Advanced Worker Protection System -- Phase I

Topical Report

Jeff Myers

July 1995

Work Performed Under Contract No.: DE-AC21-93MC30178

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

For

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Oceaneering Space Systems
Houston, Texas

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Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

By

**Oceaneering Space Systems
16665 Space Center Boulevard
Houston, Texas 77058-2268**

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Acronym List

AAPD	Advanced All-Position Dewar
AWPE	Advanced Worker Protection Ensemble
AWPS	Advanced Worker Protection System
CIL	Critical Items List
D & D	Decontamination and Decommissioning
FMEA	Failure Modes and Effects Analysis
KSU	Kansas State University
LCC	Life Cycle Cost
LCG	Liquid Cooling Garment
LCP	Liquid Crystal Polymer
NIOSH	National Institute of Occupational Safety and Health
OSS	Oceaneering Space Systems
PLSS	Portable Life Support System
PPE	Personal Protective Equipment
SAR	Supplied Air Respirators
SCBA	Self Contained Breathing Apparatus

Figure 1-1: Advanced Worker Protection System

1.0 Introduction

The Department of Energy (DOE) is in the process of defining the magnitude and diversity of Decontamination and Decommissioning (D&D) obligations at its numerous sites. The DOE believes that existing technologies are inadequate to solve many challenging problems such as how to decontaminate structures and equipment cost effectively, what to do with materials and wastes generated, and how to adequately protect workers and the environment. Preliminary estimates show a tremendous need for effective use of resources over a relatively long period (over 30 years).

Several technologies are being investigated which can potentially reduce D&D costs while providing appropriate protection to DOE workers. The DOE recognizes that traditional methods used by the EPA in hazardous waste site clean up activities are insufficient to provide the needed protection and worker productivity demanded by DOE D&D programs. As a consequence, new clothing and equipment which can adequately protect workers while providing increases in worker productivity are being sought for implementation at DOE sites.

This project will result in the development of an Advanced Worker Protection System (AWPS). The AWPS will be built around a life support backpack that uses liquid air to provide cooling as well as breathing gas to the worker. The backpack will be combined with advanced protective garments, advanced liquid cooling garment, respirator, communications, and support equipment to provide improved worker protection, simplified system maintenance, and dramatically improve worker productivity through longer duration work cycles.

Phase I of the project has resulted in a full scale prototype Advanced Worker Protection Ensemble (AWPE, everything the worker will wear), with sub-scale support equipment, suitable for integrated testing and preliminary evaluation. Phase II, if the project continues, will culminate in a full scale, certified, pre-production AWPS and a site demonstration.

This topical report describes the prototype hardware developed in Phase I, presents a Failure Modes and Effects Analysis (FMEA) for the hardware, describes planned changes to the pre-production hardware for Phase II, updates mass / cost budgets for both prototype and pre-production hardware, updates the cost model, and provides reports on the Phase I testing, both in-house and the Independent evaluation at Kansas State University (KSU).

1.1 Overview of Current Technologies and Applications

The AWPS will establish a revolutionary and distinctive category of Personal Protective Equipment (PPE). The respiratory protection system will provide as a by-product an effective form of cooling to relieve heat stress. The AWPS will also include protective clothing which provides consistent protection to the worker commensurate with different types of chemical and radiological hazards. This will be the first such unit to provide respiratory protection, full body skin protection, and full body cooling in one package.

Current systems for respiratory protection offer limited duration and provide little to no relief from heat stress for extended work periods or in hot environments. When cooling is provided, it must be provided separately and often adds significant weight to the overall worker protective ensemble.

1.1.1 Potential hazards and related requirements

DOE D&D workers face a multitude of hazards at each of the sites. These hazards include:

- Contamination (radiological or chemical);
- Physical (punctures, cuts, tears, and abrasions);
- Thermal (contact with molten metal from welding operations, flame impingement, chemical flash fires); and
- Thermal stress (heat or cold-related exposures).

Contamination hazards exist at different levels of severity. Based on site visits, 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, phthalates, 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 machinery. Therefore, worker PPE and other equipment must protect workers from the excessive vibration, sharp edges, and rough surfaces found in these environments.

As determined in site visits, the potential for flame contact and hot surfaces is expected to be at a minimum. Nevertheless, certain operations will involve extensive welding or cutting. These operations provide the potential for worker contact with flame or small amounts of molten metal. To meet these specialized protection needs, additional external protective items may be required.

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 must be designed to minimize the impact of heat stress. In addition, worker mobility must not be impaired as limitations in worker function also affect increases in heat stress and overall energy expenditures.

1.1.2 Anticipated Work Tasks and Related Requirements

Work activity at DOE sites will vary from relatively low metabolic energy costs at 100 watts (standing) to well over 500 watts (heavy two-handed work). The variability of work tasks have a large bearing on the design of the AWPS cooling system. The cooling can be adjusted independently of the breathing system. However, the more that is understood about the anticipated work loads, the more accurate the design of the AWPS.

Figure 1-2: Photo of Typical Current Practice

The DOE also expects a large variety of contamination hazards at the different D&D sites. Different contamination hazards will dictate different levels of protection. In those cases involving the most severe hazards, totally encapsulating protective ensembles must be used. More routine work involving self-contained respiratory protection will require protection against well-defined or incidental contamination hazards and a lower level of skin protection. For this reason, the AWPS will encompass two different forms of protective clothing: a vapor-protective totally encapsulating fully-integrated clothing system (EPA Level A); and a liquid splash-protective multi piece protective clothing system (Level B).

1.1.3 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. Some users are employing an air supplied cooling vest. However this system consumes large quantities of compressed air usually requiring an umbilical, and has limited comfort because of the air flow into the suit and the hot air ejected by the vortex mechanism. 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.

Many outer protective garments worn today 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, nearly all protective clothing in use today does not provide 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.

Goals for the proposed AWPS address each of these areas by:

- Providing 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;
- Integrating 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;
- Replacing 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
- Improving cost efficiency of D&D operations.

1.2 AWPS Performance Objectives

The unique features of the AWPS objectives should dictate design for proper apparatus development. The primary source of this information has come from the potential end users of the AWPS, specifically the personnel involved in cleanup at the DOE sites. Site visits have been completed to Fernald, Hanford, and Oak Ridge. Information compiled from the visits is being used to guide the development of the respirator, cooling garment, and outer garment portions of the AWPS, and its associated support equipment.

Based on this information, the Portable Life Support System (PLSS), Liquid Cooling Garment (LCG), and protective clothing used as part of the Advanced Worker Protection System will have the following characteristics:

1. The PLSS will provide at least 2.0 hours of breathing air at an average respiratory consumption rate of 40 liters per minute per National Institute of Occupational Safety and Health (NIOSH) certification standards;
2. The PLSS will operate in any orientation;
3. The PLSS will operate in the pressure demand mode only and provide positive pressure operation at breathing rates up to 120 liters per minute. A normal breathing rate is considered to be 40 liters per minute while a heavy work rate is 100 liters a minute as prescribed by the National Institute for Occupational Safety and Health (NIOSH).
4. The PLSS will provide a clear indication of remaining air supply and provide a low air warning (audible and visual);
5. The overall PLSS weight will be no more than 40 pounds fully charged with liquid air. However, 30 pounds will be used as a design goal;
6. The PLSS outer shell will provide for ease of decontamination;
7. The PLSS will be refillable in a time similar to that of an SCBA high pressure (4500 psig) bottle. The typical fill time for a 4500 psig air bottle of an 60 minute rated SCBA is approximately 5 minutes with a cascade or compressor-based fill system
8. The LCG will weigh less than 6 pounds when fully filled with water;

9. The LCG will provide effective cooling for work rates ranging from 100 to 500 watts for a period of up to 2 hours at the highest work levels;
10. The garments in conjunction with the PLSS will form a complete protective envelope around the wearer. Interfaces between clothing items and the PLSS will maintain protective qualities commensurate with the clothing and PLSS systems separately;
11. The clothing will provide barrier protection consistent with the actual or potential hazards at DOE remediation sites;
12. The clothing will possess adequate strength and durability to prevent loss of suit or system integrity from the physical hazards of the DOE remediation site through the intended number of clothing use cycles;
13. The clothing will afford the wearer less than a 20 percent decrease in mobility, tactility, and time necessary to complete task functions when compared to the same activity without the protective clothing; and
14. The clothing, LCG, and PLSS in combination will extend working times compared to existing PPE ensembles by at least 100%.

2.0 Hardware Description

Hazards associated with the AWPS will be no greater than those associated with breathing apparatus used today. The AWPS is a low pressure (60 psi) system that has passive safeguards to protect against failure of the system and injury to the wearer.

The design of the cooling garment represents a well established technology which has been optimized for increased efficiency, decreased production cost, and decreased weight. Likewise, protective clothing systems will be based on existing, demonstrated materials used in current commercial products. Protective clothing improvements will encompass design enhancements, attention to interfaces, and complete integration with other equipment, all of which contribute to improved worker safety over existing systems.

2.1 Hazardous Materials PLSS

Figure 2-1: Photo of PLSS

The functional schematic for the PLSS is shown in Figure 2-2.

The liquid air in the AWPS is contained in the Advanced All-Position Dewar (AAPD). A dewar is essentially a pressure vessel within an outer vessel. A vacuum is drawn between the two vessels to minimize convective heat transfer to the cryogen. It is also designed in such a way as to reduce conductive and radiative heat transfer. The Phase 1 AAPD uses machined aluminum Inner and Outer Vessels. This generation of Outer Vessel is also flanged so that the AAPD may be opened for inspection.

The AAPD uses a pivot mechanism to maintain 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 pivot mechanism goes through the Liquid Hub and Liquid Line into the Vaporizer, a tube-in-tube heat exchanger. In the Vaporizer, the cryogen is warmed to a breathable

temperature and the LCG water is chilled to provide body cooling. It is located in the vacuum space between the Inner and Outer Vessel to reduce heat transfer with the ambient environment and increase efficiency.

If, due to a LCG Pump failure, the Vaporizer water freezes, the cryogen would freeze the water and the air leaving the vaporizer gets progressively colder. The Ambient Heat Exchanger (AHX) is a length of finned tubing that uses heat from the environment to warm the cryogen to a breathable temperature in the event of a Vaporizer freeze.

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. The Interspiro Face Mask/Regulator used for the Phase 1 AWPS was chosen for its ability to operate at the 60 psig inlet pressure.

Figure 2-2: Hazardous Materials PLSS Functional Schematic

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, the cooling due to breathing at a certain metabolic rate is on average 2/3 of the desired level. That is, the heat required to vaporize and warm the cryogen to provide sufficient breathing gas at a given metabolic (breathing) rate is about 2/3 of the metabolic heat produced by the body. Since the liquid cooling garment provides the heat for vaporizing and warming the cryogen, breathing requirements provide about 2/3 of the required heat sink capacity for the LCG. The Metering Valve allows the user to increase cryogen flow through the Vaporizer and therefore his/her cooling rate.

As liquid is drawn from the AAPD, 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 AAPD 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 to 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 after the Phase 1 AWPS is filled but before it is used due to heat leak into the vessel. This was a particular concern with the all aluminum construction of the Phase I prototype, which has a relatively large heat leak rate, compared the materials that will be used in the Phase II backpack. The Burst Disc provides redundant pressure relief in the event of a relief valve failure.

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.

The LCG Pump drives the water through the Vaporizer and the LCG. 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.

The Pumpout Valve is a commonly used device in dewars that allow the vacuum space to be pumped out easily.

The AWPS also has a Volume and Warning Display mounted on the Face Mask that allows the user to monitor the system. A pair of Pressure Switches trigger a red or yellow LED if the system pressure is high or low, respectively. Failure Modes which would cause this can be seen in the FMEA/CIL. A Temperature Sensor is located in the LCG loop after the Vaporizer switches on a blue LED to warn the user that the vaporizer may be in danger of freezing and that the Metering Valve should be turned off. The volume of liquid air is displayed in eight divisions of green LED's that turn off as the volume is used. When the user gets to the last 3/8's of the volume, the 3/8 and 1/4 indicator LED's turn yellow and the 1/8 one turns red. When the volume reaches 1/4, an audible alarm is set off. For the AWPS, this could still mean 30 minutes of time remains so a "snooze" button has been added. However, when the volume reaches 1/8, the button no longer works and the audible alarm remains on.

The liquid air volume is measured using a Capacitance Gauge integrated into the Pivot Mechanism. The gauge is a pair of parallel plates in a geometry such that the liquid height between them in all orientations is a uniform function of the volume remaining.

Figure 2-3: Photo of modified InterSpiro Face piece and Regulator

Panels in the Bottom Box provide access to the Electronics and Pump Batteries and the Power Switch for the system.

2.2 Face-Piece, Regulator, Helmet, Communications

An InterSpiro face-piece and regulator were modified to incorporate backpack status displays and optional communications. The InterSpiro regulator and face-piece system is used in existing NIOSH certified compressed air SCBAs.

The Phase I AWPS incorporated off-the-shelf helmets and communications. The communication system was modified to mount directly to the InterSpiro face piece.

2.3 High Performance LCG

Figure 2-4: Photo of High Performance LCG

The three primary methods the body uses to reject heat (radiation, convection, and evaporation) are all severely impaired in the environment of protective clothing. The result of this heat build-up is heat stress and impaired mental awareness. The High Performance LCG eliminates heat stress by assisting the body in rejecting heat.

The High Performance LCG consists of a body-suit type garment constructed of stretchable material with tubing outside and patches attached to the inside. Heat is conducted away from the subject by circulating chilled water from the vaporizer through the patches that lie against the surface of the skin. The patches provide a large surface area for heat conduction, and are located in various locations such as on the upper torso, thighs, and upper arms. The large area of contact between the patches and the subject's skin will allow a comfortable temperature cooling water to be used.

Many of the cooling suits available on the market today are constructed of small water carrying tubes which are either sewn or woven into a snug fitting suit. The process of attaching and routing the tubes within the suit is time consuming and expensive. The tubing itself is also expensive when compared to the raw materials used in the patch garments. The patch manufacturing process is also much less expensive and less time consuming. Because the patch system has much less flow resistance, and can effectively utilize warmer water, it is inherently a more efficient system to be integrated with the AWPS.

2.4 Protective Clothing

Based on the three site visits, a designs were developed for both Level A (vapor protective) and Level B (liquid splash protective) suits. The two suit are described in the following sections. Section 2.4.3 summarizes a trade study performed to determine the configuration of the liquid splash protective suit.

The current philosophy supports the selection of a durable/reusable material for the vapor protective suit, due to the high initial purchase cost for this relatively complex item of protective clothing, while a disposable material is recommended for liquid

splash protection. Table 2-1 provides and compares a complete list of features for both types of suits.

Design Feature	Level A Suit	Level B/C Clothing
Overall protection goal	Vapor protection	Liquid splash and particulate protection
Expected application	Emergency response	D&D activities requiring Level B or C protection
Certification standard	NFPA 1991	NFPA 1993
General configuration	Single piece with gloves and boots, totally encapsulates wearer and PLSS	Two piece, overall and splash hood with sleeve, gloves, and visor. Separate gloves. Totally covers wearer and PLSS
Design approach	Use existing NFPA 1991 compliant suit, with minor modification	New two piece design with attention to glove, boot interfaces, closure design, overall form and fit
Base material	Challenge 6400	Tychem 9400
Chemical resistance of base materials	> 480 minutes ASTM F 1001 chemical battery	Effective against ASTM F 1001 liquid chemical battery; no penetration to 18 of 21 chemicals
Durability of base materials	Resists repeated flexing and abrasion; may be reused if properly decontaminated and not damaged	Intended for single wearing use (single shift)
Flame resistance of base materials	No ignition or burn time per ASTM F 1358	Not rated for flame resistance
Seam construction	Heat sealed, taped both sides	Sewn, heat sealed, taped one side
Visor	10 mil FEP	20 mil PVC
Gloves	20 mil Neoprene over 4 mil Silvershield	Base recommendation - Neoprene coated knit; other gloves may be used
Glove attachment	Hard plastic glove ring attached to inner suit sleeve; gloves attached with rubber band; sleeve splash guard provided	plastic glove ring with nylon cable ties; sleeve splash guard provided
Footwear design	Soft bootie (extension of suit leg); Bata Shoe PVC blend outer boot, cuff splash guard provided	Soft bootie (extension of suit leg); Bata Shoe PVC blend outer boot, cuff splash guard provided
Closure	PVC/brass pressure-sealing zipper; outer flap with velcro tape	N/A
Closure location	Rear of suit	N/A
Exhaust valves and PLSS interface	3 Valves at top of the suit and on both side of suit hips; top provides direct exhaust of breathed air	Valve provided for direct exhaust of PLSS at back of hood
LCG interface	None required	Pass-through in overall in underarm area
Wearing configuration	Suit donned as a single unit over PLSS and LCG, but requires adding outer boots	Overall portion donned first over LCG, followed by PLSS, and then splash hood
Donning assistance	Requires helper	Can be donned without assistance
Sizes	Two sizes (large and extra large); inc. internal straps to shorten torso length	Minimum of five sizes; coverall conforms to ANSI/ ISEA 101-85
Projected cost	\$3500	\$175
Proto-types for Phase I	One (size large)	Eight (all sized large)

Table 2-1: Comparison of Design Features for Levels A and B/C PPE

Figure 2-5: Chemfab
"Challenge 6400" Vapor
Protective Suit

2.4.1 Vapor Protective Suit (Level A)

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 2-6 is a photo of the Chemfab 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 HazMax 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.

Figure 2-6: AWPS Liquid Splash Protective Suit

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 which 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 delrin 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 HazMax boots are used as the outer boots.
5. Garment seams are sewn and taped on the outside.

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 2-3 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.

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 2-2.

Figure 2-7: Liquid Splash Protective Suit Design Options

		OPTION 1		OPTION 2		OPTION 3		
		<u>Two-Piece</u> Coverall w/Gloves and Sep. Splash Hood w/Short Sleeves		<u>Two-Piece</u> Overall w/ Suspenders and Sep. Splash Hood w/ Gloves		<u>One-Piece</u> 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 2-2: Comparison and Rating of Liquid Splash Protective Suit Design Options

		OPTION 1 <u>Two-Piece</u> Coverall w/Gloves and Sep. Splash Hood w/Short Sleeves		OPTION 2 <u>Two-Piece</u> Overall w/ Suspenders and Sep. Splash Hood w/ Gloves		OPTION 3 <u>One-Piece</u> 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 accommodate 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		

Table 2-2: Comparison and Rating of Liquid Splash Protective Suit Design Options
(cont)

2.5 Sub Scale Recharge Station

The sub scale recharge station is a prototype system that uses liquid nitrogen to convert compressed breathing air into subcritical liquid air. The recharge system consists of a heat exchanger with all the necessary monitoring instrumentation to ensure that the system is operating properly. The consumables, breathing air and industrial grade LN₂, are standard items and will be purchased from outside gas suppliers as required for use.

Figure 2-8: Schematic of Recharge System

The AWPS Fill System uses cooling coils immersed in a liquid nitrogen bath to chill compressed air to cryogenic temperatures. Air from a high pressure source is reduced to 300 psig by the Primary Regulator. The gas then flows through length of tubing immersed in liquid nitrogen in a foam insulated, stainless steel container. The Main Shutoff Valve controls the flow to the Secondary Regulator which reduces the pressure to 40 psig. Flow from the Secondary Regulator goes through a line that is

connected to the AWPS Fill Check Valve. A Bleed Valve is teed off this line so the pressure may be vented in the line after filling is completed and the Main Shutoff Valve is closed. All the components after the cooling coils are located in the ullage of the LN2 Bath to maximize efficiency by reducing heat leak. All the cryogen sections of tubing that can be contained are relieved and the Relief Valve exhausts flow back into the LN2 Bath.

Other service equipment included controls for the Vaporizer De-icer, an auxiliary power supply, and a small water reservoir to bleed air bubbles out of the LCG loop, if necessary.

Figure 2-9: Photo of System undergoing Recharge

3.0 Failure Modes and Effects Analysis

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. Appendix A contains the worksheets created for the analysis which is summarized below. 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 analysis 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.

For example, consider an SCBA high pressure air bottle rupture. The failure mode would be very dangerous to the user and the SCBA itself and would definitely end an operation early. There is also no redundancy for a loss of an air bottle. For that reason however, the bottles are designed and tested for certification so that the likelihood of that failure is greatly reduced. The safe design does not necessarily have to have redundancy but also components and fittings that can well withstand the environment the unit will be operating in.

Failure detection methods include either the warning systems built into the hardware or user feedback. The corrective action describes what is to be done in the event of a failure. The failures and effects are assessed in the following manner. Each FMEA/CIL item is identified by hardware and function criticality.

Hardware criticality is the categorization of the singular effect of the identified failure mode of a hardware item.

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

Functional criticality is the categorization of the effect of loss of all redundancy for a given function.

<u>Criticality</u>	<u>Potential Effect Of Failure</u>
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.

For example, an entry of 2/1R in the criticality column of the FMEA indicates at least two redundant hardware items. A failure of all the items could cause injury; however, the first failure is not threatening but would cancel an operation.

The criticality summary of the AWPS is as follows:

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

The 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 to 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 he or she 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 the backpack is not performing properly. In these cases, the user should go to a proper 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.

4.0 Mass and Cost Budgets

Table 4-1 lists the masses of the Phase I AWPS backpack and accessories. Table 4-2 lists the projected masses of the Phase II hardware. Most of the major mass savings over the Phase I components have been tested in OSS's independent research.

Backpack Component	Mass (lbs)
LCG loop	
Motor/pump	0.4
Fittings, tubing	0.4
Structure	
Frame, straps, fasteners, etc.	3.0
Lower Box	1.1
Vessels & Pickup Parts	
Inner vessel	6.5
Outer vessel	9.1
Getter	0.5
Getter Heater	0.15
Suspension system	0.5
Tubing	0.2
Capacitance gage	0.11
Hubs	0.08
Pickups	0.3
Heat Exchangers	
Primary heat exchanger	0.85
Excess heat exchanger	1.5
Fittings	?
Valves	
Regulator	0.49
Cryogen relief valves	0.11
Pressure closing valve	0.23
Cryogen check valve	0.12
Metering valve	0.18
Burst disk	0.09
3 way valve	0.47
Electrical pass through	0.07
Pump out valve	0.02
Metal seals	0.0
Fittings	0.35
2 pressure switches	0.12
Electronics	
Batteries, holder	1.7
Voltage regulator	0.3
PC boards	0.3
Cryogen	13.52
Backpack Sub-Total	42.76
Accessory Components	
LCG	3.0
Face Piece, hose	1.99
Display	0.40
Accessory Sub-Total	5.39
AWPS Total	48.15

Table 4-2: AWPS Prototype Mass / Cost Budget (actual)

Backpack Component	Minimum Mass (lbs)	Maximum Mass (lbs)
LCG		
Motor/pump	0.3	0.4
Fittings, tubing	0.3	0.4
Structure		
Frame, straps, fasteners, etc.	2.4	3
Lower Box	0.5	1.1
Vessels & Pickup Pieces		
Inner vessel	5.7	6.5
Outer vessel	4.8	5.5
Getter	0.25	0.5
Getter Heater	0.1	0.15
Suspension system	0.35	0.5
Tubing	0.15	0.2
Capacitance gage	0.11	0.11
Hubs	0.05	0.08
Pickups	0.19	0.3
Heat Exchangers		
Primary heat exchanger	0.75	0.85
Excess heat exchanger	1.1	1.5
Fittings		
Valves		
Cryogen relief valves	0.11	0.11
Pressure closing valve	0.23	0.23
Cryogen check valve	0.12	0.12
Metering valve	0.18	0.18
Burst disk	0.09	0.09
3 way valve	0.3	0.5
Electrical pass through	0.07	0.09
Pump out valve	0.01	0.02
Metal seals	0	0
Fittings	0.24	0.42
2 pressure switches	0.12	0.12
Electronics		
Batteries, holder	1.1	1.7
Voltage regulator	0.18	0.3
PC boards	0.2	0.3
Cryogen	13.52	13.52
Backpack Sub-Total	33.52	38.79
Accessory Components		
LCG	2.3	3
Face Piece, hose, regulator	2.09	2.09
Display	0.2	0.4
Accessory Sub-Total	4.59	5.49
AWPS Total	38.11	44.28

Table 4-3: AWPS Production Mass / Cost Budget (estimated)

5.0 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 clothing and Equipment (PPE) used in the existing ensembles. This information has been applied in the form of a model which can also determine the equivalent life cycle costs for proposed AWPS configurations.

A detailed derivation of the model and all component costs is included in "Performance/Design Criteria Review Topical Report | Advanced Worker Protection System", which is available from the Department of Energy. 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.

5.1 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:

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

Equation 1

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--respirator, protective clothing, cooling system, communications device, and any other equipment. In comparing ensembles, only those items which are different need be considered. However, each item must be placed on the same time basis to allow a comparison of the total support cost. For the purposes of this study, the total PPE support costs for a specific job (with a defined amount of actual work) has been chosen as the basis for providing estimates.

5.2 Model Variables

Different variables affect each of the individual cost areas in Equation 1. 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 5-1 below lists the different variables involved in determining the costs in each PPE 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	No	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

Table 5-1: Model Variables for Each Cost Area

5.3 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) are 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 a over boots, cooling system, communications device, and 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
- The liquid air PLSS.

The suit in this scenario is expected to provide five uses before requiring disposal and costs \$3500. The PLSS also is estimated to have a 5 year service life (1000 uses) with a purchase price of ____.

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.

5.3.1 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,"¹ 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.

5.3.2 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 work load;
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).

¹ Schwope, A.D. and Renard, E.P., "Estimation of the Cost of Using Chemical Protective Clothing," Performance of Protective Clothing: Fourth Volume, ASTM STP 1133, James P. McBriarity and Norman W. Henry, Eds., American Society for Testing and Materials, Philadelphia, 1992. 972-981.

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 5-2 below shows the individual times associated with operational uses of each ensemble (applies to both Level A and B):

Activity	Amount of Time Each 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 actual work to total time required	0.27	0.62

Table 5-2: Time Required in Ensemble Operations

Other specific assumptions were required for other costs, particularly purchasing labor consumable 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. These costs are based on the case of equipment needs for a 5000 man-hour job as described above.
- Operation consumable 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 consumable have been previously estimated (by Schwope and Renard) at \$50/entry for disposable supplies (e.g., detergents, rags, ground cloths) and \$25/entry for reusable supplies, such as buckets, brushes, and decontamination showers.
- Maintenance costs are assumed to be the same for AWPS PLSS and the existing ensemble SCBA at \$25/maintenance cycle and 10 uses for every maintenance cycle. Likewise, the principal maintenance for protective clothing is the replacement of the gloves at \$25/pair with a total of 20 use and decontamination cycles assumed for each set of gloves.

5.4 Life Cycle Cost Calculations (Base Case)

Table 5-3 shows the values used for each variable in the model based on the estimates and assumptions above. The AWPS shows a significantly smaller life cycle cost for both Level A and B operations for the 5000 work hours.

Variable	Existing Ensemble	AWPS
Level A suit purchase cost	\$400	\$3500
Level B suit purchase cost	\$25	\$150
SCBA purchase cost	\$2200	_____
Labor rate (except operations)	\$25/hour	same
Purchasing hours	20/year	same
Actual work time/use	20 minutes	120 minutes
Support time/use (see table 5-2)	55 minutes	75 minutes
Total time/use	75 minutes	195 minutes
Ratio actual to total time	0.27	0.62
Operations labor rate	\$40/hour	same
Consumable/use	\$1.35	\$16.65
Decontamination consumable/mission	\$25	\$50

Table 5-3: Cost Model Variable Values

Results using the life cycle cost model are presented in Table 5-4. The overall Life Cycle Cost (LCC) 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 demonstrated 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 5-1 shows the relative proportion of costs for each ensemble. 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.

Figure 5-1: Proportion of Costs for LCC

Table 5-4 also provides estimates that show 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.

Total # of work hours	5000
Ratio of Level A work	.05
Ratio of Level B work	.95
Total Hours Level A	250
Total hours Level B	4750
Working days/year	260

	Total Time	Actual Time	Support Time	Ratio Act./Tot.	Individ. Uses	Missions Required	Days Required
Op. Time - Existing	75	20	15	0.27	15000	3750	625
Op. Time - AWPS	195	120	35	0.62	2500	625	156

Cost	Variable	Level A				Level B			
		Existing SCBA		AWPS		Existing SCBA		AWPS	
		Suit	SCBA	Suit	PLSS	Suit	SCBA	Suit	PLSS
Purchase Price	I\$	\$400	\$2,200	\$	\$	\$25	\$2,200	\$	\$
Uses per PPE Item	IU	1	1000	5	1000	1	1000	1	1000
Purchasing Hrs	HRS(P)		20		20		20		20
Purchasing Labor Rate	L\$(P)		\$25		\$25		\$25		\$25
Purchasing Labor Cost			\$1,202		\$300		\$1,202		\$300
Total Purchasing Cost	P		\$302,852		\$88,738		\$98,102		\$374,363
PPE Uses	AU		750		125		14250		2375
Support Hours	HRS(O)		.25		0.58		0.25		0.58
Support Labor Rate	L\$(O)		\$25		\$25		\$25		\$25
Consumables	C(O)		\$1.35		\$16.65		\$1.35		\$16.65
Operation Hrs	HRS(W)		1.25		3.25		1.25		3.25
Operation Labor Rate	L\$(W)		\$40		\$40		\$40		\$40
Total Operation Cost	O		\$43,200		\$20,154		\$820,800		\$382,929
# Missions	AM		187.5		31.25		3562.5		593.75
Cons. Cost/Mission	C ^o		\$75		\$75		\$75		\$75
decontamination Hrs	HRS ^o		.292		0.667		0.102		0.201
Decontamination Labor Rate	L\$(C)		\$25		\$25		\$25		\$25
Total Decontamination Cost	C		\$19,544		\$4,427		\$303,503		\$56,489
# Uses / Maint. Cycle	UMC		20		10		20		10
Consumables	C(M)		\$25		\$50		\$25		\$50
Maintenance Hrs	HRS(M)		0.475		1.310		0.131		0.301
Maint. Labor Rate	L\$(M)		\$25		\$25		\$25		\$25
Total Maint. Cost	M		\$1,383		\$1,034		\$20,154		\$13,664
Total Storage Cost	S		\$2,925		\$2,063		\$47,559		\$27,253
Total Disposal Cost	D		\$975		\$688		\$15,853		\$9,084
LIFE CYCLE COST	T		\$370,879		\$117,103		\$1,305,972		\$863,782

Table 5-4: Calculation of Life Cycle Costs (Simple Model - Best Case)

5.5 LCC Summary

The most efficient way to define the feasibility of producing a new system is to determine if the initial cost of the system will benefit the user/industry in the long run. That is to say, the system being developed must give the end user a more productive system that will save time and money. Based on the LCC analysis, we feel the AWPS will provide significant cost benefits to the industry. The sensitivity analysis performed on the key variables shows continued cost benefits, even with the least favorable assumptions.

6.0 In House Testing

In house testing was divided into four areas of focus, component testing, sub-system testing, system testing and complete ensemble testing. Complete ensemble testing in house was limited, with more extensive testing at Kansas State University, which is described in Section 7.0.

6.1 Hazardous Materials PLSS

Most of the component and sub-system testing focused on the AWPS backpack. Data was taken during much of this testing, but it was primarily for engineering development, and is not reported here. Tests included -

- Dewar development
 - inner vessel pressure and vacuum tests
 - epoxy seal tests
 - outer vessel vacuum tight penetration tests
 - support cone load testing
 - support cone vacuum out-gasing tests
 - getter and heater MLI / LCP compatibility
- AAPD Pickup Mechanism
 - Evaluate seal friction and reliability for different designs and materials
- Vaporizer Efficiency
 - Tested Vaporizer in vacuum bell jar to evaluate performance
- Ambient Heat Exchanger
 - Tested Phase 1 design to determine duration at various flow rates in the event of pump failure
- Pressure Control Components Evaluation
 - Tested to determine compatibility and performance
- Capacitance Gauge Testing
 - Tested Capacitance Gauge in test dewars to verify operation and multi-orientation capability
- Duration Testing
 - Tested on Posichek Breathing Machine to verify backpack duration and proper operation at normal, hard, and NFPA maximum work rates
- O₂% Testing
 - Monitored O₂% during duration testing to verify acceptability

during spacewalks). The NASA tube LCG has approximately twice the length of tubing and number of circuits as commercially available tube type LCGs. The AWPS high performance LCG also has a much lower pressure drop (which allows a smaller pump and battery) than the tube LCGs.

6.4 Protective Clothing

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.

Circumstances involved in 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.

Remaining tests, specifically qualitative assessments of clothing integrity, fit, function, and comfort, are being postponed until Phase II where sizing schemes will be incorporated in the suit design and thus provide a more appropriate evaluation of these suit characteristics.

6.5 Sub Scale 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 (ie. - 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%.

6.6 In-House Manned Testing

The AWPS in house manned testing utilized engineer test subjects, exercising on a Nordic Track or treadmill wearing the Level B suit. While data was taken and analyzed to evaluate the system's performance, 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.

7.0 Kansas State University Independent Evaluation

The Institute for Environmental Research (IER) at Kansas State University was subcontracted to independently evaluate the Advanced Worker Protection System (AWPS) 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.

7.1 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.

7.1.1 Ensembles Tested

Four different ensembles were evaluated, including:

1. The first ensemble consisted of the prototype PLSS, 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 PLSS 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.

7.1.2 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)

7.1.3 Human Subjects

A total of four different human 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 full body cotton coverall under protective clothing.

7.1.4 Exercise Protocol

Human subjects were exposed to a constant work rate using a tread mill adjusted to a sufficient rate and incline to achieve an average energy expenditure of 400 to 500 kcal per hour. This work rate was used in all tests.

7.1.5 Test Measurements

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.

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 indentation 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 **thermal comfort** using a nine point scale. Subjects were also asked to fill out the ensemble comfort evaluation at the end of the test.

Test subject weight before and after testing was measured. **Total ensemble weight** before and after testing was also be measured. These measurements allowed the calculation of sweat rate for test subjects.

7.1.6 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 (See Table 7-1). Only one subject at a time was tested:

1. A total of twenty (20) tests were undertaken, including the baseline, for comparing AWPS and SCBA-based ensemble testing.

2. Eight (8) additional tests were 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, or when the test subject's core temperature or heart rate exceeded prescribed exercise levels (39°C or [220 - subject's age] beats per minute, respectively).

7.1.7 Data Analysis

Each attribute which is measured continuously or discretely during testing was be plotted versus test time showing a comparison of baseline and each ensemble. For the first series of tests, curves of each attribute versus time was shown for the four different ensembles plus baseline. A separate curve was shown for:

- AWPS with Level A suit, PLSS, and LCG;
- AWPS with Level B suit, PLSS, and LCG;
- Level A suit with SCBA;
- Level B suit with SCBA; and
- Baseline condition (no protective clothing or breathing apparatus).

In the second series of tests, splash suit performance was shown for each of the three different environmental conditions using the AWPS with Level B suit, PLSS, and LCG:

- 85°F and 75% relative humidity;
- 45°F and 75% relative humidity, and
- 105°F and 75% relative humidity.

Test participants were asked to rate ensembles and ensemble performance through a questionnaire following the testing.

Test No.	Day	Conditions	Subject	Ensemble
1	1 (morning)	85°F/ 75% RH	A	None (baseline)
2	1 (afternoon)	85°F/ 75% RH	B	None (baseline)
3	1 (evening)	85°F/ 75% RH	C	None (baseline)
4	2 (morning)	85°F/ 75% RH	D	None (baseline)
5	2 (afternoon)	85°F/ 75% RH	A	Level A AWPS
6	2 (evening)	85°F/ 75% RH	B	Level B AWPS
7	3 (morning)	85°F/ 75% RH	C	Level B SCBA
8	3 (afternoon)	85°F/ 75% RH	D	Level A SCBA
9	3 (evening)	85°F/ 75% RH	A	Level B AWPS
10	4 (morning)	85°F/ 75% RH	B	Level A AWPS
11	4 (afternoon)	85°F/ 75% RH	C	Level A SCBA
12	4 (evening)	85°F/ 75% RH	D	Level B SCBA
13	5 (morning)	85°F/ 75% RH	A	Level B SCBA
14	5 (afternoon)	85°F/ 75% RH	B	Level A SCBA
15	5 (evening)	85°F/ 75% RH	C	Level A AWPS
16	6 (morning)	85°F/ 75% RH	D	Level B AWPS
17	6 (afternoon)	85°F/ 75% RH	A	Level A SCBA
18	6 (evening)	85°F/ 75% RH	B	Level B SCBA
19	7 (morning)	85°F/ 75% RH	C	Level B AWPS
20	7 (afternoon)	85°F/ 75% RH	D	Level A AWPS
21	8 (morning)	45°F/ 75% RH	A	Level B AWPS
22	8 (afternoon)	45°F/ 75% RH	B	Level B AWPS
23	9 (morning)	45°F/ 75% RH	C	Level B AWPS
24	9 (afternoon)	45°F/ 75% RH	D	Level B AWPS
25	10 (morning)	105°F/ 95% RH	B	Level B AWPS
26	10 (afternoon)	105°F/ 95% RH	C	Level B AWPS
27	11 (morning)	105°F/ 95% RH	D	Level B AWPS
28	11 (afternoon)	105°F/ 95% RH	A	Level B AWPS

Table 7-1: Testing Matrix

7.2 Hardware

The AWPS hardware performed remarkably well during the manned testing at KSU. 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 which 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 location will be used to update the design for 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. A connector was replaced and solved the problem.

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 scfm of gas flow in addition to what was being breathed by the test subject. Future modifications to the metering valve to limit gas flow, and adjustments to the LCG water low temperature warning light should serve to minimize the possibility of future freezing. 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.

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. An external exhaust was planned, but not implemented in this phase because of difficulties adapting the face piece regulator to an exhaust hose.

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. It is believed that adjustments to the self-pressurization system will eliminate this problem.

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 will minimize the effects of body movement on flow variations.

[which one??] 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 eights. 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. Further integration of the radio with the complete AWPS will alleviate these difficulties.

7.2.1 Test Procedures

Prior to each test, the AWPS backpack was filled with liquid air. This was done using the fill 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 fill station box was then filled with liquid nitrogen which acts as a heat sink to liquefy the breathing air. After the box is full, breathing air is allowed to flow through the fill station and into the backpack. Heat from the air is transferred to the liquid nitrogen in the fill station, and once everything is sufficiently cool, the backpack begins to fill with liquid air. When it is full, excess liquid air is vented from the bottom of the pack. The pack was then pressurized to operating pressure (60 psig).

Meanwhile, the test subject was getting ready. As discussed in section 7.1.5, EKG and skin temperature sensors were attached at various locations on his 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.

Figure 7-1: Manned Test Preparation

As the test subject began walking, he was asked to rate his thermal comfort from 1 to 9 (1 = very cold, 9 = very hot). Every five minutes, he was again asked to rate his 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 the 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 his physiological indicators showed signs of stress that he could and should stop if he 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-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-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.

7.2.2 Support Equipment

The tests were conducted in an environmental chamber as described in 7.1.2. 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, 9v and C cell alkaline batteries.

7.3 Results and Discussions

An extensive amount of data were collected during this evaluation. While much of this data is presented as part of the subcontractor's report (Appendix B), additional observations and findings are offered in this section.

7.3.1 Physiological Data

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 inner of all test subjects was soaked with perspiration following each test.

Figure 7-2: Representative Skin Temperature Graph with Standard SCBA

Figures 7-2 and 7-3 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 7-3: Representative Skin Temperature Graph with AWPS Backpack

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 100F and 45F. Again, the observations to be made from this graph are duration and rate of temperature change.

Figure 7-4: Representative Core Temperature Graph

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.

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 45F AWPS had the smallest core temperature rise. Both tests lasted approximately 60 minutes and had similar core temperature increases. The 100F AWPS had the next fastest core temperature rise ($\sim .9^{\circ}\text{C}$) and a duration of 65 minutes. While the SCBA (with no cooling) had the steepest core temperature rise of .7 F in 20 minutes. A good

indication of thermal stress is a core temperature rise of 1C. The SCBA test would have reached this level at approximately 28.5 minutes, less than half the duration of the 100F test which had a 15 F warmer environment.

7.3.2 Design Feedback

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 an 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 test 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.

7.4 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. Specifically, design changes were identified which will be incorporated into the Phase II prototypes. 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.

8.0 Conclusion

The performance criteria for the AWPS have been developed and Phase I has demonstrated the ability to meet them. These criteria were developed with both an understanding of the AWPS capabilities combined with the identification of DOE Decontamination and Decommissioning activities protection needs. 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.

We have identified, and feel we can meet, 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 which will govern the use of the AWPS once in production, have had a bearing on the design of the AWPS. 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 have 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. Calculations of life cycle cost also demonstrated the preferred configuration for Level A clothing as being a more durable, reusable product.

The prototype hardware developed in Phase I has served to verify the design approaches for the AWPS, and gathered manned operations and integration

information. The testing at KSU will provide 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 Phase I, has brought the technical risk for Phase II of the AWPS project down to a low level.

Independent testing at the KSU's Institute for Environmental Research provided a comprehensive human 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 PLSS without any major failure and 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 were major benefits realized from increased extended mission performance and increases in productivity.

OSS is ready to continue the AWPS project into Phase II. The duration of Phase II is planned for 13 months and will consist of seven tasks -

- Design Modification and Optimization - incorporate all advances from independent research and Phase I to design pre-production backpack and full scale support hardware for certification and site demonstration
- Incorporation of Sizing Requirements into Suit Design - Design next generation of Advanced LCG and Splash Protective Garment (Level B), with multiple sizes. Design modifications to commercially available Vapor Protective Garment (Level A).
- Full Scale AWPS Development - Fabrication and in house testing of hardware and garments.
- AWPS Use Documentation Manuals - Produce Operator, Service, and Training Manuals.
- Certification and Outside Evaluation of System / Components - DOT certification of the Vessel, NIOSH certification of the breathing system, DOT (LANL) evaluation of protective garments.
- Production Version AWPS Development Topical Report - Topical report on Phase II tasks and test plan for site demonstration.
- DOE Site Demonstration - Field tests at a DOE site (to be determined).

At the completion of Phase II, OSS is committed making the NIOSH certified AWPS available in the commercial market, and continues to invest company resources

towards developing that market potential. In addition, OSS continues to support internally funded research and development of other hostile environment life support products related to the AWPS.

Appendix A - Failure Modes And Effects Analysis

Item Name: Advanced All-Position Dewar (AAPD) Pickup Mechanism
Function: Mechanism that routes vent flow to the ullage and keeps a liquid inlet at the lowest point in the AAPD Inner Vessel in all orientations. Integral Capacitance Gauge measures liquid volume in all orientations.

Item.Mode #: 1.1

Failure Mode: Vent Hub Seal failure

Cause:

- Improper seal installation.
- Debris in system.
- Seal wear.

Effect on Unit:

- Liquid cryogen is vented before AAPD is full during fill.
- Liquid cryogen is vented during pressure relief when Vent Hub is immersed.

Effect on User:

- None during fill.
- Possible exposure to cryogen in Relief Valve vent flow.

Effect on Operation: ◦ None, if no secondary failure is causing Relief Valve venting when Vent Hub is immersed.

Failure Detection:

- Liquid cryogen is vented before AAPD is full during fill.
- Liquid cryogen is vented during pressure relief when Vent Hub is immersed.

Corrective Action:

- Do not use pack if failure is detected during fill.
- Complete operation if detected during use and no secondary failure is causing Relief Valve venting. Service before next operation.

Criticality: 2/2

Item.Mode #: 1.2

Failure Mode: Liquid Hub Seal failure

Cause:

- Improper seal installation.
- Debris in system.
- Seal wear.

Effect on Unit:

- Two-phase fluid delivered to Vaporizer and Vaporizer is less efficient when Liquid Hub is exposed to ullage.
- Large leak can result in system pressure decay when Liquid Hub is exposed to ullage during operation.

Effect on User:

- Reduced cooling in orientations where Liquid Hub is exposed to ullage.
- Reduced air flow to mask if large leak and unit is in orientations where Liquid Hub is exposed to ullage.

Effect on Operation:

- None, if small leak.
- Large leak results in withdrawal from operation.

Failure Detection:

- Pressure decay from large leaks if in orientations where Liquid Hub would be exposed to ullage
- Slight reduction in cooling level if in orientations where Liquid Hub would be exposed to ullage.

Corrective Action:

- Complete operation if detected during use and leak is not large enough to cause pressure decay. Service before next operation.

Criticality: 2/2

<u>Item.Mode #:</u>	1.3
<u>Failure Mode:</u>	Bottom Pivot Seal failure
<u>Cause:</u>	<ul style="list-style-type: none"> ◦ Improper seal installation. ◦ Debris in system. ◦ Seal wear.
<u>Effect on Unit:</u>	<ul style="list-style-type: none"> ◦ Two-phase fluid delivered to Vaporizer and Vaporizer is less efficient when Bottom Pivot Seal is exposed to ullage.
<u>Effect on User:</u>	<ul style="list-style-type: none"> ◦ Reduced cooling in orientations where Bottom Pivot Seal is exposed to ullage.
<u>Effect on Operation:</u>	<ul style="list-style-type: none"> ◦ None, if small leak. ◦ Large leak results in withdrawal from operation.
<u>Failure Detection:</u>	<ul style="list-style-type: none"> ◦ Pressure decay from large leaks if in orientations where Liquid Hub would be exposed to ullage ◦ Slight reduction in cooling level if in orientations where Liquid Hub would be exposed to ullage.
<u>Corrective Action:</u>	<ul style="list-style-type: none"> ◦ Complete operation if detected during use and leak is not large enough to cause pressure decay. Service before next operation.
<u>Criticality:</u>	2/2

Item Name: AAPD Inner Vessel
Function: Machined aluminum pressure vessel in the vacuum that contains the Pivot Mechanism and holds the Liquid Air.
Item.Mode #: 2.1
Failure Mode: Vacuum leak
Cause:

- Weld failure at vessel halves weld seam.

Effect on Unit:

- Loss of vacuum.
- Heat transfer to cryogen would cause excessive boiling.
- Large pressure leak into vacuum would cause Pumpout Valve to blow.

Effect on User:

- Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.

Effect on Operation:

- Duration would be shortened due to venting of contents.
- User should withdraw from operation

Failure Detection:

- Blown Pumpout Valve.
- Excessive cryogen boil off.
- Condensation or frost on Outer Vessel.

Corrective Action:

- Stop operation. Service before next operation.

Criticality: 2/2

<u>Item Name:</u>	Support Cones
<u>Function:</u>	Fiberglass & epoxy cones that support between the Inner and Outer Vessel and minimize heat leak into Inner Vessel.
<u>Item.Mode #:</u>	3.1
<u>Failure Mode:</u>	Structural failure
<u>Cause:</u>	<ul style="list-style-type: none">o Mechanical fatigue.o Thermal fatigue.
<u>Effect on Unit:</u>	<ul style="list-style-type: none">o Inner Vessel might come in contact with Outer Vessel or warm tubing.o Heat transfer to cryogen would cause excessive boiling.
<u>Effect on User:</u>	<ul style="list-style-type: none">o Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">o Duration would be shortened due to venting of contents.o User should withdraw from operation
<u>Failure Detection:</u>	<ul style="list-style-type: none">o Inner Vessel can be heard "rattling" in Outer Vessel.o Excessive cryogen boil off.o Condensation or frost on Outer Vessel at contact points.
<u>Corrective Action:</u>	<ul style="list-style-type: none">o Stop operation. Service before next operation.
<u>Criticality:</u>	2/2

Item Name: Support Cone Bushings
Function: Low thermal conductivity bushings between Inner Vessel and Support Cones that also reduces heat leak into Inner Vessel. Bushings are used in the Phase 1 AWPS to account for tolerance stackup of machined and welded parts.
Item Mode #: 4.1
Failure Mode: Structural failure
Cause:

- Mechanical fatigue.
- Thermal fatigue.

Effect on Unit:

- Large fragments would be contained between Support Cones and Inner Vessel.
- Loss of enough small fragments could cause stress concentrations on the Support Cones.
- See Failure Mode # 3.1 when applicable.
- See Failure Mode # 3.1 when applicable.
- See Failure Mode # 3.1 when applicable.
- See Failure Mode # 3.1 when applicable.
- See Failure Mode # 3.1 when applicable.

Effect on User:
Effect on Operation:
Failure Detection:
Corrective Action:
Criticality: 2/2R

<u>Item Name:</u>	Liquid Tube
<u>Function:</u>	Flow passage for the Liquid Air from the Inner Vessel Liquid Hub to the Vaporizer.
<u>Item Mode #:</u>	5.1
<u>Failure Mode:</u>	Vacuum leak
<u>Cause:</u>	<ul style="list-style-type: none">◦ Fitting failure between Liquid Tube and Vaporizer◦ Loss of vacuum.◦ Heat transfer to cryogen would cause excessive boiling.◦ Large pressure leak into vacuum would cause Pumpout Valve to blow.
<u>Effect on Unit:</u>	<ul style="list-style-type: none">◦ Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.◦ Duration would be shortened due to venting of contents.◦ User should withdraw from operation
<u>Effect on User:</u>	
<u>Effect on Operation:</u>	<ul style="list-style-type: none">◦ Blown Pumpout Valve.◦ Excessive cryogen boil off.◦ Condensation or frost on Outer Vessel.◦ Stop operation. Service before next operation.
<u>Failure Detection:</u>	
<u>Corrective Action:</u>	
<u>Criticality:</u>	2/2

A7

<u>Item Name:</u>	Vaporizer
<u>Function:</u>	Heat exchanger located in the vacuum that warms the Liquid Air to a breathable temperature and cools the LCG water.
<u>Item Mode #:</u>	6.1
<u>Failure Mode:</u>	LCG water freeze
<u>Cause:</u>	<ul style="list-style-type: none"> ◦ Pump failure. ◦ Metering Valve flow too high. ◦ LCG Freeze Warning Indicator faulty or ignored by user.
<u>Effect on Unit:</u>	◦ Loss of cooling.
<u>Effect on User:</u>	◦ Loss of cooling.
<u>Effect on Operation:</u>	◦ Operation can continue depending on user ability to perform without cooling.
<u>Failure Detection:</u>	<ul style="list-style-type: none"> ◦ Loss of cooling. ◦ LCG Freeze Warning Indicator.
<u>Corrective Action:</u>	◦ Thaw ice in Vaporizer
<u>Criticality:</u>	2/2
<u>Item Mode #:</u>	6.2
<u>Failure Mode:</u>	Rupture between LCG and pressure sides of Vaporizer
<u>Cause:</u>	<ul style="list-style-type: none"> ◦ Failure to service Vaporizer protective device.
<u>Effect on Unit:</u>	◦ Possible pressure leak into water space.
<u>Effect on User:</u>	◦ Potential reduction or loss of breathing air supply.
<u>Effect on Operation:</u>	◦ Packs needs to be returned to manufacturer for repair.
<u>Failure Detection:</u>	◦ Substantial air bubbles in LCG flow.
<u>Corrective Action:</u>	◦ Stop operation. Service before next operation.
<u>Criticality:</u>	2/2
<u>Item Mode #:</u>	6.3
<u>Failure Mode:</u>	Vacuum leak
<u>Cause:</u>	<ul style="list-style-type: none"> ◦ Weld failure at tube welds
<u>Effect on Unit:</u>	<ul style="list-style-type: none"> ◦ Loss of vacuum. ◦ Heat transfer to cryogen would cause excessive boiling. ◦ Large pressure leak into vacuum would cause Pumpout Valve to blow.
<u>Effect on User:</u>	◦ Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.
<u>Effect on Operation:</u>	<ul style="list-style-type: none"> ◦ Duration would be shortened due to venting of contents. ◦ User should withdraw from operation
<u>Failure Detection:</u>	<ul style="list-style-type: none"> ◦ Blown Pumpout Valve. ◦ Excessive cryogen boil off. ◦ Condensation or frost on Outer Vessel.
<u>Corrective Action:</u>	◦ Stop operation. Service before next operation.
<u>Criticality:</u>	2/2

AB

<u>Item Name:</u>	Fill Tube
<u>Function:</u>	Flow passage through which the AAPD is filled with Liquid Air.
<u>Item Mode #:</u>	7.1
<u>Failure Mode:</u>	Vacuum leak
<u>Cause:</u>	<ul style="list-style-type: none">◦ Weld failure at tube weld
<u>Effect on Unit:</u>	<ul style="list-style-type: none">◦ Loss of vacuum.◦ Heat transfer to cryogen would cause excessive boiling.◦ Large pressure leak into vacuum would cause Pumpout Valve to blow.◦ Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.
<u>Effect on User:</u>	<ul style="list-style-type: none">◦ Duration would be shortened due to venting of contents.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">◦ User should withdraw from operation
<u>Failure Detection:</u>	<ul style="list-style-type: none">◦ Blown Pumpout Valve.◦ Excessive cryogen boil off.◦ Condensation or frost on Outer Vessel.
<u>Corrective Action:</u>	<ul style="list-style-type: none">◦ Stop operation. Service before next operation.
<u>Criticality:</u>	2/2

Item Name: Vent Tube
Function: Flow passage through which the AAPD is self-pressurized during operation or vented during fill. Also connects one plate of the Capacitance Gauge to the Outer Vessel.
Item Mode #: 8.1
Failure Mode: Vacuum leak
Cause:

- Weld failure at tube weld
- Loss of vacuum.
- Heat transfer to cryogen would cause excessive boiling.
- Large pressure leak into vacuum would cause Pumpout Valve to blow.
- Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.

Effect on Unit:

- Duration would be shortened due to venting of contents.
- User should withdraw from operation

Effect on User:

- Blown Pumpout Valve.
- Excessive cryogen boil off.
- Condensation or frost on Outer Vessel.

Effect on Operation:

- Stop operation. Service before next operation.

Failure Detection:
Corrective Action:
Criticality: 2/2

A10

<u>Item Name:</u>	Self-Pressurization Tube
<u>Function:</u>	Flow passage through which Liquid Air from the Liquid Hub flows from the Outer Vessel. Also is connected to the other plate of the Capacitance Gauge.
<u>Item Mode #:</u>	9.1
<u>Failure Mode:</u>	Vacuum leak
<u>Cause:</u>	<ul style="list-style-type: none">◦ Weld failure at tube weld
<u>Effect on Unit:</u>	<ul style="list-style-type: none">◦ Loss of vacuum.◦ Heat transfer to cryogen would cause excessive boiling.◦ Large pressure leak into vacuum would cause Pumpout Valve to blow.◦ Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.
<u>Effect on User:</u>	<ul style="list-style-type: none">◦ Duration would be shortened due to venting of contents.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">◦ User should withdraw from operation
<u>Failure Detection:</u>	<ul style="list-style-type: none">◦ Blown Pumpout Valve.◦ Excessive cryogen boil off.◦ Condensation or frost on Outer Vessel.
<u>Corrective Action:</u>	<ul style="list-style-type: none">◦ Stop operation. Service before next operation.
<u>Criticality:</u>	2/2

All

Item Name: Outer Vessel Metal Seal Tube Penetration
Function: Penetrations for the Fill, Vent, LCG In, LCG Out, and Gas tubes (the LCG In, LCG Out, and Gas Tubes are connections from the Vaporizer).
Item Mode #: 10.1
Failure Mode: Ambient leak into vacuum
Cause:

- Improper installation
- Thermal fatigue
- Loss of vacuum.
- Heat transfer to cryogen would cause excessive boiling.

Effect on Unit:

- Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.

Effect on User:

- Duration would be shortened due to venting of contents.

Effect on Operation:

- User should withdraw from operation
- Excessive cryogen boil off.
- Condensation or frost on Outer Vessel.

Failure Detection:

- Stop operation. Service before next operation.

Corrective Action:
Criticality: 2/2

A12

Item Name: Outer Vessel Insulative Seal Penetration
Function: Outer Vessel Penetration that electrically isolates the Self-Pressurization Line from the Outer Vessel with a Teflon vacuum seal.
Item Mode #: 11.1
Failure Mode: Ambient leak into vacuum
Cause:

- Improper installation.
- Thermal fatigue.
- Loss of vacuum.
- Heat transfer to cryogen would cause excessive boiling.

Effect on Unit:

- Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.

Effect on User:

- Duration would be shortened due to venting of contents.

Effect on Operation:

- User should withdraw from operation
- Excessive cryogen boil off.
- Condensation or frost on Outer Vessel.

Failure Detection:

- Stop operation. Service before next operation.

Corrective Action:
Criticality: 2/2

A13

<u>Item Name:</u>	Pumpout Valve
<u>Function:</u>	The Pumpout Valve is used to seal the Outer Vessel after evacuation.
<u>Item Mode #:</u>	12.1
<u>Failure Mode:</u>	Ambient leak into vacuum
<u>Cause:</u>	<ul style="list-style-type: none">◦ Improper installation.◦ Thermal fatigue.◦ Loss of vacuum.◦ Heat transfer to cryogen would cause excessive boiling.
<u>Effect on Unit:</u>	<ul style="list-style-type: none">◦ Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.
<u>Effect on User:</u>	<ul style="list-style-type: none">◦ Duration would be shortened due to venting of contents.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">◦ User should withdraw from operation
<u>Failure Detection:</u>	<ul style="list-style-type: none">◦ Excessive cryogen boil off.◦ Condensation or frost on Outer Vessel.
<u>Corrective Action:</u>	<ul style="list-style-type: none">◦ Stop operation. Service before next operation.
<u>Criticality:</u>	2/2

<u>Item Name:</u>	Outer Vessel
<u>Function:</u>	The vessel that protects and insulates the Inner Vessel and Vaporizer.
<u>Item Mode #:</u>	13.1
<u>Failure Mode:</u>	Ambient leak into vacuum across O-ring seal
<u>Cause:</u>	<ul style="list-style-type: none">◦ Improper installation.◦ Thermal fatigue.◦ Loss of vacuum.◦ Heat transfer to cryogen would cause excessive boiling.
<u>Effect on Unit:</u>	<ul style="list-style-type: none">◦ Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.
<u>Effect on User:</u>	<ul style="list-style-type: none">◦ Duration would be shortened due to venting of contents.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">◦ User should withdraw from operation◦ Excessive cryogen boil off.◦ Condensation or frost on Outer Vessel.
<u>Failure Detection:</u>	<ul style="list-style-type: none">◦ Stop operation. Service before next operation.
<u>Corrective Action:</u>	
<u>Criticality:</u>	2/2

A15

Item Name: Fill Check Valve
Function: A check valve through which the AAPD is filled.
Item Mode #: 14.1
Failure Mode: Fails open
Cause:

- Debris in system.
- Seal wear.
- Unable to check back flow after fill.
- No effect, failure occurs during fill.
- Fill Check Valve needs to be replaced.
- Liquid flow from Fill Check Valve after fill line is disconnected.
- Vent system and replace Fill Check Valve.

Effect on Unit:
Effect on User:
Effect on Operation:
Failure Detection:
Corrective Action:
Criticality: 2/2

Item Mode #: 14.2
Failure Mode: Fails closed
Cause:

- Debris in system.
- Seal wear.
- Unable to fill.
- No effect, failure occurs during fill.
- Fill Check Valve needs to be replaced.
- AAPD will not fill.
- No vent flow during fill
- Replace Fill Check Valve.

Effect on Unit:
Effect on User:
Effect on Operation:
Failure Detection:
Corrective Action:
Criticality: 2/2

<u>Item Name:</u>	3-Way Valve
<u>Function:</u>	The 3-way valve is attached to the Outer Vessel Vent Penetration. One position allows the AAPD to be vented during fill and the other position allows the self-pressurization gas to flow into the ullage.
<u>Item Mode #:</u>	15.1
<u>Failure Mode:</u>	Will not turn to self-pressurizing position after fill
<u>Cause:</u>	<ul style="list-style-type: none"> ◦ Debris in system. ◦ Moisture on packing or stem froze and bound up the valve during fill. ◦ Cannot close and pressurize system for use after fill.
<u>Effect on Unit:</u>	◦ No effect, failure occurs during fill.
<u>Effect on User:</u>	◦ 3-Way Valve needs to be replaced.
<u>Effect on Operation:</u>	◦ Manual valve cannot be turned.
<u>Failure Detection:</u>	◦ Thaw valve with heat gun and attempt to turn.
<u>Corrective Action:</u>	◦ Vent system and replace 3-Way Valve.
<u>Criticality:</u>	2/2

<u>Item Mode #:</u>	15.2
<u>Failure Mode:</u>	Will not turn from self-pressurizing position in order to fill
<u>Cause:</u>	<ul style="list-style-type: none"> ◦ Debris in system. ◦ Cannot fill system.
<u>Effect on Unit:</u>	◦ No effect, failure occurs during fill.
<u>Effect on User:</u>	◦ 3-Way Valve needs to be replaced.
<u>Effect on Operation:</u>	◦ Manual valve cannot be turned.
<u>Failure Detection:</u>	◦ Replace 3-Way Valve.
<u>Corrective Action:</u>	
<u>Criticality:</u>	2/2

A17

<u>Item Name:</u>	Relief Valve
<u>Function:</u>	Vents gas from the ullage if the AAPD pressure rises above the set point.
<u>Item Mode #:</u>	16.1
<u>Failure Mode:</u>	Fails open
<u>Cause:</u>	<ul style="list-style-type: none"> ◦ Debris in system.
<u>Effect on Unit:</u>	<ul style="list-style-type: none"> ◦ System pressure drops.
<u>Effect on User:</u>	<ul style="list-style-type: none"> ◦ Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve. ◦ Potential reduction or loss of breathing air supply due to lower pressure.
<u>Effect on Operation:</u>	<ul style="list-style-type: none"> ◦ Duration would be shortened due to venting of contents. ◦ Relief Valve needs to be replaced.
<u>Failure Detection:</u>	<ul style="list-style-type: none"> ◦ Excessive venting from Relief Valve with possible decrease in system pressure.
<u>Corrective Action:</u>	<ul style="list-style-type: none"> ◦ Stop operation. Vent system and replace Relief Valve before next operation.
<u>Criticality:</u>	2/2

<u>Item Mode #:</u>	16.2
<u>Failure Mode:</u>	Fails closed
<u>Cause:</u>	<ul style="list-style-type: none"> ◦ Debris in system.
<u>Effect on Unit:</u>	<ul style="list-style-type: none"> ◦ No effect unless another failure causes excessive cryogen boil off. In that case Burst Disc provides redundancy.
<u>Effect on User:</u>	<ul style="list-style-type: none"> ◦ None unless Burst Disc ruptures then venting of contents could cause user discomfort due to cold air flow from Burst Disc.
<u>Effect on Operation:</u>	<ul style="list-style-type: none"> ◦ Relief Valve and possibly Burst Disc needs to be replaced. .
<u>Failure Detection:</u>	<ul style="list-style-type: none"> ◦ High pressure warning light goes on with no Relief Valve flow.
<u>Corrective Action:</u>	<ul style="list-style-type: none"> ◦ Stop operation. Vent system and replace Relief Valve before next operation. Replace Burst Disc if necessary.
<u>Criticality:</u>	3/1R

<u>Item Name:</u>	Burst Disc
<u>Function:</u>	The Burst Disc provides redundant pressure relief should the Relief Valve fail closed.
<u>Item Mode #:</u>	17.1
<u>Failure Mode:</u>	Bursts lower than design pressure
<u>Cause:</u>	<ul style="list-style-type: none"> o Faulty unit. o Damaged.
<u>Effect on Unit:</u>	o System vents entire contents.
<u>Effect on User:</u>	<ul style="list-style-type: none"> o Venting of contents could cause user discomfort due to cold air flow from Burst Disc. o Potential reduction or loss of breathing air supply due to lower pressure.
<u>Effect on Operation:</u>	o Burst Disc needs to be replaced.
<u>Failure Detection:</u>	o Burst Disc ruptures below design pressure.
<u>Corrective Action:</u>	o Stop operation. Vent system and replace Burst Disc.
<u>Criticality:</u>	2/2
<u>Hazards/Remarks:</u>	Situation requires multiple failures to occur.

<u>Item Mode #:</u>	17.2
<u>Failure Mode:</u>	Bursts higher than design pressure
<u>Cause:</u>	<ul style="list-style-type: none"> o Faulty unit. o Damaged.
<u>Effect on Unit:</u>	o Potential pressure system rupture if coupled with a Relief Valve fail closed and a failure causing excessive cryogen boil off.
<u>Effect on User:</u>	o Potential injury from pressure system rupture and/or cryogen exposure due to rupture if coupled with a Relief Valve fail closed and a failure causing excessive cryogen boil off.
<u>Effect on Operation:</u>	o Pack needs to be returned to manufacturer for inspection and repair.
<u>Failure Detection:</u>	o Burst Disc does not rupture at design pressure.
<u>Corrective Action:</u>	o Stop operation. Vent system and replace Burst Disc.
<u>Criticality:</u>	3/1R

Item Name: Pressure Switch - High
Function: Switch closes if the AWPS ullage pressure increases above a certain point.
Item Mode #: 18.1
Failure Mode: Closes switch lower than design pressure
Cause:

- Faulty unit.
- Mechanical fatigue.
- No effect.

Effect on Unit:

- User might be warned of a problem when no problem exists.

Effect on User:

- Operation might be prematurely halted.

Effect on Operation:

- Red LED indicates when pressure is normal.

Failure Detection:

- Replace Pressure Switch unit.

Corrective Action:
Criticality: 3/3

Item Mode #: 18.2
Failure Mode: Closes switch higher than design pressure.
Cause:

- Faulty unit.
- Mechanical fatigue.
- No effect.

Effect on Unit:

- User might not be warned of a problem when problem exists.

Effect on User:

- No effect.

Effect on Operation:

- Red LED does not indicate when pressure is high.

Failure Detection:

- Replace Pressure Switch unit.

Corrective Action:
Criticality: 3/3

Item Name: Pressure Switch - Low
Function: Switch closes if the AWPS pressure decreases below a certain point.
Item Mode #: 19.1
Failure Mode: Closes switch lower than design pressure
Cause:

- Faulty unit.
- Mechanical fatigue.
- No effect.

Effect on Unit:

- User might not be warned of a problem when problem exists.

Effect on User:

- No effect.

Effect on Operation:

- Yellow LED does not indicate when pressure is low.

Failure Detection:

- Replace Pressure Switch unit.

Corrective Action:
Criticality: 3/3

Item Mode #: 19.2
Failure Mode: Closes switch higher than design pressure
Cause:

- Faulty unit.
- Mechanical fatigue.
- No effect.

Effect on Unit:

- User might be warned of a problem when no problem exists.

Effect on User:

- Operation might be prematurely halted.

Effect on Operation:

- Yellow LED indicates when pressure is normal.

Failure Detection:

- Replace Pressure Switch unit.

Corrective Action:
Criticality: 3/3

Item Name: Pressure Closing Valve (PCV)
Function: Shuts off self-pressurization flow into the AAPD until the pressure drops below the operating point.
Item Mode #: 20.1
Failure Mode: Fails to close at set pressure
Cause:

- Debris in system.

Effect on Unit:

- System pressure increases.
- Relief Valve vents.

Effect on User:

- Relief venting of contents could cause user discomfort due to cold air flow from Relief Valve.

Effect on Operation:

- Duration would be shortened due to venting of contents.
- Item needs to be replaced.

Failure Detection:

- System operating at a higher pressure.

Corrective Action:

- Stop operation. Vent system and replace Pressure Closing Valve.

Criticality: 2/2R

Item Mode #: 20.2
Failure Mode: Fails to open at set pressure
Cause:

- Debris in system.

Effect on Unit:

- System pressure drops.

Effect on User:

- Potential reduction or loss of breathing air supply due to lower pressure.

Effect on Operation:

- User should withdraw from operation

Failure Detection:

- System operating at a lower pressure.

Corrective Action:

- Do not pack if situation is detected during service. Vent system and replace PCV.
- Stop operation. Vent system and replace Pressure Closing Valve.

Criticality: 2/2

<u>Item Name:</u>	Volume and Warning Display
<u>Function:</u>	The V&W Display indicates Liquid Air volume in 1/8's and provides individual warning lights if Pressure Switch closes of if the LCG Temperature Sensor drops below the set point.
<u>Item Mode #:</u>	21.1
<u>Failure Mode:</u>	Fails to display
<u>Cause:</u>	<ul style="list-style-type: none">o Damaged.o Low Battery.o No effect.
<u>Effect on Unit:</u>	<ul style="list-style-type: none">o No effect.
<u>Effect on User:</u>	<ul style="list-style-type: none">o No effect.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">o Items needs to be replaced.
<u>Failure Detection:</u>	<ul style="list-style-type: none">o Display not working.
<u>Corrective Action:</u>	<ul style="list-style-type: none">o Stop operation. Replace Volume and Warning Display.
<u>Criticality:</u>	3/3

A23

<u>Item Name:</u>	Ambient Heat Exchanger
<u>Function:</u>	The Ambient Heat Exchanger is a length of finned tubing that will bring the Liquid Air up to a breathable temperature in the event of a pump failure and resulting Vaporizer freeze.
<u>Item Mode #:</u>	22.1
<u>Failure Mode:</u>	Fails to convert cryogen to a breathable temperature
<u>Cause:</u>	<ul style="list-style-type: none">◦ Metering Valve left on after Vaporizer freeze.◦ Secondary failure causes extra flow through Ambient Heat Exchanger.◦ No effect.
<u>Effect on Unit:</u>	<ul style="list-style-type: none">◦ Possible exposure to cold gas.
<u>Effect on User:</u>	<ul style="list-style-type: none">◦ Operation should have been stopped with Vaporizer freeze.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">◦ Gas coming from Regulator begins to get colder.
<u>Failure Detection:</u>	<ul style="list-style-type: none">◦ Close Metering Valve.
<u>Corrective Action:</u>	<ul style="list-style-type: none">◦ End operation and use another pack if detected during use.
<u>Criticality:</u>	3/1R

A24

Item Name: Shutoff Valve
Function: Shuts off the flow to the Regulator when not in use.
Item Mode #: 23.1
Failure Mode: Fails closed
Cause:

- Damaged.
- Debris in valve.

Effect on Unit:

- System cannot be turned on for use.

Effect on User:

- No effect.

Effect on Operation:

- Shutoff Valve needs to be replaced.

Failure Detection:

- Valve cannot be opened.

Corrective Action:

- Replace Shutoff Valve.

Criticality: 2/2

Item Mode #: 23.2
Failure Mode: Fails open
Cause:

- Damaged.
- Debris in valve.

Effect on Unit:

- System cannot be turned off for fill.

Effect on User:

- No effect.

Effect on Operation:

- Shutoff Valve needs to be replaced.

Failure Detection:

- Valve cannot be closed.

Corrective Action:

- Replace Shutoff Valve

Criticality: 2/2

Item Name: Regulator
Function: An Interspiro Spirolite Regulator.
Item Mode #: 24.1
Failure Mode: Regulates too high pressure
Cause:

- Damaged.
- Faulty unit.
- Pressure to regulator too high.
- Mask free flows.
- Shorter duration.
- No effect.
- System problem need to be identified.
- User feedback.
- Stop operation. Close Shutoff Valve and replace Regulator.

Effect on Unit:
Effect on User:
Effect on Operation:
Failure Detection:
Corrective Action:
Criticality: 2/2

Item Mode #: 24.2
Failure Mode: Regulates too low pressure
Cause:

- Damaged.
- Faulty unit.
- Pressure to regulator too low.
- Mask no longer positive pressure.
- User can suck in contaminants.
- System problem need to be identified.
- User feedback.
- Stop operation. Close Shutoff Valve and replace Regulator.

Effect on Unit:
Effect on User:
Effect on Operation:
Failure Detection:
Corrective Action:
Criticality: 2/1R

A26

<u>Item Name:</u>	Metering Valve
<u>Function:</u>	Used to increase flow through the Vaporizer, thereby increasing cooling.
<u>Item Mode #:</u>	25.1
<u>Failure Mode:</u>	Fails open
<u>Cause:</u>	<ul style="list-style-type: none"> o Damaged. o Debris in valve.
<u>Effect on Unit:</u>	<ul style="list-style-type: none"> o Vaporizer may freeze due to excess flow and heat exchange.
<u>Effect on User:</u>	<ul style="list-style-type: none"> o Shorter duration. o Possible exposure to cold gas if Vaporizer freezes and Metering Valve is failed open.
<u>Effect on Operation:</u>	<ul style="list-style-type: none"> o Item needs to be replaced.
<u>Failure Detection:</u>	<ul style="list-style-type: none"> o User feedback. o Vaporizer Freeze Warning Indicator.
<u>Corrective Action:</u>	<ul style="list-style-type: none"> o Stop operation. Replace Metering Valve.
<u>Criticality:</u>	2/2

<u>Item Mode #:</u>	25.2
<u>Failure Mode:</u>	Fails closed
<u>Cause:</u>	<ul style="list-style-type: none"> o Damaged. o Debris in valve.
<u>Effect on Unit:</u>	<ul style="list-style-type: none"> o Cooling level set only by breathing rate.
<u>Effect on User:</u>	<ul style="list-style-type: none"> o Limited cooling.
<u>Effect on Operation:</u>	<ul style="list-style-type: none"> o Item needs to be replaced.
<u>Failure Detection:</u>	<ul style="list-style-type: none"> o User feedback.
<u>Corrective Action:</u>	<ul style="list-style-type: none"> o Stop operation. Replace Metering Valve
<u>Criticality:</u>	2/2

A27

<u>Item Name:</u>	Face Piece
<u>Function:</u>	An Interspiro Spirolite mask that has been modified for a microphone and mounting points for the Volume and Warning Display
<u>Item Mode #:</u>	26.1
<u>Failure Mode:</u>	Leaks
<u>Cause:</u>	<ul style="list-style-type: none">◦ Damaged.◦ Improper seal.◦ Mask free flows.◦ Shorter duration.◦ No effect.
<u>Effect on Unit:</u>	<ul style="list-style-type: none">◦ Item needs to be replaced.
<u>Effect on User:</u>	<ul style="list-style-type: none">◦ User feedback.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">◦ Stop operation. Replace Mask.
<u>Failure Detection:</u>	
<u>Corrective Action:</u>	
<u>Criticality:</u>	2/2

A28

<u>Item Name:</u>	LCG Pump
<u>Function:</u>	Pumps the cooling water through the Vaporizer and LCG.
<u>Item Mode #:</u>	27.1
<u>Failure Mode:</u>	Stops pumping
<u>Cause:</u>	<ul style="list-style-type: none">◦ Debris in pump head.◦ Battery dead.◦ Impact.◦ Vaporizer will freeze.
<u>Effect on Unit:</u>	<ul style="list-style-type: none">◦ See Ambient Heat Exchanger
<u>Effect on User:</u>	<ul style="list-style-type: none">◦ Item needs to be replaced.
<u>Effect on Operation:</u>	<ul style="list-style-type: none">◦ Vaporizer Freeze Warning Indicator.
<u>Failure Detection:</u>	<ul style="list-style-type: none">◦ Stop operation. Replace Pump.
<u>Corrective Action:</u>	
<u>Criticality:</u>	2/2

A29

Item Name: Temperature Sensor
Function: Located in the LCG loop after the Vaporizer. Used to trigger a warning LED if the water coming out of the Vaporizer gets cold enough to indicate that the vaporizer might freeze.
Item Mode #: 28.1
Failure Mode: Senses High
Cause:

- Faulty calibration.
- Damaged.
- Possible Vaporizer freeze.

Effect on Unit:

- User might not be warned of a problem when problem exists.

Effect on User:

- Effects associated with Vaporizer freeze.

Effect on Operation:

- Effects associated with Vaporizer freeze.

Failure Detection:

- Blue LED does not indicate when temperature is low.

Corrective Action:

- Replace/recalibrate Temperature Sensor.

Criticality: 3/3

Item Mode #: 28.2
Failure Mode: Senses low
Cause:

- Faulty calibration.
- Damaged.
- No effect.

Effect on Unit:

- User might be warned of a problem when no problem exists.

Effect on User:

- Operation might be prematurely halted.

Effect on Operation:

- Blue LED indicates when temperature is normal.

Failure Detection:

- Replace/recalibrate Temperature Sensor.

Corrective Action:

- Replace/recalibrate Temperature Sensor.

Criticality: 3/3

A30

Appendix B - Kansas State University Testing Report

Physiological Evaluation of an Advanced Worker Protection System

Objectives

The purpose of prototype testing was to determine the relative physiologically-based advantages of the Advanced Worker Protection System (AWPS) as compared to conventional chemical protective clothing ensembles. Specifically, the testing of human subjects in environmental chambers was performed to:

1. measure the duration of cooling provided by the Liquid Cooling Garment (LCG) and the Portable Life Support System (PLSS) of the AWPS as compared to a similar ensemble using a self-contained breathing apparatus (SCBA); and
2. evaluate the effectiveness of the AWPS ensembles under different environmental conditions.

Ensemble performance was determined for two different protective clothing ensembles: (1) a Level A vapor-protective suit, and (2) a Level B splash-protective suit. Ensemble performance will be compared with similar clothing ensembles using a conventional self-contained breathing apparatus (SCBA).

Background

Oceaneering Space Systems (OSS) has been awarded a contract by the Department of Energy (DOE) to investigate protective clothing and equipment ensemble developments to address the needs of workers engaged in the decontamination and decommissioning the many DOE sites which handle hazardous materials. This project will result in the development of an Advanced Worker Protection System (AWPS). The AWPS is being built around a life support backpack that uses liquid air to provide cooling as well as breathing gas to the worker. The backpack is being combined with advanced protective garments, an advanced liquid cooling garment, respirator facepiece, and support equipment to provide improved worker protection, simplified system maintenance, and dramatically improved worker productivity through longer duration work cycles.

The current phase of the project entails the design and fabrication of full scale prototypes of the AWPS with sub-scale support equipment suitable for integrated testing and preliminary evaluation. Components of the AWPS will be evaluated for different performance areas specific to the item being tested. Full integration of the ensemble will require additional evaluations to assess how the AWPS affects worker comfort and productivity, as compared to existing systems used by DOE.

A large portion of this overall ensemble evaluation was conducted at the Institute for Environmental Research at Kansas State University.

Methods

The protocol for this evaluation will be presented as follows:

- products tested,
- test conditions,
- human subjects,
- exercise procedures,
- test measurements,
- test matrix, and
- method of data analysis.

Products Tested. Two different versions of the AWPS were evaluated.

1. The first ensemble consisted of the prototype PLSS, the prototype LCG, and prototype Level A vapor-protective suit. The protective suit was a ChemFab totally-encapsulating training suit which includes attached gloves and booties. Attached Neoprene gloves were used and outer boots were worn over the booties. The diaphragm type suit exhaust valve was replaced with the spring type valve normally used in ChemFab Challenge 6400 suits. In addition, the hood area of the suit was retrofitted with a diaphragm type exhaust valve for directly venting PLSS exhalation air to the outside environment. One suit, sized extra large, was used. A second suit was provided as backup. A passthrough in the back of the suit was provided for sensor leads.
2. The second ensemble also consisted of the prototype PLSS and LCG but included a two-piece Level B splash-protective suit. A prototype splash-protective suit was fabricated using the TyChem 7500 material. For the purposes of these trials, seams were sewn but not sealed with tape. Separate gloves and outer boots were worn with the suit which were the same as the ensemble above. A total of two prototype suits were fabricated, all size large.

No equipment other than hard hats were worn with the ensembles.

Similar ensembles were tested in which the PLSS and LCG were replaced with an SCBA (Cairns Pioneer). One extra facepiece and one extra cylinder were provided as backup. The identical protective clothing was worn to compare the duration

and effectiveness of the cooling system.

Test Conditions. All testing was conducted in a humidity and temperature controlled environmental chamber. Specifications for the chamber are listed below:

Size: 11.2 ft x 11.2 ft x 9 ft (3.4 m x 3.4 m 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 (<0.15 m/s)

A single set of conditions was selected for comparing AWPS and SCBA-based ensembles. Preliminary recommendations were based on a moderate set of conditions representative of the average DOE D&D workplace environment.

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

In addition, the effectiveness of the AWPS was separately determined under two other sets of conditions representing a low temperature environment and a high temperature environment. The conditions chosen were 45°F (7.2°C) and 100°F (37.8°C).

Human Subjects. A total of four different male subjects were evaluated. Test subjects were all volunteers who were employed locally as firefighters. Their ages ranged from 26 to 42. Since only one size of the AWPS was produced initially, all test subjects were of average build and dimensions, sufficient to fit large-sized protective clothing. All test subjects were in good physical condition as demonstrated in baseline treadmill testing (without protective clothing or equipment). No one was accepted who was taking any medication or had any illness in the past two weeks prior to testing.

The subjects read the Subject Orientation and Protocol Statement (Appendix A) and signed the Informed Consent Statement (Appendix B) before participating. Test subjects provided their own underwear briefs. IER provided sweat socks. The test protocol was approved by the KSU Human Subjects Committee.

Exercise Protocol. Human subjects were exposed to a constant work rate using a treadmill adjusted to a sufficient rate and inclined to achieve an average energy

expenditure of 400 to 500 kcal per hour. This work rate was used in all tests.

The following physiological and physical measurements were monitored during each test:

- Core temperature
- Skin temperature
- Heart rate
- Temperature inside the protective garment

In addition, at the end of each test, subjects were asked to rate aspects of their comfort using a qualitative scale.

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 to prevent it from pulling out during the test. The lead from the rectal sensor was routed through the respective suit passthrough fitting.

Skin temperature was measured at the 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 thermistors. The leads from these six sensors were routed through the respective suit passthrough fitting.

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

- at the indentation below the clavicle on the left and right sides,
- below the last rib in line with the nipple on the left and right sides.

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

Internal suit temperature was measured in the waist region of the protective garment using a thermistor. The lead from this sensor was routed through the respective suit passthrough fitting.

Subjective responses to thermal comfort were measured at 15 minute intervals during the test. The subjects were asked to rate **thermal comfort** using the nine-point Thermal Sensation Scale. Subjective responses to **ensemble comfort** were measured at the conclusion of each test. The subjects were asked to rate **ensemble comfort** using a five-point scale. (See Appendix C and D.)

Test subject weight before and after testing was measured. **Total ensemble weight** before and after testing was also measured. These measurements were taken to allow us to calculate the **sweat rate** of the subjects.

Test Matrix. All test subjects underwent baseline testing in shorts, briefs, T-shirt, socks, and athletic shoes 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 of the four test subjects. (See Table 1.) Only one subject at a time was tested.

1. A total of 21 tests (1 repeated test) were conducted, including the baseline, for comparing AWPS and SCBA-based ensemble testing.
2. Eight additional tests were conducted using the liquid splash-protective ensemble (Level B AWPS) at the two extreme environmental conditions.

Test duration was a maximum of 2 hours, once actual exercise started. However, the test was terminated if the subject wished to stop for any reason or if his core temperature or heart rate exceeded prescribed exercise levels (39°C or 180 beats per minute, respectively).

Data Analysis and Results

Each attribute which was measured continuously or periodically during testing was plotted versus test time. For the first series of testing at 85°F, curves of each attribute versus time were shown for the four different ensembles plus the baseline ensemble. A separate curve was shown for each test subject:

- AWPS with Level A suit, PLSS, and LCG,
- AWPS with Level B suit, PLSS, and LCG,
- Level A suit with SCBA,
- Level B suit with SCBA, and
- baseline condition (no protective clothing or breathing apparatus).

In the second series of testing, splash suit performance was shown for each of the other two different conditions using the AWPS with Level B suit, PLSS, and LCG:

- 45°F and 75% relative humidity, and
- 100°F and 75% relative humidity.

The data collected in this research represented only four test subjects, hence statistical analysis was not performed. However, the graphical data organized by ensemble type and condition, and then by subject, may be found in Appendix E

through K. Raw weight data collected in an effort to determine sweat rate was sent directly to the client but not included in this report. (Changes in the cooling system (LCG) weight over time lead to inconsistent results.)

Overall, comparing AWPS and SCBA-based ensembles, subjects wearing AWPS ensembles averaged longer duration work cycles, 57 minutes versus 29 minutes respectively. The work cycle duration of the AWPS under the low and high temperature environments averaged 66 minutes and 42 minutes. In general, the test subjects noted the increased weight and noise of the prototype AWPS system backpack and the uncomfortable footwear provided. The test duration under the extreme conditions (later tests) may have been affected somewhat by sore feet and muscles. Mean subjective responses to ensemble comfort listed in decreasing order of comfort were AWPS Level B suit, AWPS Level A suit, SCBA Level B suit, and SCBA Level A suit.

Conclusion

It appears that the new Advanced Worker Protection System will increase the tolerance time, and consequently, work performance of persons as compared to the traditional suit worn with a SCBA.

Table 1
Testing Matrix

Test Number	Day	Conditions	Subject	Ensemble
1	1/11/95	85°F/ 75% RH	D	None (baseline)
2	1/12/95	85°F/ 75% RH	C	None (baseline)
3	1/12/95	85°F/ 75% RH	B	None (baseline)
4	2/09/95	85°F/ 75% RH	A	None (baseline)
5	2/20/95	85°F/ 75% RH	C	Level A SCBA
6	2/20/95	85°F/ 75% RH	D	Level A AWPS
7	2/20/95	85°F/ 75% RH	A	Level B SCBA
8	2/20/95	85°F/ 75% RH	C	Level B AWPS
9	2/21/95	85°F/ 75% RH	D	Level B AWPS
10	2/21/95	85°F/ 75% RH	A	Level A SCBA
11	2/21/95	85°F/ 75% RH	B	Level B AWPS
12	2/22/95	85°F/ 75% RH	D	Level B SCBA
13	2/22/95	85°F/ 75% RH	A	Level A AWPS
14	2/22/95	85°F/ 75% RH	C	Level B SCBA
15	2/23/95	85°F/ 75% RH	B	Level A AWPS
16	2/23/95	85°F/ 75% RH	D	Level A SCBA
17	2/23/95	85°F/ 75% RH	A	Level B AWPS
18	2/24/95	85°F/ 75% RH	B	Level A SCBA
19	2/24/95	85°F/ 75% RH	C	Level A AWPS
20	2/24/95	85°F/ 75% RH	B	Level B SCBA
20	2/25/95	85°F/ 75% RH	B	Level A AWPS2

21	2/26/95	45°F/ 75% RH	C	Level B AWPS
22	2/26/95	45°F/ 75% RH	B	Level B AWPS
23	2/27/95	45°F/ 75% RH	D	Level B AWPS
24	2/27/95	45°F/ 75% RH	A	Level B AWPS
25	2/28/95	100°F/ 75% RH	C	Level B AWPS
26	2/28/95	100°F/ 75% RH	B	Level B AWPS
27	3/1/95	100°F/ 75% RH	D	Level B AWPS
29	3/1/95	100°F/ 75% RH	A	Level B AWPS

* A pretest was also conducted on an extra subject.

Appendix A

Subject Orientation and Protocol Statement

Physiological Evaluation of an Advanced Worker Protection System

The purpose of this study is to determine your comfort level while wearing special chemical protective clothing. You should be aware that the conditions to which you will be exposed entail some physical risk such as heat stress. If you decide to become a subject, you should be aware of the following: 1) you are volunteering to act as a subject and are participating on your own volition; 2) if you choose not to participate there will be no penalty or loss of benefits to which you are otherwise entitled; 3) you may leave the experiment any time you wish; 4) your identity as a subject will not be disclosed and anonymity will be maintained; 5) Kansas State University, as an agency of the State of Kansas, does not provide financial compensation (and/or long-term care) to human subjects for injuries resulting from participation in research; and 6) this study will help the government provide more comfortable chemical protective clothing systems to workers.

To participate in this project, you must be a U.S. male citizen and a firefighter, aged 18 - 35. In addition, you must be physically fit and not overweight. You should not be taking any medication or have any heart problems. If you decide to participate in this experiment, you will be expected to attend seven 2 to 2 1/2 hour test sessions in an environmental test chamber. The times for the test sessions include time for orientation, dressing, etc., in addition to the actual experiment. Please do not sign up unless you plan to participate in all seven sessions of the project. During the test session, you will be given a T-shirt, shorts, socks, and a special suit to put on over your underwear. You should provide your own athletic shoes. We will tape thermistors to your skin in several places to measure your skin temperature, several electrodes to your chest to measure heart rate, and ask you to insert a flexible rectal sensor to measure your body core temperature. These measurement devices are painless. During the experiment, you will walk on a treadmill. Every 15 minutes, you will fill out comfort scales that tell us how you feel.

After you have participated in the test sessions, you will be paid \$30 per session, plus a bonus of \$140 upon participating in all seven sessions for a total of \$350. If you quit the study before all seven sessions are completed, you will receive only \$30 for each session you attended.

Appendix B

Informed Consent Statement

Physiological Evaluation of an Advanced Worker Protection System

1. I, _____, volunteer to participate in a project in connection with research studies to be conducted by Kansas State University.
2. I fully understand the purpose of the study as outlined in the orientation statement.
3. I also understand that my performance as an individual will be treated as research data and will in no way be associated with me for other than identification purposes, thereby assuring anonymity of my performance and response.
4. I understand that I will be permitted to leave the test at any time and I may discontinue participation without penalty of loss of benefits to which I am otherwise entitled.
5. If I have any questions concerning the study, I understand that I can contact Dr. Elizabeth McCullough at (913) 532-5620 during the day and (913) 776-3402 at night.
6. If I have any questions about my rights as a subject or the manner in which this research was conducted, I understand that I can contact Dr. James Shanteau, Chair, Institutional Review Board, 103 Fairchild Hall, Kansas State University, Manhattan, KS 66506, (913) 532-6195.

I have read the Subject Orientation and Tests Protocol Statement and signed this Informed Consent.

signature

date

Appendix C

Thermal Sensation Scale

Subject _____

Condition _____

Ensemble _____

Place an X by the adjective that best describes how you feel.

_____	1 very cold
_____	2 cold
_____	3 cool
_____	4 slightly cool
_____	5 neutral
_____	6 slightly warm
_____	7 warm
_____	8 hot
_____	9 very hot

Appendix D

Clothing Comfort Sensation Scale

Subject _____

Condition _____

Ensemble _____

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	_____	:	_____	:	_____	:	_____	:	_____	uncomfortable
soft	_____	:	_____	:	_____	:	_____	:	_____	not soft
not rough	_____	:	_____	:	_____	:	_____	:	_____	rough
flexible	_____	:	_____	:	_____	:	_____	:	_____	stiff
not binding	_____	:	_____	:	_____	:	_____	:	_____	binding
not scratchy	_____	:	_____	:	_____	:	_____	:	_____	scratchy
lightweight	_____	:	_____	:	_____	:	_____	:	_____	heavy
quiet	_____	:	_____	:	_____	:	_____	:	_____	noisy
not clingy	_____	:	_____	:	_____	:	_____	:	_____	clingy
dry	_____	:	_____	:	_____	:	_____	:	_____	clammy

Appendix E

Baseline Condition at 85°F

Clothing Comfort Sensation Scale

Subject A

Condition 1

Ensemble BASE

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	___	:	<u>X</u>	:	___	:	___	rough
flexible	<u>X</u>	:	___	:	___	:	___	:	___	stiff
not binding	<u>X</u>	:	___	:	___	:	___	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	<u>X</u>	:	___	:	___	:	___	:	___	heavy
quiet	<u>X</u>	:	___	:	___	:	___	:	___	noisy
not clingy	<u>X</u>	:	___	:	___	:	___	:	___	clingy
dry	___	:	___	:	<u>X</u>	:	___	:	___	clammy

Errata:

1. Restarted test after 1 minute.

Subject A
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject A
Condition: 85 F / 75% RH
Ensemble: BASELINE

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Subject A
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject A
Condition: 85 F / 75% RH
Ensemble: BASELINE

Clothing Comfort Sensation Scale

Subject B

Condition 1

Ensemble BASE

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	<u>X</u>	:	___	:	___	:	___	:	___	uncomfortable
soft	<u>X</u>	:	___	:	___	:	___	:	___	not soft
not rough	<u>X</u>	:	___	:	___	:	___	:	___	rough
flexible	<u>X</u>	:	___	:	___	:	___	:	___	stiff
not binding	<u>X</u>	:	___	:	___	:	___	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	<u>X</u>	:	___	:	___	:	___	:	___	heavy
quiet	<u>X</u>	:	___	:	___	:	___	:	___	noisy
not clingy	___	:	<u>X</u>	:	___	:	___	:	___	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Restarted test due to sensor failure.
2. Left calf skin sensor failed to give reading.

Subject B
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject B
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject B
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject B
Condition: 85 F / 75% RH
Ensemble: BASELINE

B 22

Clothing Comfort Sensation Scale

Subject C

Condition 1

Ensemble BASE

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	<u>X</u>	:	___	:	___	:	___	:	___	uncomfortable
soft	___	:	<u>X</u>	:	___	:	___	:	___	not soft
not rough	___	:	<u>X</u>	:	___	:	___	:	___	rough
flexible	<u>X</u>	:	___	:	___	:	___	:	___	stiff
not binding	<u>X</u>	:	___	:	___	:	___	:	___	binding
not scratchy	___	:	<u>X</u>	:	___	:	___	:	___	scratchy
lightweight	___	:	<u>X</u>	:	___	:	___	:	___	heavy
quiet	<u>X</u>	:	___	:	___	:	___	:	___	noisy
not clingy	___	:	<u>X</u>	:	___	:	___	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Subject C
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject C
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject C
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject C
Condition: 85 F / 75% RH
Ensemble: BASELINE

B 27

Clothing Comfort Sensation Scale

Subject D

Condition 1

Ensemble BASE

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	<u>X</u>	:	___	:	___	:	___	:	___	uncomfortable
soft	<u>X</u>	:	___	:	___	:	___	:	___	not soft
not rough	<u>X</u>	:	___	:	___	:	___	:	___	rough
flexible	<u>X</u>	:	___	:	___	:	___	:	___	stiff
not binding	<u>X</u>	:	___	:	___	:	___	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	<u>X</u>	:	___	:	___	:	___	:	___	heavy
quiet	<u>X</u>	:	___	:	___	:	___	:	___	noisy
not clingy	___	:	___	:	<u>X</u>	:	___	:	___	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Subject D
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject D
Condition: 85 F / 75% RH
Ensemble: BASELINE

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Subject D
Condition: 85 F / 75% RH
Ensemble: BASELINE

Subject D
Condition: 85 F / 75% RH
Ensemble: BASELINE

Appendix F

Level A Suit, SCBA at 85°F

Clothing Comfort Sensation Scale

Subject A

Condition 1

Ensemble ASCBA

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	___	:	___	:	<u>X</u>	:	___	rough
flexible	___	:	___	:	<u>X</u>	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	___	:	___	:	<u>X</u>	:	___	scratchy
lightweight	___	:	<u>X</u>	:	___	:	___	:	___	heavy
quiet	___	:	<u>X</u>	:	___	:	___	:	___	noisy
not clingy	<u>X</u>	:	___	:	___	:	___	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Heart rate became unstable at 10 minutes.
2. Test stopped due to heart rate at 27 minutes.

Subject A
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject A
Condition: 85 F / 75% RH
Ensemble: ASCBA

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Subject A
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject A
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject A
Condition: 85 F / 75% RH
Ensemble: ASCBA

Clothing Comfort Sensation Scale

Subject B

Condition 1

Ensemble ASCBA

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	___	:	<u>X</u>	:	___	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	___	:	___	:	<u>X</u>	:	___	rough
flexible	___	:	___	:	___	:	<u>X</u>	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Stopped test due to subject indicating he was very hot at 27 minutes.
2. Core temperature increased 1°.

Subject B
Condition: 85 F / 75% RH
Ensemble: ASCBA

B 40

Subject B
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject B
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject B
Condition: 85 F / 75% RH
Ensemble: ASCBA

1943

Subject B
Condition: 85 F / 75% RH
Ensemble: ASCBA

Clothing Comfort Sensation Scale

Subject C

Condition 1

Ensemble ASCBA

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	___	:	<u>X</u>	:	___	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	___	:	___	:	<u>X</u>	:	___	rough
flexible	___	:	___	:	___	:	<u>X</u>	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	<u>X</u>	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	___	:	<u>X</u>	heavy
quiet	___	:	<u>X</u>	:	___	:	___	:	___	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Stopped test at 27 minutes due to irregular heart rate.

Subject C
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject C
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject C
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject C
Condition: 85 F / 75% RH
Ensemble: ASCBA

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Subject C
Condition: 85 F / 75% RH
Ensemble: ASCBA

Clothing Comfort Sensation Scale

Subject D

Condition 1

Ensemble ASCBA

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	___	:	___	:	<u>X</u>	:	___	not soft
not rough	___	:	___	:	___	:	___	:	<u>X</u>	rough
flexible	___	:	___	:	___	:	___	:	<u>X</u>	stiff
not binding	___	:	___	:	___	:	___	:	<u>X</u>	binding
not scratchy	___	:	___	:	___	:	___	:	<u>X</u>	scratchy
lightweight	___	:	___	:	<u>X</u>	:	___	:	___	heavy
quiet	___	:	___	:	<u>X</u>	:	___	:	___	noisy
not clingy	___	:	___	:	___	:	___	:	<u>X</u>	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Stopped test due to fatigue.

Subject D
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject D
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject D
Condition: 85 F / 75% RH
Ensemble: ASCBA

Subject D
Condition: 85 F / 75% RH
Ensemble: ASCBA

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Subject D
Condition: 85 F / 75% RH
Ensemble: ASCBA

B 56

Appendix G

Level B Suit, SCBA at 85°F

Clothing Comfort Sensation Scale

at A Condition 1 Ensemble BSCBA

an X in a blank between each pair of comfort descriptors that indicates how overall feels when you are wearing it.

comfortable	___	:	___	:	X	:	___	:	___	uncomfortable
soft	___	:	X	:	___	:	___	:	___	not soft
not rough	___	:	X	:	___	:	___	:	___	rough
flexible	___	:	X	:	___	:	___	:	___	stiff
not binding	___	:	X	:	___	:	___	:	___	binding
not scratchy	___	:	X	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	X	:	___	heavy
quiet	___	:	___	:	___	:	___	:	X	noisy
not clingy	___	:	___	:	X	:	___	:	___	clingy
dry	___	:	___	:	___	:	___	:	X	clammy

Heart rate became irregular at 16 minutes.
 Stopped test due to headache at 19 minutes.

Subject A
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject A
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject A
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject A
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject A
Condition: 85 F / 75% RH
Ensemble: BSCBA

Clothing Comfort Sensation Scale

Subject B

Condition 1

Ensemble BSCBA

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	___	:	___	:	<u>X</u>	:	___	not soft
not rough	___	:	___	:	___	:	<u>X</u>	:	___	rough
flexible	___	:	___	:	___	:	<u>X</u>	:	___	stiff
not binding	___	:	___	:	___	:	<u>X</u>	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Heart rate became irregular at 20 minutes.
2. Stopped test due to fatigue, especially feet at 25 minutes.

Subject B
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject B
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject B
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject B
Condition: 85 F / 75% RH
Ensemble: BSCBA

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Subject B
Condition: 85 F / 75% RH
Ensemble: BSCBA

Clothing Comfort Sensation Scale

Subject C

Condition 1

Ensemble BSCBA

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	<u>X</u>	:	___	:	___	:	___	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	___	:	<u>X</u>	:	___	:	___	rough
flexible	___	:	<u>X</u>	:	___	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	___	:	<u>X</u>	:	___	:	___	scratchy
lightweight	<u>X</u>	:	___	:	___	:	___	:	___	heavy
quiet	___	:	<u>X</u>	:	___	:	___	:	___	noisy
not clingy	___	:	___	:	<u>X</u>	:	___	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Liz monitored test.
2. Boots weight not recorded after test.
3. Note "no sensors."
4. Test ended at 35 minutes.

Subject C
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject C
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject C
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject C
Condition: 85 F / 75% RH
Ensemble: BSCBA

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Subject C
Condition: 85 F / 75% RH
Ensemble: BSCBA

B 74

Clothing Comfort Sensation Scale

Subject D

Condition 1

Ensemble BSCBA

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	___	:	___	:	<u>X</u>	:	___	not soft
not rough	___	:	___	:	___	:	___	:	<u>X</u>	rough
flexible	___	:	___	:	___	:	<u>X</u>	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	___	:	___	:	___	:	<u>X</u>	scratchy
lightweight	___	:	<u>X</u>	:	___	:	___	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	<u>X</u>	:	___	:	___	:	___	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Stopped test due to core temperature at 39°.
2. Added insoles to boots for this test for comfort.
3. Chamber conditions 28.4°C/47% RH.

Subject D
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject D
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject D
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject D
Condition: 85 F / 75% RH
Ensemble: BSCBA

Subject D
Condition: 85 F / 75% RH
Ensemble: BSCBA

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Appendix H

Level A Suit, AWPS at 85°F

Clothing Comfort Sensation Scale

Subject A

Condition 1

Ensemble AAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	X	:	___	:	___	uncomfortable
soft	___	:	X	:	___	:	___	:	___	not soft
not rough	___	:	X	:	___	:	___	:	___	rough
flexible	X	:	___	:	___	:	___	:	___	stiff
not binding	___	:	X	:	___	:	___	:	___	binding
not scratchy	X	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	___	:	X	heavy
quiet	___	:	___	:	___	:	___	:	X	noisy
not clingy	___	:	___	:	X	:	___	:	___	clingy
dry	___	:	___	:	___	:	X	:	___	clammy

Errata:

1. Cooling in LCG suit was increased at 5 minutes, 10 minutes, 16 minutes.
2. Heart rate became less stable at 36 minutes.
3. Stopped test due to sore feet at 73 minutes.
4. I entered the PS backwards but corrected.

Subject A
Condition: 85 F / 75% RH
Ensemble: AAWPS

Subject A
Condition: 85 F / 75% RH
Ensemble: AAWPS

Subject A
Condition: 85 F / 75% RH
Ensemble: AAWPS

Subject A
Condition: 85 F / 75% RH
Ensemble: AAWPS

85

Subject A
Condition: 85 F / 75% RH
Ensemble: AAWPS

86 B

Clothing Comfort Sensation Scale

Subject B

Condition •1

Ensemble AAWPS2

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	___	:	<u>X</u>	:	___	uncomfortable
soft	___	:	___	:	___	:	<u>X</u>	:	___	not soft
not rough	___	:	___	:	___	:	<u>X</u>	:	___	rough
flexible	___	:	___	:	___	:	<u>X</u>	:	___	stiff
not binding	___	:	___	:	___	:	<u>X</u>	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Cooling was added at 1 minute and 21 minutes.
2. Stopped test at 50 minutes due to fatigue, especially feet.
3. Feet began hurting at 40 minutes.
4. This test was a repeat.

Subject B
Condition: 85 F / 75% RH
Ensemble: AAWPS2

B 88

Subject B
Condition: 85 F / 75% RH
Ensemble: AAWPS2

Subject B
Condition: 85 F / 75% RH
Ensemble: AAWPS2

Subject B
Condition: 85 F / 75% RH
Ensemble: AAWPS2

1691

Subject B
Condition: 85 F / 75% RH
Ensemble: AAWPS2

26.9

Clothing Comfort Sensation Scale

Subject C

Condition 1

Ensemble AAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	<u>X</u>	:	___	:	___	:	___	rough
flexible	___	:	<u>X</u>	:	___	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	<u>X</u>	:	___	:	___	:	___	scratchy
lightweight	___	:	<u>X</u>	:	___	:	___	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	<u>X</u>	:	___	:	___	:	___	clingy
dry	___	:	<u>X</u>	:	___	:	___	:	___	clammy

Errata:

1. Cooling added at 1 minute and 30 minutes.
2. Heart rate became irregular at 64 minutes.
3. Subject noted sore feet at 75 minutes.
4. Test ended at 90 minutes due to fatigue.

Subject C
Condition: 85 F / 75% RH
Ensemble: AAWPS

Subject C
Condition: 85 F / 75% RH
Ensemble: AAWPS

Subject C
Condition: 85 F / 75% RH
Ensemble: AAWPS

Subject C
Condition: 85 F / 75% RH
Ensemble: AAWPS

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Subject C
Condition: 85 F / 75% RH
Ensemble: AAWPS

86 98

Clothing Comfort Sensation Scale

Subject D

Condition 1

Ensemble AAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	X	:	___	:	___	uncomfortable
soft	___	:	X	:	___	:	___	:	___	not soft
not rough	X	:	___	:	___	:	___	:	___	rough
flexible	X	:	___	:	___	:	___	:	___	stiff
not binding	___	:	X	:	___	:	___	:	___	binding
not scratchy	X	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	___	:	X	heavy
quiet	___	:	___	:	X	:	___	:	___	noisy
not clingy	___	:	___	:	___	:	X	:	___	clingy
dry	___	:	___	:	___	:	X	:	___	clammy

Errata:

1. Stopped test for a rest at 20 minutes (upper body warm, but legs cool).
2. Subject rested from minute 21 until resumed test at minute 26 due to heart rate at 80% of maximum.
3. Subject rested from minute 28 until resumed test at minute 30.
4. Stopped test after 45 minutes due to blisters on feet and irregular heart rate.

Subject D
Condition: 85 F / 75% RH
Ensemble: AAWPS

B 100

Subject D
Condition: 85 F / 75% RH
Ensemble: AAWPS

B 101

Subject D
Condition: 85 F / 75% RH
Ensemble: AAWPS

Subject D
Condition: 85 F / 75% RH
Ensemble: AAWPS

Subject D
Condition: 85 F / 75% RH
Ensemble: AAWPS

Appendix I

Level B Suit, AWPS at 85°F

Clothing Comfort Sensation Scale

Subject A

Condition 1

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	<u>X</u>	:	___	:	___	:	___	not soft
not rough	___	:	___	:	___	:	<u>X</u>	:	___	rough
flexible	___	:	___	:	<u>X</u>	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	<u>X</u>	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	<u>X</u>	:	___	:	___	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. LCG suit leaked so changed suits before test began. Pant was very tight at knees.
2. Cooling added at 1 minute, 5 minutes, 10 minutes.
3. Subject noted the air mask seemed to have less air at 27 minutes.
4. Stopped test due to fatigue, especially feet at 35 minutes.

Subject A
Condition: 85 F / 75% RH
Ensemble: BAWPS

Subject A
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 107

Subject A
Condition: 85 F / 75% RH
Ensemble: BAWPS

Subject A
Condition: 85 F / 75% RH
Ensemble: BAWPS

Subject A
Condition: 85 F / 75% RH
Ensemble: BAWPS

110

Clothing Comfort Sensation Scale

Subject B

Condition 1

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	___	:	<u>X</u>	:	___	uncomfortable
soft	___	:	___	:	___	:	<u>X</u>	:	___	not soft
not rough	___	:	___	:	<u>X</u>	:	___	:	___	rough
flexible	___	:	___	:	___	:	<u>X</u>	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	___	:	<u>X</u>	heavy
quiet	___	:	___	:	___	:	___	:	<u>X</u>	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Cooling added at 14 minutes and 21 minutes.
2. Subject complained of headache at 25 minutes possibly due to shoulder strap.
3. Subject complained about weight of pack at 27 minutes.
4. Test stopped due to subject fatigue at 41 minutes.
5. Boots very uncomfortable.

Subject B
Condition: 85 F / 75% RH
Ensemble: BAWPS

Subject B
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 113

Subject B
Condition: 85 F / 75% RH
Ensemble: BAWPS

Subject B
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 115

Subject B
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 116

Clothing Comfort Sensation Scale

Subject C

Condition 1

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	<u>X</u>	:	___	:	___	:	___	uncomfortable
soft	___	:	<u>X</u>	:	___	:	___	:	___	not soft
not rough	___	:	<u>X</u>	:	___	:	___	:	___	rough
flexible	___	:	___	:	<u>X</u>	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	<u>X</u>	:	___	:	___	:	___	noisy
not clingy	___	:	<u>X</u>	:	___	:	___	:	___	clingy
dry	___	:	<u>X</u>	:	___	:	___	:	___	clammy

Errata:

1. Cooling added at 27 minutes and 45 minutes.
2. Stopped test due to irregular heart rate at 57 minutes.

Subject C
Condition: 85 F / 75% RH
Ensemble: BAWPS

Subject C
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 119

Subject C
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 120

Subject C
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 121

Subject C
Condition: 85 F / 75% RH
Ensemble: BAWPS

Clothing Comfort Sensation Scale

Subject D

Condition 1

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	<u>X</u>	:	___	:	___	:	___	uncomfortable
soft	<u>X</u>	:	___	:	___	:	___	:	___	not soft
not rough	<u>X</u>	:	___	:	___	:	___	:	___	rough
flexible	<u>X</u>	:	___	:	___	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	seratchy
lightweight	___	:	<u>X</u>	:	___	:	___	:	___	heavy
quiet	___	:	<u>X</u>	:	___	:	___	:	___	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Batteries went out on scale, so used manual scale.
2. Removed foot from suit.
3. Added cooling at minute 17.
4. Heart rate was irregular at 20 minutes, subject tired.
5. Stopped test when oxygen ran out.
6. Calf sensor was out for 1 minute.

Subject D
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 124

Subject D
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 125

Subject D
Condition: 85 F / 75% RH
Ensemble: BAWPS

Subject D
Condition: 85 F / 75% RH
Ensemble: BAWPS

Subject D
Condition: 85 F / 75% RH
Ensemble: BAWPS

B 128

Appendix J

Level B Suit, AWPS at 100°F

Clothing Comfort Sensation Scale

Subject A

Condition 2

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	<u>X</u>	:	___	:	___	:	___	not soft
not rough	___	:	<u>X</u>	:	___	:	___	:	___	rough
flexible	___	:	<u>X</u>	:	___	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	<u>X</u>	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	___	:	<u>X</u>	:	___	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Cooling was added at 1 minute, 11 minutes, 16 minutes, and 30 minutes.
2. Left calf sensor went out at 30 minutes.
3. Liz monitored test.

Subject A
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 130

Subject A
Condition: 100 F / 75% RH
Ensemble: BAWPS

Subject A
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 132

Subject A
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 133

Subject A
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 134

Clothing Comfort Sensation Scale

Subject B

Condition 2

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	___	:	___	:	<u>X</u>	uncomfortable
soft	___	:	___	:	___	:	<u>X</u>	:	___	not soft
not rough	___	:	___	:	___	:	<u>X</u>	:	___	rough
flexible	___	:	___	:	___	:	<u>X</u>	:	___	stiff
not binding	___	:	___	:	___	:	<u>X</u>	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	___	:	<u>X</u>	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	___	:	___	:	___	:	<u>X</u>	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Cooling added at 1 minute, 18 minutes, and 22 minutes.
2. Subject noted legs were not cool after 6 minutes.
3. Client stopped the test to check for kinks in tubing.
4. Test was restarted and continued for 20 more minutes.
5. Heart rate became irregular at 20 minutes.
6. Stopped test due to dizziness and fatigue at 26 minutes.

Subject B
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 136

Subject B
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 137

Subject B
Condition: 100 F / 75% RH
Ensemble: BAWPS

Subject B
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 139

Subject B
Condition: 100 F / 75% RH
Ensemble: BAWPS

Clothing Comfort Sensation Scale

Subject C

Condition 2

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	<u>X</u>	:	___	:	___	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	___	:	<u>X</u>	:	___	:	___	rough
flexible	___	:	___	:	<u>X</u>	:	___	:	___	stiff
not binding	___	:	___	:	<u>X</u>	:	___	:	___	binding
not scratchy	___	:	___	:	<u>X</u>	:	___	:	___	scratchy
lightweight	___	:	<u>X</u>	:	___	:	___	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	___	:	<u>X</u>	:	___	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Added cooling at 1 minute, 5 minutes, 11 minutes, and 25 minutes.
2. Heart rate became irregular at 30 minutes.
3. Test stopped at 31 minutes due to frozen vaporizer.

Subject C
Condition: 100 F / 75% RH
Ensemble: BAWPS

Subject C
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 143

Subject C
Condition: 100 F / 75% RH
Ensemble: BAWPS

B
144

Subject C
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 145

Subject C
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 146

Clothing Comfort Sensation Scale

Subject D

Condition 2

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	<u>X</u>	:	___	:	___	:	___	uncomfortable
soft	___	:	<u>X</u>	:	___	:	___	:	___	not soft
not rough	___	:	<u>X</u>	:	___	:	___	:	___	rough
flexible	___	:	<u>X</u>	:	___	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	<u>X</u>	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	___	:	<u>X</u>	:	___	:	___	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Cooling added at minute 11, minute 20, minute 21, and minute 28.
2. Heart rate became irregular at 22 minutes.
3. Test stopped at minute 42 due to subject fatigue.

Subject D
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 148

Subject D
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 149

Subject D
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 150

Subject D
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 151

Subject D
Condition: 100 F / 75% RH
Ensemble: BAWPS

B 152

Appendix K

Level B Suit, AWPS at 45°F

Clothing Comfort Sensation Scale

Subject A

Condition 3

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	___	:	___	:	<u>X</u>	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	___	:	<u>X</u>	:	___	:	___	rough
flexible	___	:	<u>X</u>	:	___	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	___	:	<u>X</u>	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	___	:	<u>X</u>	:	___	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Subject took 2 small sips of water prior to test.
2. Cooling was added at 35 minutes.
3. Heart rate became irregular at 63 minutes.
4. Test ended due to fatigue, especially feet, at 75 minutes.

Subject A
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 154

Subject A
Condition: 45 F / 75% RH
Ensemble: BAWPS

Subject A
Condition: 45 F / 75% RH
Ensemble: BAWPS

Subject A
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 157

Subject B
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 158

Clothing Comfort Sensation Scale

Subject B

Condition 3

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	___	:	___	:	<u>X</u>	:	___	uncomfortable
soft	___	:	___	:	___	:	<u>X</u>	:	___	not soft
not rough	___	:	___	:	___	:	<u>X</u>	:	___	rough
flexible	___	:	___	:	___	:	<u>X</u>	:	___	stiff
not binding	___	:	___	:	___	:	<u>X</u>	:	___	binding
not scratchy	<u>X</u>	:	___	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	<u>X</u>	:	___	heavy
quiet	___	:	___	:	___	:	<u>X</u>	:	___	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	___	:	<u>X</u>	clammy

Errata:

1. Computer did not work so 2 minutes elapsed before it recorded.
2. Subject adjusted pack throughout test, indicating it was heavy.
3. Test stopped at 45 minutes to prevent frozen pack.

Subject B
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 160

Subject B
Condition: 45 F / 75% RH
Ensemble: BAWPS

B
161

Subject B
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 162

Subject B
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 163

Subject B
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 164

Clothing Comfort Sensation Scale

Subject C

Condition 3

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	<u>X</u>	:	___	:	___	:	___	uncomfortable
soft	___	:	<u>X</u>	:	___	:	___	:	___	not soft
not rough	___	:	<u>X</u>	:	___	:	___	:	___	rough
flexible	___	:	<u>X</u>	:	___	:	___	:	___	stiff
not binding	___	:	<u>X</u>	:	___	:	___	:	___	binding
not scratchy	___	:	<u>X</u>	:	___	:	___	:	___	scratchy
lightweight	___	:	<u>X</u>	:	___	:	___	:	___	heavy
quiet	___	:	<u>X</u>	:	___	:	___	:	___	noisy
not clingy	___	:	<u>X</u>	:	___	:	___	:	___	clingy
dry	___	:	<u>X</u>	:	___	:	___	:	___	clammy

Errata:

1. Had problems with sensors #5 and #9, possibly due to the cold temperature.
2. Stopped test due to irregular heart rate.

Subject C
Condition: 45 F / 75% RH
Ensemble: BAWPS

Subject C
Condition: 45 F / 75% RH
Ensemble: BAWPS

Subject C
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 168

Subject C
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 169

Subject C
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 170

Clothing Comfort Sensation Scale

Subject D

Condition 3

Ensemble BAWPS

Place an X in a blank between each pair of comfort descriptors that indicates how the coverall feels when you are wearing it.

comfortable	___	:	<u>X</u>	:	___	:	___	:	___	uncomfortable
soft	___	:	___	:	<u>X</u>	:	___	:	___	not soft
not rough	___	:	<u>X</u>	:	___	:	___	:	___	rough
flexible	___	:	___	:	<u>X</u>	:	___	:	___	stiff
not binding	<u>X</u>	:	___	:	___	:	___	:	___	binding
not scratchy	___	:	<u>X</u>	:	___	:	___	:	___	scratchy
lightweight	___	:	___	:	___	:	___	:	<u>X</u>	heavy
quiet	___	:	<u>X</u>	:	___	:	___	:	___	noisy
not clingy	___	:	___	:	___	:	<u>X</u>	:	___	clingy
dry	___	:	___	:	___	:	<u>X</u>	:	___	clammy

Errata:

1. Vote at 60 minutes should be cold, not cool.

Subject D
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 172

Subject D
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 173

Subject D
Condition: 45 F / 75% RH
Ensemble: BAWPS

Subject D
Condition: 45 F / 75% RH
Ensemble: BAWPS

B 175