flow. The pant supply and return tubes had a similar problem. When they were not situated correctly they rolled the attached patches up and cut off the flow. The other problem was the return patch on the back of the pant and the upper header on the thigh patch. When the test subject laid on his back or sat down the pants flow was reduced or shut down via these patches. The patch headers were not as severe of a problem as originally thought. If the garment was filled properly the headers were only marginally susceptible to crimps.

Two kinds of changes in flow and pressure drop were observed. One was a pinch-off somewhere in the garment, which results in low flow and high pressure. The second was a change in inlet pressure due to the position or motion of the test subject. This resulted in flow and pressure fluctuations.

LCG Flow Restriction Test

Test is to determine the restrictions on the LCG caused by other equipment like the backpack harness, splash suit, etc. The flow and pressure drop is recorded as a set of standard motions is performed. Each piece of equipment is tested individually with each LCG and a cumulative test is done last. Any excessively restrictive or unrestrictive equipment may be excluded from the cumulative test. All tests are performed on the same test subject.

<u>Equipment Needed</u>

Backpack with full harness.
Confined space harness
Coveralls
Splash suit
LCG's (required versions)
LCG QD belt with manifold
Backpack style pump and umbilicals
Instrumentation to record flow and pressure drop through jacket and pant
Test subject who fits all LCG's and can perform the "standard motions"

<u>Standard Motions</u>

1) Lay on back for 20 seconds
2) Lay on stomach for 20 seconds
3) From a standing position:
   a) kneel for 20 seconds
   b) move to crawling position, crawl for 5 steps
   c) return to kneel, pause
   d) stand up
4) From a standing position, do a full squat, pause, stand up. 2 repetitions.
5) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
6) Touch toes, 3 repetitions.
7) From a standing position, lean back, lean left, lean right, return to upright.

<u>Test 1</u> (LCG only)

1) Don LCG (full).
2) Don LCG QD belt and umbilicals.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start garment flowing.
6) Test subject performs the standard motions.
7) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
8) Repeat for each type of LCG.

<u>Test 2</u> (LCG and confined space harness)

1) Don LCG (full).
2) Don confined space harness.

3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

Test 3 (LCG and coveralls)

1) Don LCG (full).
2) Don coveralls.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

Test 4 (LCG and splash suit)

1) Don LCG (full).
2) Don splash suit pants.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

Test 5 (LCG and backpack)

1) Don LCG (full).
2) Don backpack and adjust harness.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start garment flowing.
6) Test subject performs the standard motions.
7) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
8) Repeat for each type of LCG.

Test 6 (Cumulative)

1) Don LCG (full).
2) Don splash suit pants.
3) Don confined space harness.
4) Don backpack and adjust harness.
5) Attach instrumentation to QD block.
6) Attach garment to instrumentation.
7) Start garment flowing.
8) Test subject performs the standard motions.
9) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
10) Repeat for each type of LCG.

LCG Fit Test

Test is to evaluate the fit, mobility, and comfort of the LCG garment. The garments are evaluated without any other equipment and are not "running". All tests are performed on the same test subject.

Equipment Needed

LCG's (required versions)
LCG QD belt with manifold and umbilicals
Test subject who fits all LCG's and can perform the "fit motions"

Fit Motions

1) Reach forward and around as far as possible.
2) Reach back as far as possible.
3) Reach up as far as possible.
4) Squat
5) Kneel, both knees, one knee.
6) Bend forward, bend back, lean side to side.
7) Sit down, lean on back rest.

Test

1) Don LCG (full).
2) Answer data sheet questions 1-3.
3) Test subject performs the fit motions. Record the rating after each motion.
4) Don LCG QD belt and umbilicals.
5) Connect LCG to QD block.
6) Disconnect LCG. Record the rating.
7) Doff the LCG.
8) Answer the remaining questions.
9) Repeat for each type of LCG.

LCG Fit Test

Test Summary

Most of the scores for all of the garments were a 3 or 4. The shorty and the single QD LCG were the best fitting/looking/feeling garments. The test subject commented that the single QD LCG was noticeably better. The improvement on that particular garment is due to a change to a better quality fabric.

Observed Problems

Most of the scores below "good" were associated with the sleeve/shoulder tubes when reaching forward.

Connecting to the QD block is very difficult. Due to both the location of the block and the logistics of hooking up two sets of QD's.

During the fit test and the other tests the pants had a tendency to slip down. This is most likely due to the weight of the pants and the tubes that run up the back of the leg "pulling" down on the pants.

The sized patch IUOE LCG was not as comfortable as the other garments. The comments were that it felt like body armor and it was too stiff. The increased amount of patch coverage seems of decrease the wearer's comfort.

LCG Function Test

Test is to establish baseline data for the basic functions of various LCG's. Maximum, minimum, and average pressure drop is recorded. Heat transfer is determined through the in and out water temperatures for the suit and a "cool scale" rating assigned by the test subject.

Equipment Needed

LCG's (required versions)
LCG QD belt with manifold
Chiller
Backpack style pump and umbilicals.
Instrumentation to record flow, pressure drop, water temperature in, and water temperature out for the jacket and pant.
Test subject who fits all LCG's and can perform the "standard motions" and exercise.

Standard Motions

1) Lay on back for 20 seconds
2) Lay on stomach for 20 seconds
3) From a standing position:
    a) kneel for 20 seconds
    b) move to crawling position, crawl for 5 steps
    c) return to kneel, pause
    d) stand up
4) From a standing position, do a full squat, pause, stand up. 2 repetitions.
5) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
6) Touch toes, 3 repetitions.
7) From a standing position, lean back, lean left, lean right, return to upright.

Exercise

1) Walk on treadwill at 3 mph, no incline. Duration is 15 minutes.

Test

1) Don LCG (full).
2) Don LCG QD belt.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start system and data recording.
6) Test subject stands at rest for 3 minutes.
7) Record cool scale rating for resting.
8) Test subject performs the standard motions.
9) Record cool scale rating for standard motions.
10) Test subject performs exercise.
11) Record cool scale rating for exercise.
12) Repeat for each type of LCG.

LCG Function Test

Test Summary

Each test run consisted of the standard motions portion and the treadmill. There were five tests completed: an IUOE LCG, a second IUOE LCG, a shorty IUOE LCG, a sized patch IUOE LCG, a single QD LCG. The IUOE LCG configuration was run twice due to a flow problem in the first test. The exact cause of the lack of flow could not be targeted, but the problem was isolated to one test. For all tests the inlet temperature was started at 60 deg. F for the motions and the first 10 minutes of treadmill work. During the treadmill work, the temperature was to reduced to reach 55 deg. F at 15 minutes, 50 deg. F at 30 minutes, and 45 deg. F at 40 minutes. Flow and pressure drop were recorded and heat transfer was calculated using the inlet and outlet temperatures. Cool scale ratings were assigned by the test subject and recorded every five minutes. All tests were run closed loop.

Observed Problems

All of the garments were slightly large for the test subject. Extra elastic bands had to be used to keep the lower back supply and return tubes from twisting and pinching off the shirt flow. The sized patch garment was not as comfortable as the others - due to the increased patch coverage. The instrumentation was unreliable at times (usually the pants pressure transducer). The configuration to hook up the single QD LCG with the instrumentation in line was difficult and cumbersome.

Results

IUOE LCG

The first test with this garment was disregarded in the conclusions because of a low flow problem. While the test subject was standing still the flow in the pants and coat dropped to almost zero and was never recovered. The cause of the problem was never determined, except to theorize that the garment was not properly filled or a tube was severely twisted. See "11/21 Function Test".

2nd IUOE LCG

The second test with the garment was more successful. The elastic bands were used to help keep the supply and return tubes in place. The average flows were the most variable of all the tests. The heat transfer was acceptable for the work rate. The pressure drops were fairly low, but varied like the flow rates. The test subject reported average cool scale ratings (5-6). See "12/8 Function Test".

Shorty LCG

The shorty LCG showed about 20 - 25 watts less cooling than the full version of the IUOE LCG. It had a higher but more consistent pressure drop and a more even flow rate. It also had the highest percentage of Jasco patches. The test subject reported slightly higher cool scale ratings (5-6) and felt warmer towards the end of the test. See "11/22 Function Test".

Sized IUOE LCG

This LCG has patches that have been sized proportionately with the garment size, this gives the garment more cooling surface area than the regular IUOE LCG. This garment provided about 50 watts more cooling than the other IUOE LCG. It had a higher flow rate than any other garment and a very low pressure drop. It was the only garment with 100% OSS patches. The test subject reported average cool scale ratings (5). See "11/25 Function Test".

Single QD LCG

This garment provided about 90 - 100 watts more cooling than the regular IUOE LCG. It fit better and the patches were better situated on the test subject. The pressure drop was higher due to more Jasco patches and some instrumentation that was in line between the coat and pant. The test subject reported slightly better cool scale ratings (4.5 - 5). See "12/11 Function Test".

Conclusions

The heat transfer at this work rate is in the right range. The treadmill averages ranged from 176 to 312 watts. (Considering that the KSU data ranged from 176 to 400 watts at the same walking rate but with a backpack and splashsuit.)

The difference in pressure drop between the garments corresponds to the patch system testing results which showed a higher pressure drop in the Jasco patches. Through all of the function tests the pressure drop was higher when the percentage of Jasco patches was higher.

The three IUOE LCG's can be compared because they all have the same flow path and vary only in surface area and make of patch. The shorty provided less cooling as expected, but not so much less that it is not a viable option for certain work environments. The sized patch garment did provide more cooling than the regular version, but not substantially more. This garment was also the only all OSS patch garment and some of the improvement in heat transfer can be attributed to better flow. It was less comfortable than the smaller patch version. It does not seem to be necessary to size the patches, especially considering the manufacturing problems and decreased comfort associated with it.

The single QD LCG should be compared to the IUOE LCG because they have similar surface areas but vary in flow path and fabric. The better heat transfer was most likely due to more balanced flow through the jacket and pants and better contact with the patches. The fabric used for this LCG was a higher quality with a higher lycra content than the previous garments.

LCG QD Bypass Testing

Problem

During certain types of manned test situations the LCG flow becomes constricted which increases the current draw by the water pump. At a preset current, the electronics shuts the pump off to conserve the battery power. The assumption is that total water loop constriction is probably caused by a vaporizer freeze up in the backpack. A by-pass valve is incorporated into the LCG connection manifold. This by-pass would recirculate water back to the pack, by-passing the LCG to keep the vaporizer from freezing, if the flow to the LCG were restricted.

This test is designed to determine what spring/spacer combination is needed for the bypass valve so it opens at the correct pressure.

How it works

1) The LCG constricts, or other problem causes a pressure rise in the system.

2) The by-pass opens, allowing the water to recirculate back to the pack.

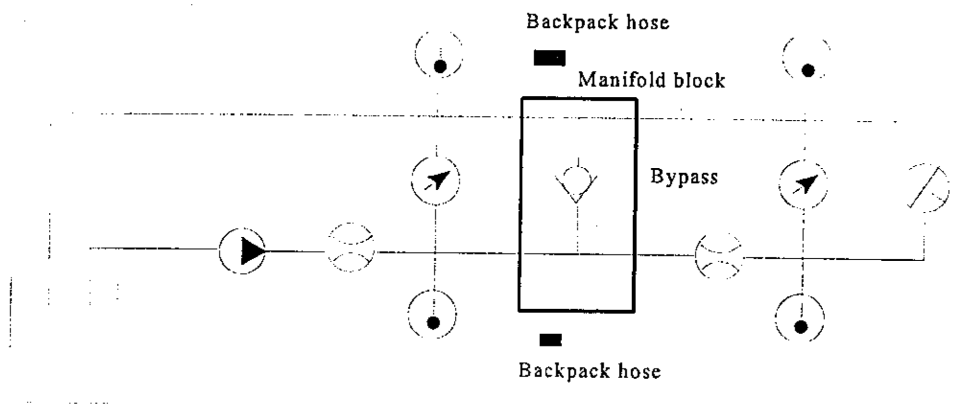
3) If the by-pass does not open, or the restriction is due to the vaporizer freezing, the motor current increases until the motor shuts down and the user loses cooling.

The following table lists the various pressures expected in the cooling loop:

Action	Pressure drop (assumed)	Pressure drop (measured)
normal operation	3 psi	3-6 avg 5
bypass opens	5 psi	8-10
pump shuts off	8 psi	10-12
LCG MAWP	12 psi	12
LCG Burst Press	22 psi	22-25

Equipment:

QD block
2 sets of umbilical instruments (flow meter, dPress, temp in/out (not used))
pump
water bucket
misc hose & connectors
various size and strength springs
spacers to pre-load springs



Procedure:

- plug normal backpack connections on manifold block
- connect pump and one instrument set to manifold block
- connect control valve and second instrument set to manifold block
- circulate water through block
- monitor water flow and pressure drop on both "sides" while closing control valve
- note when the manifold bypass appears to open (flow & dP)
- adjust spring and spacer block to set bypass cracking pressure and flow rate to acceptable limits

crack/max dP		Spring number						
Spacer length	flow rate	3	4	5	6	7	8	9
0		too short	too short					
.1		too short	14.5/ 17					
.2		12.2/ 14.0	17.2/ 18					
.3		14/ 24						

Results

Initial tests were done using a .25" diameter ball with the two weakest springs and short spacers between .1" and .3" in length. This resulted in either a cracking pressure too high > 12 psi, or the bypass being continually open. A weaker spring was quickly looked for in various catalogs and spring collections in the building. None was found.

A theory was presented that the ball was not presenting enough surface area, so higher pressures were required to produce the force needed to move the spring. A "poppet" flat ended plug was substituted for the ball, and spacers added to determine if this was true.

Using the .1" spacer as the poppet, and the .2" spacer to set the length, the bypass would not seal even with the plug threaded all the way in. Using the .3" spacer to set the length, the bypass worked correctly with ~.1" of the plug not threaded in. These results indicated that ~.31" of spacer was needed using the #3 spring. A single poppet was constructed with a flat sealing surface ~.25" diameter, .31" long, with an alignment pin .175" diameter, ~.5" long, to fit inside the spring. This configuration allowed the cracking pressure to be adjusted using the threaded plug. Cracking pressures from 5-15 psi were achieved. The desired cracking pressure of 8 psi is nicely in the middle of this range. Another poppet was constructed and tested in a second bypass manifold to conform performance. The second manifold block appeared to be drilled slightly differently, but there was sufficient adjustment in the threaded plug to achieve the same performance.

LCG Pump Evaluation

Problem
What is the performance of the LCG pump?

Experiment
Provide a variety of LCG pumps with a constant voltage and varying pressure drop. Measure current draw and flow rate produced. Graph flow versus current and pressure drop.

These "pump curves" allow comparison of pump performance, prediction of shutoff currents, and maximum pressure.

Results
The pump taken from IUOE pack #1 (pump 2) flowed at .4 gpm with a pressure drop of ~5 psi at a current of ~1 A. This conforms to expected pump performance. Other pumps were tested for comparison. The old Tuthill did not produce as much pressure, but also did not draw as much current. The new tuthill pumped slightly better (more pressure) with very similar current draw. The new custom pump performed very badly (low pressure, high current). It was determined that the motor was wound incorrectly, and the final optimization of the pump head was not complete. This pump will be re-tested when its modifications are complete.

The current draw graph was used to re-set the pump shutoff in the microcontroller. Also, several new features were added to help diagnose LCG flow problems. The new pump cutoff program works as follows:
If the current draw by the LCG pump is more than XXX mA, the microcontroller starts a 2 second counter. (to eliminate transients)
If the current draw continues to exceed the limit after the 2 second wait, the red LED will flash, and a 4 second timer will start.
If the current draw continues to exceed the limit after the 4 second wait (6 sec total) the LED will remain on (steady), and the pump will shut off.

Pressing the "snooze button" snoozes the low cryo alarm.
Holding down the "snooze button" shows the battery voltage on the LED display.
Holding down the "snooze button" for more than 4 seconds switches the display to a "flow" indication (8 lights indicates full flow (min current), fewer lights indictes lower flow (higher current)).
Holding down the "snooze button" for a total of 9 seconds will restart the pump if it was shut down.

The actual values programmed in the microcontroller will be adjusted as parts are finalized and complete system testing can be accomplished.

LCG Weight Test

Test Summary

Because the available LCG's were a mixture of fabric and patch types and had extra tubing from multiple repairs, a garment weight was calculated using patch sets and an empty fabric garment. The weighed fabric garment was used as a constant. The only empty fabric garment was an XX-Large constructed from a heavier weight fabric. Therefore the weight of the empty fabric garment represents a worst case. The patch sets that were used were glued together in an IUOE configuration with typical tubing and tubing lengths. A set of unpaired QD's was included in the weights. Patch sets were weighed completely empty/dry and full. They were filled by bleeding and then stabilizing at .4 gpm.

Observed Problems

Garment weight should be minimized. Headers balloon and hold a lot of excess water. If water weight is reduced the surface area should not be compromised.

Results

	Patch Set Empty			Patch Set Full		
Patch Set	**Total**	**Coat**	**Pant**	**Total**	**Coat**	**Pant**
OSS				4.4	2.2	2.2
Jasco	3.1	1.6	1.5	5.8	2.95	2.85
Jasco w/dots	3.1	1.6	1.5	4.7	2.2	2.5

	Garment Empty			Garment Full		
Garment	**Total**	**Coat**	**Pant**	**Total**	**Coat**	**Pant**
OSS				6.7	3.35	3.35
Jasco	5.4	2.75	2.65	8.1	4.1	4
Jasco w/dots	5.4	2.75	2.65	7	3.35	3.65

Conclusions

The increase in weight from the OSS patches to the Jasco patches is due to a material change. In order to produce the Jasco patches with available materials the connector tubing was changed to a larger ID. The OD of the tubing in the garment was changed to fit the patches, but the ID was kept the same. The thicker wall tubing added some weight, but also solved some other material problems (tube crimps and creases).

The substantial weight reduction from the Jasco to the Jasco with dots is a result of the headers retaining less water. With the dots the headers cannot balloon and overfill. The dotted patches retain the surface area of the original design, but reduce the total water weight by 1.1 pounds.

Single Patch Pressure Drop Test

Test Summary

Six variations of a basic (H-style) calf patch were tested.

1. Original OSS made patch
2. OSS made patch with Jasco number of ribs.
3. Jasco production patch
4. Jasco production patch with dots added to top and bottom headers
5. Jasco production patch with dots added to top, bottom, and center headers
6. Jasco production patch with dots added to all headers

These variations were chosen to target the possible differences between OSS made patches and patches made by Jasco. Known discrepancies were the number of flow ribs within the calf patches and the cross sectional shape of the flow ribs. Due to sealing differences there were fewer ribs per inch in a Jasco patch and the Jasco ribs were less "open" than the original OSS patches.

All patches were run from 0 - .4 gpm through a single patch. Typical patch to patch (3/16" ID) tubing was glued into all connector tubes. Those tubes were hose barbed to a short piece of 3/16" ID tubing which was glued inside 3/8" ID tubing to connect to a QD. All tests were flowing open loop.

Observed Problems

Garments with a higher percentage of Jasco patches typically have a higher pressure drop.Because, the cross sectional shape of the Jasco flow ribs do not form open flow channels, these patches should require more inflation pressure. At higher pressures the patch headers overinflate which pinches off and reduces the flow in the ribs. These headers are also susceptible to pinch-offs and "pulses" in the garment flow. Headers that are not near an outlet tube can be an "air trap", which makes the garment hard to bleed.

Results

1. Original OSS made patch
   The patch fills evenly (left side first, then right side), the headers need to be pushed to clear the air, pressure drop is relatively low but it rises with the flow rate.
2. OSS made patch with Jasco number of ribs.
   The patch fills less evenly than the #1, the headers also have to be bled, pressure drop is slightly higher and also rises with the flow rate.
3. Jasco production patch
   The patch does not fill evenly, the bottom headers fill and balloon first and then the ribs flow. The headers have to be bled. The pressure drop is substantially higher than in the first two patches but it does not rise with the flow in the same way. The graph suggests that there may be a leveling out effect as the flow rises.

4. Jasco production patch with dots added to top and bottom headers
5. Jasco production patch with dots added to top, bottom, and center headers
   Both of these patches fill more evenly than the unmodified Jasco patch but not as well as the OSS patches. The headers bleed better without help where they are dotted. The pressure drop is slightly higher than the unmodified Jasco patch and follows a similar leveling trend. The headers do not balloon where there are dots and the patch feels lighter and more flexible.
6. Jasco production patch with dots added to all headers
   The patch fills evenly like the OSS patches. The headers bleed pretty well and they do not balloon. This patch feels the lightest and most flexible of all of them. The pressure drop is the highest of all the patches, but it is not substantially higher than the other Jasco patches. The pressure drop rises with the flow but shows the same to slightly more of a leveling effect.

See graph "Single Patch Test 12/6/96".

<u>Conclusions</u>

The Jasco patches showed a higher pressure drop and a different rise in pressure drop over increasing flow rates. This is due to the difference in inflation pressures required to flow each type of patch. The OSS patches have open ribs which can handle some amount of flow before inflating or stretching. So, at a certain flow they require an increasing inflation pressure. The ribs on the Jasco patches are not open and require some inflation pressure to flow any amount. Once they are inflated and flowing they can accommodate increasing flow. This is seen in the leveling off of the pressure drop as the flow increases.

Considering all factors but pressure, the fully dotted Jasco patch is the preferable design. (better quality, lighter, bleeds, even filling) However the pressure drop is high. Based on the results of this test, three garment systems will be tested to determine the pressure drop and characteristics of an entire system of patches. Heat-sealing variations will be explored to produce a production patch with more open ribs (highly unlikely).

Part 1B

Testing conducted during Part 1B is intended to confirm the improved LCG design and the upgrades made to the bypass and pump electronics. The improved design was based on the Part 1 test results. Select tests will be repeated from Part 1 to directly compare the new design to the old. One new variation of the restriction test has been added to simulate the real water loop and the backpack is used in one of the function tests.

1. Equipment
    a. Backpack
    b. LCG's
        i. AWPS3 garment (single QD style)
    c. Simulated water loop
        i. Backpack pump, QD block with bypass, electronics, etc.
2. Known problems
    a. Flow restrictions on LCG caused by equipment interface.
    b. Cracking pressure on LCG bypass.
    c. Water loop compatibility with LCG
3. Tests
    a. Fit
        i. Range of motion.
        ii. Interface locations and overlap areas.
        iii. Comfort
        iv. Patch and tube location.
    b. LCG flow restrictions
        i. Restrictions by movement.
        ii. Restrictions by backpack and harness.
        iii. Restrictions by confined space harness.
        iv. Restrictions by coveralls.
        v. Restrictions by splash suit.
        vi. Restriction by combination of i - v.
    c. LCG & Water loop compatibility
        i. Restrictions by movement.
        ii. Restrictions by backpack and harness.
        iii. Restrictions by confined space harness.
        iv. Restrictions by coveralls.
        v. Restrictions by splash suit.
        vi. Restriction by combination of i - v.
    d. LCG function
        i. Pressure drop.
            1) static
            2) typical positions and motions
        ii. Heat transfer.
        iii. Comfort scale
    e. LCG and backpack function
        i. Pressure drop.
            1) static
            2) typical positions and motions
        ii. Heat transfer.
        iii. Comfort scale

Manned Testing Part 1B Summary

Questions/Issues	Solutions
1. What was the effect of using all production (Jasco) patches?	As expected the pressure drop was higher than an OSS patch or mixed patch garment. However, the garments withstand a machine wash and dry without problem.
2. What was the effect of using dotted headers in the patches?	The dotted headers reduced the water volume in the garment by preventing the overfilling of the headers. They also helped bleed the garments by breaking up the large air bubbles. The shape of an inflated patch with dotted headers is not as concave as with undotted headers, so separate left and right patches do not have to be made. They did increase the pressure drop further, but smaller dots may provide the same benefits and affect the pressure drop less. Dotted headers are less susceptible to pinch-offs than the undotted headers. The dots may have contributed to the more stable flow and pressure drop during movement by reducing the wave effect in the garment.
3. Is the redesigned garment less susceptible to pinch-offs and flow/pressure fluctuations?	Yes, the relocation of the inlet and outlet tubes alleviated the pinch-offs associated with those tubes. The single QD design simplified the tube runs to the pack QD block and reduced the possibility of hang-ups. The pants are still susceptible to a slight pinch-off when laying down and sometimes when squatting. The garment does not pinch-off when sitting down. Overall, the flow and pressure fluctuations that are indicative of pinch-offs are not as extreme as seen before. Also, the flow and pressure fluctuations that happen with a change in head pressure are not as extreme.

4. Does the new garment operate within the parameters assumed in Part 1?	The garment runs at .4 gpm and about 5.5 to 7.5 psi. The pressure drop is a little higher than expected, but may drop with smaller dots and no leaks. (That number includes some of the extra QD's and stuff needed to instrument the garment.) The heat transfer for the work rate was about what we expected, ranging from about 160 watts for rest and standard motion sessions to about 300 watts for moderate treadmill work.
5. Is the bypass functioning in response to garment pinch-offs and extreme fluctuations?	The bypass did function when the pressure approached 10 psi. It cracked partially at about 8 psi and opened fully at about 10 - 12 psi. It did not always fully open during quick spikes.
6. How does the complete water loop function?	Only the LCG and bypass were tested. The pump required external power to provide the proper flow so power consumption was not evaluated. The electronics were not installed for any of the tests so the pump cut-off and time out features were not tested.

LCG Flow Restriction Test

Test is to determine the restrictions on the LCG caused by other equipment like the backpack harness, splash suit, etc. The flow and pressure drop is recorded as a set of standard motions is performed. Each piece of equipment is tested individually with each LCG and a cumulative test is done last. Any excessively restrictive or unrestrictive equipment may be excluded from the cumulative test. All tests are performed on the same test subject.

Equipment Needed

Backpack with full harness.
Confined space harness
Coveralls
Splash suit
LCG's (required versions)
LCG QD belt with manifold
Backpack style pump and umbilicals
Instrumentation to record flow and pressure drop through jacket and pant
Test subject who fits all LCG's and can perform the "standard motions"

Standard Motions

1) Lay on back for 20 seconds
2) Lay on stomach for 20 seconds
3) From a standing position:
   a) kneel for 20 seconds
   b) move to crawling position, crawl for 5 steps
   c) return to kneel, pause
   d) stand up
4) From a standing position, do a full squat, pause, stand up. 2 repetitions.
5) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
6) Touch toes, 3 repetitions.
7) From a standing position, lean back, lean left, lean right, return to upright.

Test 1 (LCG only)

1) Don LCG (full).
2) Don LCG QD belt and umbilicals.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start garment flowing.
6) Test subject performs the standard motions.
7) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
8) Repeat for each type of LCG.

Test 2 (LCG and confined space harness)

1) Don LCG (full).
2) Don confined space harness.

3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

<u>Test 3</u> (LCG and coveralls)
1) Don LCG (full).
2) Don coveralls.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

<u>Test 4</u> (LCG and splash suit)
1) Don LCG (full).
2) Don splash suit pants.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

<u>Test 5</u> (LCG and backpack)
1) Don LCG (full).
2) Don backpack and adjust harness.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start garment flowing.
6) Test subject performs the standard motions.
7) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
8) Repeat for each type of LCG.

<u>Test 6</u> (Cumulative)

1) Don LCG (full).
2) Don splash suit pants.
3) Don confined space harness.
4) Don backpack and adjust harness.
5) Attach instrumentation to QD block.
6) Attach garment to instrumentation.
7) Start garment flowing.
8) Test subject performs the standard motions.
9) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
10) Repeat for each type of LCG.

LCG Flow Restriction Test

Test Summary

The test consisted of five parts which tested one LCG with several pieces of equipment. The five parts were: LCG only, LCG and confined space harness, LCG and coveralls, LCG and splash suit pants and boots, LCG and splash suit pants and boots and backpack. The AWPS3, size large and the 2hr PackC (empty) were used. Flow and pressure drop were recorded over all the standard motions. When a low flow or high pressure was observed the probable cause was recorded. All tests were run closed loop.

Observed Problems

When the garment was hooked up initially the water loop had accidentally been left open. This may have changed the balance of water in the garment. The garment was hooked up to the filling setup and "topped off" before continuing. The garment had a slow leak in it during the test which affected its fullness. This caused the flow to drop off during the test and the pressure drop to rise. The coveralls were a problem because the tubes were passed through the slit in the pocket. This slit was a little low and cut off the main in/out tubes. For future tests a custom tube slit should be cut in the coveralls.

Results

The flow slowly dropped off during the test, probably due to the water leak. The lower the flow dropped the higher the pressure was. Some of the low flows may have been due to the high pressure causing the bypass to open partially. Although some motions did cause the flow to drop off, they did not completely kill it the way they did before.

Conclusions

Overall this garment was not as susceptible to the wild fluctuation in flow and pressure. I was fairly stable, although some motions did affect it. Laying on the back did slow or almost shut the flow off, but not as severely as before. Sitting down did not stop the flow, in fact the garment flowed best while sitting down during some of the runs. The confined space harness was not as much of a hindrance as before. The coveralls were the biggest problem, due to the interference with the pocket slit.

With the dotted headers the garment was not as susceptible to pinch-offs at the headers and it was not as susceptible to "waves" in the garment during motions.

LCG Water Loop Compatibility Test

Test is to determine the restrictions on the LCG caused by other equipment like the backpack harness, splash suit, etc. and how the pump, bypass, and electronics respond to those restrictions. The flow and pressure drop is recorded as a set of standard motions is performed. Additionally, observed problems and equipment reactions are recorded. Each piece of equipment is tested individually with each LCG and a cumulative test is done last. Any excessively restrictive or unrestrictive equipment may be excluded from the cumulative test. All tests are performed on the same test subject.

Equipment Needed

Backpack with full harness.
Confined space harness
Coveralls
Splash suit
LCG's (required versions)
LCG QD belt with manifold
Backpack style pump, bypass, electronics, and umbilicals
Instrumentation to record flow and pressure drop through jacket and pant
Test subject who fits all LCG's and can perform the "standard motions"

Standard Motions

1) Lay on back for 20 seconds
2) Lay on stomach for 20 seconds
3) From a standing position:
   a) kneel for 20 seconds
   b) move to crawling position, crawl for 5 steps
   c) return to kneel, pause
   d) stand up
4) From a standing position, do a full squat, pause, stand up. 2 repetitions.
5) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
6) Touch toes, 3 repetitions.
7) From a standing position, lean back, lean left, lean right, return to upright.

Test 1 (LCG only)

1) Don LCG (full).
2) Don LCG QD belt and umbilicals.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start garment flowing.
6) Test subject performs the standard motions.
7) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
8) Repeat for each type of LCG.

Test 2 (LCG and confined space harness)

1) Don LCG (full).
2) Don confined space harness.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

Test 3 (LCG and coveralls)

1) Don LCG (full).
2) Don coveralls.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

Test 4 (LCG and splash suit)

1) Don LCG (full).
2) Don splash suit pants.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
9) Repeat for each type of LCG.

Test 5 (LCG and backpack)

1) Don LCG (full).
2) Don backpack and adjust harness.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start garment flowing.
6) Test subject performs the standard motions.
7) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
8) Repeat for each type of LCG.

Test 6 (Cumulative)

1) Don LCG (full).
2) Don splash suit pants.
3) Don confined space harness.
4) Don backpack and adjust harness.
5) Attach instrumentation to QD block.
6) Attach garment to instrumentation.
7) Start garment flowing.
8) Test subject performs the standard motions.
9) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.
10) Repeat for each type of LCG.

LCG Water Loop Compatibility Test

Test Summary

This test was shortened to include the AWPS3 LCG and 2hr Pack C only. The standard motions were performed twice with a stabilize period in between. The pack was empty and was not used for breathing air. The pump and QD block with a bypass were installed. The electronics were not used for this test. The pump was drawing a lot of current and was hooked up to external power to allow the proper amount of flow. Flow and pressure drop were recorded.

Observed Problems

The electronics were not used for this test. The pump output was not sufficient and had to be hooked to external power for adequate flow. A slow leak in the garment caused slow water loss. The garment was refilled to compensate. A QD fell off during the second set of motions and more water was lost. The garment was not refilled after this.

Results

The flow and pressure drop were reasonable, given the problems. The pressure drop was lower than the test runs with the pump and umbilical configuration. Again, this garment seemed less prone to dramatic swings in flow and pressure drop.

Conclusions

A lower and more stable pressure drop was achieved due to the fact that the pump was located relative to the garment and user. Previous tests were conducted with the pump on a table and umbilicals to the garment. With the pack on, the pump moved relative to the garment. So, less change in head pressure resulted. Water loss resulted in lower flow and higher pressure as the test continued. With increased pressure drop the bypass may have been flowing partially which would result in lower flow through the garment.

LCG Function Test

Test is to establish baseline data for the basic functions of various LCG's. Maximum, minimum, and average pressure drop is recorded. Heat transfer is determined through the in and out water temperatures for the suit and a "cool scale" rating assigned by the test subject.

Equipment Needed

LCG's (required versions)
LCG QD belt with manifold
Chiller
Backpack style pump and umbilical.
Instrumentation to record flow, pressure drop, water temperature in, and water temperature out for the jacket and pant.
Test subject who fits all LCG's and can perform the "standard motions" and exercise.

Standard Motions

1) Lay on back for 20 seconds
2) Lay on stomach for 20 seconds
3) From a standing position:
   a) kneel for 20 seconds
   b) move to crawling position, crawl for 5 steps
   c) return to kneel, pause
   d) stand up
4) From a standing position, do a full squat, pause, stand up. 2 repetitions.
5) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
6) Touch toes, 3 repetitions.
7) From a standing position, lean back, lean left, lean right, return to upright.

Exercise

1) Walk on treadmill at 3 mph, no incline. Duration is 15 minutes.

Test

1) Don LCG (full).
2) Don LCG QD belt.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start system and data recording.
6) Test subject stands at rest for 3 minutes.
7) Record cool scale rating for resting.
8) Test subject performs the standard motions.
9) Record cool scale rating for standard motions.
10) Test subject performs exercise.
11) Record cool scale rating for exercise.
12) Repeat for each type of LCG.

LCG Function Test

Test Summary

There was only one test run consisting of the standard motions and treadmill work. The garment was an AWPS3 Large (single QD connection, fully dotted, all Jasco patches). The inlet temperature was started at 60 deg. F and was turned down after the first ten minutes of treadmill work. The temperature was further reduced during the test (see data sheets). The garment flow, pressure dro, inlet temperature, and outlet temperature were recorded. The heat transfer was calculated using the inlet and outlet temperatures. Cool scale ratings assigned by the test subject were also recorded. The water flow was always closed loop.

Observed Problems

The garment had a slow leak which caused it to loose water volume. The loss of water resulted in lower flow and higher pressure drop. The lack of flow may have contributed to the low heat transfer.

Results

Despite the leak and lack of proper water volume or flow the AWPS3 garment performed better than all the previous garments except the single QD garment. It provided about 40-50 watts less cooling than the single QD garment and about 50 more watts than the IUOE garments. The pressure drop was higher than expected, this is at least partially due to the water loss.

Conclusions

The heat transfer for this garment is fairly good at the given work rate. Especially considering the low flow rate. The pressure drop was the highest so far, but it is the first garment with all Jasco patches and fully dotted headers. Overall the garment had less flow and pressure fluctuations than previous designs. See "3/21 Function Test".

LCG and Backpack Function Test

Test is to establish baseline data for the basic function of an LCG run by the Backpack. Maximum, minimum, and average pressure drop is recorded. Heat transfer is determined through the in and out water temperatures for the suit and a "cool scale" rating assigned by the test subject. The reaction of the water loop to the LCG fluctuations is observed.

Equipment Needed

LCG's (required versions)
Backpack with current pump, bypass, and electronics.
Instrumentation to record flow, pressure drop, water temperature in, and water temperature out for the jacket and pant.
Test subject who fits all LCG's and can perform the "standard motions" and exercise.

Standard Motions

1) Lay on back for 20 seconds
2) Lay on stomach for 20 seconds
3) From a standing position:
    a) kneel for 20 seconds
    b) move to crawling position, crawl for 5 steps
    c) return to kneel, pause
    d) stand up
4) From a standing position, do a full squat, pause, stand up. 2 repetitions.
5) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
6) Touch toes, 3 repetitions.
7) From a standing position, lean back, lean left, lean right, return to upright.

Exercise

1) Walk on treadmill at 3 mph, no incline. Duration is 15 minutes.

Test

1) Don LCG (full).
2) Don backpack.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start backpack and data recording.
6) Test subject stands at rest for 3 minutes.
7) Record cool scale rating for resting.
8) Test subject performs the standard motions.
9) Record cool scale rating for standard motions.
10) Test subject performs exercise.
11) Record cool scale rating for exercise.
12) Repeat for each type of LCG.

LCG and Backpack Function Test

Test Summary

The test was run with the AWPS3 LCG and Pack D. The test was a full breathing and cooling test. The test sequence was as follows: standard motions, 20 minute treadmill, rest, invert pack (from kneeling to a head down position), 20 minute treadmill, rest, invert pack, standard motions. Flow, pressure drop, LCG inlet temperature, and LCG outlet temperature were recorded. Heat transfer was calculated using the previous measurements.

Observed Problems

The flow was low throughout the test; it did improve slightly towards the end of the test. Several factors may have contributed to the low flow including; water loss due to a slow leak in the garment and a small leak in the pack, additional weight of a full two hour pack putting too much pressure on the LCG in certain locations, the LCG bypass on Pack D was not fine tuned so it may have cracked at too low a pressure and flowed partially throughout the test.

Results

The flow was slightly lower than desired, .3 gpm instead of .4 and the pressure was on the high side of the range. The pressure drop was lower than any other test with the AWPS3 garment. The heat transfer was decent for the work rate, it averaged about 300 watts for the treadmill portion and reached about 350 watts towards the end of the treadmill runs. This was a better heat transfer than with the previous function test. This pump was still not producing the desired output and had to be run off external power.

Conclusions

The heat transfer, flow rate, and pressure drop were all pretty good for the given work rate and the technical problems. The response of the bypass to the garment fluctuations is not definite based on the data. The electronics interface (cut-offs, pump power, etc.) was not evaluated because it was not installed in this pack.

Planned Manned Testing for AWPS Phase II

Part 2

Testing conducted during Part 2 is intended to test the performance of the optimized LCG, as determined in Part 1, and other equipment. Interface issues, accessory locations, and backpack functions will also be addressed. All tests will be conducted on three common test subjects (three sizes) in a highly controlled setting. Data collected will be utilized to create an optimized ensemble and draw conclusions for expected performance levels.

1. Equipment
    - a. Backpack with harness
    - c. Mask/regulator
    - d. LCG's
        - I. AWPS3 LCG (Medium, Large, X-Large)
        - ii. AWPS4 prototype
    - e. Splash Suit
        - I. IUOE style
        - ii. Level B mockup
        - iii. Level C mockup
    - f. Accessories
        - I. Boots
        - ii. Gloves
        - iii. Coveralls
2. Known problems/questions
    - a. Splash suit visor interference and size
    - b. Glove ring security.
    - c. LCG bypass and QD
    - d. Pump efficiency.
    - e. System pressure drop.
    - f. LCG Performance criteria (heat transfer, flow, pressure drop).
    - g. Cooling effectiveness.
    - h. Core temperature control.
    - I. Backpack as a breathing only unit under overgarments
3. Tests
    - a. Fit (all equipment)
        - I. Range of motion.
        - ii. Size to measurement comparison.
        - iii. Interface locations and overlap areas.
        - iv. Access to adjustments, switches, QD's, etc.
        - v. Location/visibility of electronics display.
        - vi. Splash suit interfaces
            - 1) mask to visor
            - 2) LCG hoses
            - 3) pack coverage
            - 4) glove ring security

vii. Harness
1) range of adjustments
2) location on person
3) padding
4) weight balance

b. LCG flow restrictions (optimized garment(s))
I. Restrictions by backpack.
ii. Restrictions by confined space harness.
iii. Restrictions by coveralls.
iv. Restrictions by splash suit.
v. Restriction by combination of I - iv.

c. LCG function (optimized garment(s))
I. Pressure drop.
1) static
2) typical positions and motions
ii. Heat transfer.
iii. Comfort scale

d. Obstacle course (ensemble function)
I. Simulate IUOE and/or NIOSH protocol
ii. Evaluate performance
iii. Evaluate user interface/comfort

e. Backpack function
I. breathing only
1. level B
2. turnouts
ii. breathing & cooling
1. level B
2. turnouts

f. Equipment longevity
I. LCG
1) machine wash and dry
2) observe wear
3) record failures
ii. Splash suit
1) observe wear
2) record failures
iii. Backpack
1) observe wear
2) record failures

g. Evaluate AWPS prototype
I. LCG function test
ii. abbreviated restriction test

LCG Flow Restriction Test
Test is to determine the restrictions on the LCG caused by other equipment like the backpack harness, splash suit, etc. The flow and pressure drop is recorded as a set of standard motions is performed. Each piece of equipment is tested individually with each LCG and a cumulative test is done last. Any excessively restrictive or unrestrictive equipment may be excluded from the cumulative test. Each set of tests is performed on the same test subject.

<u>Equipment Needed</u>

Backpack with full harness.
Confined space harness
Coveralls
Splash suit
LCG's (required versions)
LCG QD belt with manifold
Pump and umbilicals
Instrumentation to record flow and pressure drop through the garment
Test subject who fits all LCG's and can perform the "standard motions"

<u>Standard Motions</u>

1) Lay on back for 30 seconds
2) Lay on side for 30 seconds
3) Lay on stomach for 30 seconds
4) From a standing position:
    a) kneel for 20 seconds
    b) move to crawling position, crawl for 5 steps forward, 5 steps back
    c) return to kneel, pause
    d) stand up
5) From a standing position, do a full squat, pause, stand up. 2 repetitions.
6) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
7) Touch toes, 3 repetitions.
8) From a standing position, lean back, lean left, lean right, return to upright.

<u>Test 1</u> (LCG only)

1) Don LCG (full).
2) Don LCG QD belt and umbilicals.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start garment flowing.
6) Test subject performs the standard motions.
7) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.

<u>Test 2</u> (LCG and confined space harness)

1) Don LCG (full).
2) Don confined space harness.

3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.

Test 3 (LCG and coveralls)
1) Don LCG (full).
2) Don coveralls.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.

Test 4 (LCG and splash suit)
1) Don LCG (full).
2) Don splash suit pants.
3) Don LCG QD belt and umbilicals.
4) Attach instrumentation to QD block.
5) Attach garment to instrumentation.
6) Start garment flowing.
7) Test subject performs the standard motions.
8) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.

Test 5 (LCG and backpack)
1) Don LCG (full).
2) Don backpack and adjust harness.
3) Attach instrumentation to QD block.
4) Attach garment to instrumentation.
5) Start garment flowing.
6) Test subject performs the standard motions.
7) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.

Test 6 (Cumulative)
1) Don LCG (full).
2) Don splash suit pants.
3) Don confined space harness.
4) Don backpack and adjust harness.

5) Attach instrumentation to QD block.
6) Attach garment to instrumentation.
7) Start garment flowing.
8) Test subject performs the standard motions.
9) When a change in pressure, flow, or pump operations is observed the problem, current motion or position, and probable cause should be recorded.

LCG Flow Restriction Test

Test Summary

The restriction tests were performed by three test subjects, one medium, one large, and one x-large. Test three and five were skipped by the medium and the x-large. Test three was determined to be unnecessary because the coveralls do not affect the LCG substantially and the coveralls would have had to be modified to allow for a correct passthrough for the LCG hoses. Test five seemed redundant with respect to Test six. A scheduling problem made the abbreviation of the large set of tests necessary. The medium and x-large garments were AWPS3 garments with all dotted, Jasco patches. The large garment was an AWPS4 mockup with some modified Jasco patches. All tests were run with the instrumentation set-up and a closed loop umbilical set-up.

Observed Problems

The large garment had a few more slight restrictions than the other garments, probably due to the fact that the patches were not completely dotted. This was most evident in motions that affected the pant back patches.

The flow dropped slightly on the medium test run. It was observed that the water loop was gaining air. This was fixed by tightening and checking all the fittings on the QD block and instrumentation.

Extra hoses had to be added to the garment to allow it to be connected to the instrumentation. This added an extra set of QD's and loose hoses.

Results

This generation of garments was much more stable than previous generations. There is a constant fluctuation in flow and pressure, relative to motion. The pressure drop is high, but the accuracy of this is suspect. The data shows a higher pressure than is typically produced by the tuthill pump at that power setting and flow. The pressure data also includes additional QD's in the main connection. The worst pinch-off is in the tubes leading from the main QD to the LCG jacket. These tubes either twist against the patches they are connected to or "walk back" in the garment causing the patch to stop flowing. This problem was accentuated in these tests by the fact that the LCG hoses were not short enough to by "tied" to the QD block.

Restriction Tests				
		GPM	PSI	
AWPS3 Medium		0.37	7.94	
	w/CS Harness	0.25	10.9	
	w/SS Pants, Boots	0.29	9.8	
	w/SS Pants, Boots, CS Harness, Pack	0.31	9.16	
AWPS4 Large		0.37	13.3	
	w/SS Pants, Boots, CS Harness, Pack	0.35	14.41	
AWPS3 X-Large		0.38	8.21	
	w/CS Harness	0.35	8.51	
	w/SS Pants, Boots	0.35	9.48	
	w/SS Pants, Boots, CS Harness, Pack	0.36	9.17	

LCG Function Test

Test is to establish baseline data for the basic function of the LCG. Maximum, minimum, and average pressure drop is recorded. Heat transfer is determined through the in and out water temperatures for the suit and a "cool scale" rating assigned by the test subject. Test is run closed loop.

Equipment Needed

LCG's (required versions)
LCG QD belt with manifold
Chiller and heat exchanger
Pump and umbilical.
Instrumentation to record flow, pressure drop, water temperature in, and water temperature out for the garment.
Test subject who fits all LCG's and can perform the "standard motions" and exercise.

Standard Motions

1) Lay on back for 30 seconds
2) Lay on side for 30 seconds
3) Lay on stomach for 30 seconds
4) From a standing position:
    a) kneel for 20 seconds
    b) move to crawling position, crawl for 5 steps forward, 5 steps back
    c) return to kneel, pause
    d) stand up
5) From a standing position, do a full squat, pause, stand up. 2 repetitions.
6) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
7) Touch toes, 3 repetitions.
8) From a standing position, lean back, lean left, lean right, return to upright.

Exercise

1) Walk on treadmill at 3 mph, no incline. Duration is 40 minutes.

Test

1) Don LCG (full).
2) Don LCG QD belt.
3) Attach instrumentation and garment to QD block.
4) Start garment flowing.
5) Start system and data recording.
6) Test subject stands at rest for 3 minutes.
7) Record cool scale rating for resting.
8) Test subject performs the standard motions.
9) Record cool scale rating for standard motions.
10) Test subject performs exercise.
11) Reduce water temperature as indicated on the data sheet.
12) Record cool scale rating for exercise at intervals listed on the data sheet.

LCG Function Test

Test Summary

The function test was performed by three test subjects, one medium, one large, and one x-large. The medium and x-large garments were AWPS3 garments with all dotted, Jasco patches. The large garment was an AWPS4 mockup with some modified Jasco patches. All tests were run with the instrumentation set-up and a closed loop umbilical set-up. Cooling was provided by creating a cold water bath with the chiller and running the LCG loop through a heat exchanger in the bath.

Observed Problems

Extra hoses had to be added to the garment to allow it to be connected to the instrumentation. This added an extra set of QD's and loose hoses.

During the large garment test the chiller maintained a constant bath temperature after about 15 minutes into the treadmill portion. As the subject continued to work and produce heat, LCG water increased in temperature and both the inlet and outlet water temps increased.

Pressure drop data was affected by the "bouncing" of the pressure transducer when the subject walked on the treadmill. The resulted in some higher than actual readings and abnormal pressure spikes.

The medium pants were not performing as well as needed, so the large pants were used with the medium jacket for the medium test. This resulted in better flow but less skin contact on the legs.

Results&Conclusions

Heat transfer was comparable to previous runs with the single connection garment and the IUOE style garments. Performance was slightly lower, due to the poor flow in the pants. The large garment had better pant flow, but was subject to the chiller malfunction. Subjectively the cool scale ratings were in the 4-6 range. The medium subject was the coolest with ratings of 4 and 5. The large subject warmed up to a 6 at the end of the test. The x-large subject was a consistent 6 throughout the test.

The large garment run was a good example of what will happen if the cooling bath maintains a constant temperature while the user continues to produce more heat. The increased heat load from the LCG increased the outlet water temperature and without increased cooling from the bath the inlet water temperature also rose. This resulted in a loss of cooling effectiveness. For the comfort level of the user to remain constant while his heat output increases the inlet water temperature needs to drop.

Function Tests				
		GPM	PSI	Watts
AWPS3 Medium				
	Motions	0.44	9.94	144
	Treadmill	0.43	9.8	219
	Overall	0.43	9.92	192
AWPS4 Large				
	Motions	0.37	12.94	226
	Treadmill	0.4	11.17	194
	Overall	0.4	11.38	209
AWPS3 X-Large				
	Motions	0.44	9.31	155
	Treadmill	0.43	9.06	257
	Overall	0.43	9.11	233

Breathing Only Function Test

Test is to establish baseline data for the basic function of the backpack as a breathing only unit. The test is run with the backpack worn over turnouts and with it worn under a Level B suit. Pack performance is monitored by ullage pressure, mask pressure, check valve pressure, AHX outlet temperature, mask temperature, and mask flow. Core temperature is monitored on the test subject.

Equipment Needed

Functional backpack with harness
Required outer garments
Instrumentation and data acquisition for pack and core temp
Test subject who fits all equipment and can perform the "standard motions" and exercise.

Standard Motions

1) Lay on back for 2 minutes.
2) Lay on side for 2 minutes.
3) From a standing position:
    a) kneel for 20 seconds
    b) move to crawling position, crawl for 5 steps forward, 5 steps back
    c) return to kneel, pause
    d) stand up
4) From a standing position, do a full squat, pause, stand up. 2 repetitions.
5) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
6) Touch toes, 3 repetitions.
7) From a standing position, lean back, lean left, lean right, return to upright.

Inversion

1) Kneel, lean forward with elbows on the ground and head down. Remain for 2 minutes.
2) Take a short deep breath. Pause.
3) Sit up on knees. Remain for 2 minutes.
4) Repeat 1-3.

Exercise

1) Walk on treadmill at 3 mph, no incline. Duration is 20 minutes.

Test

1) Don backpack and required garments.
2) Attach instrumentation.
3) Start system and data recording.
4) Start breathing on backpack.
5) Test subject stands at rest for 3 minutes.
6) Record cool scale rating for resting.
7) Test subject performs the standard motions.
8) Record cool scale rating for standard motions.

9) Test subject performs exercise.
10) Record cool scale rating for exercise.
11) Test subject performs inversion.
12) Test subject stands at rest for 5 minutes.
13) Repeat steps 7-12 at least twice or up to the duration of the pack.

Breathing Only Function Test

Test Summary

Each test subject, medium, large, and x-large wore the two hour backpack for two test runs. The first test run was in the OSS level B splashsuit, including boots and hardhat. The second test run was in a typical firefighter ensemble without boots or gloves. The subjects wore sneakers with both ensembles to avoid treadmill injuries. Core temp was recorded and the test was stopped if an increase in temperature more than 1.7 degrees F was observed. The tests were conducted indoors in an air conditioned lab.

Observed Problems

The pack was venting frequently or constantly and then the relief valves would freeze. The valves were thawed as much as possible.

It generally took about an hour of use to stabilize the ullage pressure. Most changes were gradual increases, although there were some slight changes when the user changed position.

Mask temperature rose quickly and was typically between 82 and 85 degrees.

Initial test runs had some quirky readings from the core temp instrumentation. It was discovered that the computer monitor was interferring and the test area was rearranged.

Results&Conclusions

During the set of tests with the splashsuit ensemble all subjects showed a steady increase in core temperature. All of those tests were stopped due to the subject reaching the maximum allowed temperature. The duration ranged from about one hour for the medium to about 1 ½ hours for the large and x-large. The pack delivered sufficient breathing air throughout the test. Some cooling effect was observed from the pack venting and the AHX frosting inside the suit. Therefore this was not a true breathing only baseline with respect to cooling.

During the firefighter set of tests all subjects showed a steady increase in core temperature, but not enough to terminate any tests. The pack was emptied on all test runs with approximate durations of 1:50, 1:45, and 2:10. The short durations were most likely due to the excess venting and freezing of the relief valves. Again the valves were thawed as much as possible. The users received no cooling benefit from the pack venting and frosting. However, this garment configuration allows for ambient air flow through the sleeve, jacket, and pant hems.

For all test runs the subjective cool scale ratings were in the 5-6 range. In all the tests all of the subjects were sweat soaked and tired by the end of the test. No one was exhausted or unable to continue.

Breathing and Cooling Function Test

Test is to establish baseline data for the basic function of the backpack as a breathing and cooling unit. The test is run with the backpack and cooling garment worn with turnouts and with them worn under a Level B suit. Pack performance is monitored by ullage pressure, mask pressure, check valve pressure, AHX outlet temperature, mask temperature, and mask flow. LCG performance is monitored by water inlet and outlet temperature, flow, and pressure drop. Core temperature is monitored on the test subject.

Equipment Needed

Functional backpack with harness
LCG's (required version)
Required outer garments
Instrumentation and data acquisition for pack, LCG, and core temp
Test subject who fits all equipment and can perform the "standard motions" and exercise.

Standard Motions

1) Lay on back for 2 minutes.
2) Lay on side for 2 minutes.
3) From a standing position:
    a) kneel for 20 seconds
    b) move to crawling position, crawl for 5 steps forward, 5 steps back
    c) return to kneel, pause
    d) stand up
4) From a standing position, do a full squat, pause, stand up. 2 repetitions.
5) From a standing position, sit on an unpadded chair. Remain for 1 minute. Stand up.
6) Touch toes, 3 repetitions.
7) From a standing position, lean back, lean left, lean right, return to upright.

Inversion

1) Kneel, lean forward with elbows on the ground and head down. Remain for 2 minutes.
2) Take a short deep breath. Pause.
3) Sit up on knees. Remain for 2 minutes.
4) Repeat 1-3.

Exercise

1) Walk on treadmill at 3 mph, no incline. Duration is 20 minutes.

Test

1) Don backpack and required garments.
2) Attach instrumentation.
3) Start system and data recording.
4) Connect LCG and start breathing on backpack.
5) Test subject stands at rest for 3 minutes.
6) Record cool scale rating for resting.

7) Test subject performs the standard motions.
8) Record cool scale rating for standard motions.
9) Test subject performs exercise.
10) Record cool scale rating for exercise.
11) Test subject performs inversion.
12) Test subject stands at rest for 5 minutes.
13) Repeat steps 7-12 at least twice or up to the duration of the pack.

Breathing and Cooling Function Test

Test Summary

Each test subject, medium, large, and x-large wore the two hour backpack and LCG's for two test runs. The medium and x-large LCG's were AWPS3 style. The large was an AWPS4 mockup. The first test run was in the OSS level B splashsuit, including boots and hardhat. The second test run was in a typical firefighter ensemble without boots or gloves. The subjects wore sneakers with both ensembles to avoid treadmill injuries. Core temp was recorded and the test was stopped if an increase in temperature more than 1.7 degrees F was observed. The tests were conducted indoors in an air conditioned lab.

Observed Problems

It generally took about an hour of use to stabilize the ullage pressure. Most changes were gradual increases, although there were some slight changes when the user changed position. Later tests showed more of a response in ullage pressure with head down positions.

Mask temperature rose quickly and was typically between 82 and 85 degrees.

LCG hoses were longer than normal to accommodate the added instrumentation. This made pinch-offs more likely. It was discovered that the instrumentation itself had a pinch point when it flipped forward. The solution was to hold it in place during problematic motions.

The medium AWPS3 pants were poor performers.

The pump had a constant water leak. This caused the water volume in the system to decrease and the air to increase. The flow through the garment gradually decreased and the pressure increased as the water volume dropped off.

The first test was terminated due to the pack freezing. The water temperatures at the instrumentation were normal. However, it was discovered that the LCG bypass valve was leaking so badly that a significant amount of the flow was bypassing back to the pack. So, the LCG flow was low and little heat was returned to the vaporizer. The bypass valve was disabled for the remainder of the tests.

During the first three test runs the pack outlet water temperatures stayed somewhat warm. At the heaviest work the water was typically about 55 degrees, at rest the temperature was typically 70 degrees. The temperatures were responsive to breathing rate.

The pack was filled with a new recharge station and after the liquid check valve was found stuck closed. The valve was unstuck. The pack was also pumped down to restore a better vacuum. After these modifications, the water temperatures were colder than typical. They were also somewhat less responsive to breathing rate than before. LCG was dropping off as described before, but heat transfers were in the 300-450 watt range during the freezes.

Initial core temp readings were low on each test. This was because the subjects were drinking water immediately before suiting up. Typical body temperatures for each subject were assumed as starting temperatures for determining test termination.

One test was terminated due to pain in the subject's left shoulder. He thought that the pack had shifted to the left and could not upright it.

Results&Conclusions

Cooling effectiveness was fairly successful. Core temps did rise during harder work periods, but they also dropped quickly during lower activity. Subjective cool scale ratings were in the 4-5 range most times. After all of the runs the subjects were tired and sweated, but not overheated or overly exhausted.

With the pack's tendency to freeze it was difficult to determine what a true 2 hour work cycle would be like. The pack was emptied on some of the warmer runs. The longest run was 2.5 hours.

Ensemble Fit Test

Test is to evaluate the fit, mobility, and comfort of the AWPS ensemble. The test is run with a full-up ensemble. Each test set is performed on the same test subject.

Equipment Needed

LCG's (required versions)
Splash suit including boots, gloves, and hard hat
Functional backpack with harness
Instrumentation and data acquisition
Test subject who fits all LCG's and can perform the "fit motions" and "obstacle course".

Fit Motions

1) Reach forward and around as far as possible.
2) Reach back as far as possible.
3) Reach up as far as possible.
4) Squat
5) Kneel, both knees, one knee.
6) Bend forward, bend back, lean side to side.
7) Sit down, lean on back rest.

Test

1) Don ensemble including LCG and mask connections.
2) Answer data sheet questions 1-3.
3) Test subject performs the fit motions. Record the rating after each motion.
4) Test subject performs activity course. (See "Ensemble Function Test")
5) Answer data sheet question 6.
6) Doff and disconnect the ensemble.
7) Answer data sheet questions 7-8.

Ensemble Fit Test

Test Summary

Prior to the ensemble function test the subjects self-donned the ensemble as much as possible and performed a range of motions. After the ensemble function test the subjects were asked to doff the equipment and rate the activity course motions.

Observed Problems

The hood was difficult to self donn, mainly clearing the pack.

The LCG QD's were difficult to connect and disconnect.

The visor was difficult to see through and fell forward obstructing the user's vision further. In the sun the material softened and allowed the hood to collapse.

The dimple in the center of the dewar was uncomfortable for some subjects.

The on/off switch for the pack was located on the bottom of the pack and was not recessed. Sitting down or pulling the suit against the bottom of the pack turned the electronics off.

Results&Conclusions

Most motions and activities were rated as a 4.

Ensemble Performance Test

Test is to establish performance of backpack and cooling garment by performing basic tasks similar to those seen in actual practice. The test is run with the backpack and cooling garment worn under a Level B suit. The test environment will be harsh in that most tests will be conducted outdoors during the summer in Houston. Core temperature data will be recorded throughout course of activity as well as post-test subjective interviews of subjects concerning functionality and comfort of the ensemble.

Equipment Needed

Functional backpack with harness
LCG's (required version)
Level B Splash Suit Required outer garments
Core temp data acquisition
Test subject who fits all equipment and can perform the activity course.
Activity Course Materials:

Wheelbarrow	Cinder blocks
Box of Sand	Barrel
Shovel	Chair
Ladder	Small Boxes
Small bucket	Gear shift simulator
Table	

Activity Course

1) Fill wheelbarrow with sand from box using shovel.
2) Push wheelbarrow to ladder.
3) Scoop sand into bucket, climb ladder, and set bucket on top of ladder.
4) Carry cinder block to stack of blocks.
5) Build wall of cinder blocks at least four blocks high.
6) Move barrel to table.
7) Crawl under table.
8) Sit in chair to simulate driving truck.
   a) Shift gears using "clutch", "accelerator", and "gear shift."
   b) Change lanes using "rearview mirror" and looking over shoulder.
9) Perform reading test by reading 3 lines of text each of which is a different size.

Test

1) Don backpack and required garments.
2) Attach instrumentation.
3) Start system and data recording.
4) Connect LCG and start breathing on backpack.
5) Test subject stands at rest for 3 minutes.
6) Record cool scale rating for resting.
7) Test subject performs the activity course.
8) Record cool scale rating for activity course at finish of each activity.
9) Test subject walks for 5 minutes.

10) Test subject stands at rest for 5 minutes.
11) Repeat steps 7-9 at least twice or up to the duration of the pack.

Ensemble Performance Test

Test Summary

This test was conducted outside (parking lot) during typical August weather in Houston. The large test subject was changed for this test only, so core temp data cannot be compared to earlier tests. Each test subject, medium, large, and x-large wore the two hour backpack and LCG's. The medium and x-large LCG's were AWPS3 style. The large was an AWPS4 mockup. The test was run in the OSS level B splashsuit, including boots, gloves, and hardhat. There was some deviation from the test protocol when test subjects attempted to shoot basketball, fit in cars, and jog in the ensemble.

Observed Problems

Could not fit in an 85 RX-7 with the ensemble on.

The on/off switch for the pack was located on the bottom of the pack and was not recessed. Sitting down or pulling the suit against the bottom of the pack turned the electronics off. The pump had to be restarted several times.

Some of the batteries were short lived. They typically lasted 1 to 1.5 hours.

The pack outlet water did not seem very cold. It was later discovered that the liquid check valve could have been plugged or partially stuck again. The would mean that the pack was in a breathing only mode and any cooling was from running the water through the vaporizer (without cryo flow).

Core temps were high and all subjects were too hot and tired to empty the pack.

Head and hands were very hot.