

# Terrestrial EVA Suit = FireFighter's Protective Clothing

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## ABSTRACT

Firefighters want to go to work, do their job well, and go home alive and uninjured. For their most important job, saving lives, firefighters want protective equipment that will allow more extended and effective time at fire scenes in order to perform victim search and rescue. A team, including engineers at NASA JSC and firefighters from Houston, has developed a list of problem areas for which NASA technology and know-how can recommend improvements for firefighter suits and gear. Prototypes for solutions have been developed and are being evaluated. This effort will spin back to NASA as improvements for lunar and planetary suits.

## INTRODUCTION

In 1997, two Houston firefighters came to National Aeronautics & Space Administration (NASA) Johnson Space Center (JSC) with a very damaged helmet in hand, asking for help to prevent burns that they and their buddies were getting through their protective clothing. They wanted to try some Space Shuttle tiles for insulation, because they had heard that these tiles could withstand 1100 degree Celsius (2000 degree Fahrenheit) temperatures. After the initial meetings, a team of engineers at NASA JSC and Houston firefighters developed a list of problem areas for which NASA technology and know-how could offer improvements for firefighter suits and gear. As we studied the range of problems, we determined that the firefighter helmet was not going to be the first solution area we addressed. The team met weekly for further brainstorming, sketches, and concepts. Prototypes are now being developed to address several of these problem areas. The goals for this year are to improve the basic turnout gear (pants and coat) and to address the heat stress caused by a

firefighter's metabolic heat. A firefighter will risk dangerously hot places in order to find and save a victim, then usually stay back from the extreme heat while extinguishing the fire.

More firefighters die each year from heat stress and related heart attacks than from smoke and flame. Current firefighter suits allow firefighters to work about 20 minutes before they are overcome by their own metabolic heat inside the suit. The current suits used by firefighters provide comfort for external ambient temperatures up to about 150 degrees Celsius (300 degrees Fahrenheit), but it is the firefighter's own metabolic heat that can be the killer. Current suit insulation is so good that the outside temperature could be freezing and the firefighter would still get too hot. Work rates over 250 Watts create excessive metabolic heat. The body's natural cooling mechanism, perspiration, does not work inside the suit because there is little, if any, evaporation possible inside the microclimate of the turnout gear. As a result, body core temperatures rapidly rise to dangerous levels. As body core temperature rises, mental decision making is hampered and then muscle responses are diminished. The human body has a very narrow tolerance for temperature deviations from 37 degrees Celsius (98.6 degrees Fahrenheit). At 39 degrees Celsius (102.2 degrees Fahrenheit), functions have already become inefficient. By the time body core temperature reaches 42 degrees Celsius (107.6 degrees Fahrenheit) physiological functions begin to stop and cells die.

Firefighters don't like getting burns. In fact, they would like to be just as safe and comfortable in their work place as we are in an office setting. Present suit fabrics, such as Kevlar / Poly-benzimidazole (PBI) blends, begin to disintegrate at about 260 degrees Celsius (500 degrees

Fahrenheit). At this temperature, the firefighter has about three minutes before suffering the effects of excessive ambient heat. A typical house fire may reach flashover temperatures close to 1100 degrees Celsius (2000 degrees Fahrenheit) in as little as five minutes. At this temperature, the suit will be destroyed in about 20 seconds. When skin temperatures reach 70 degrees Celsius (160 degrees Fahrenheit), permanent or lethal damage will occur in less than one second.

## **WATER COOLED GARMENTS**

It was suggested that we try to air condition the inside of a firefighter suit. However, basic physics heat transfer equations suggest that it would be very difficult to provide sufficient airflow inside a firefighter suit to significantly reduce the body core temperature.

Instead, it was decided to pursue an approach that actively circulates liquid cooling within the firefighter garment. Oceanneering Space Systems (OSS) had been working on a cooling garment for hazardous materials cleanup crews to wear under a protective outer garment. NASA has teamed with OSS to select fabrics for the structure of the cooling garment, plastic tubing and patches, and connectors. NASA is currently testing the firefighter version of the liquid cooling garment for its impact on reach limits (i.e., hand and foot touch distances, including joint range-of-motion), work envelope (i.e., volume within which dexterity and strength can be efficiently used), and heat lift (i.e., cooling capacity) in much the same way that astronaut space suits are tested for their usability.

The OSS cooling garment is based on NASA's original research in liquid cooling garments as a solution to metabolic heat buildup. However, the application of the technology has had to change to meet the cost and durability requirements of hazardous materials (hazmat) work and fire fighting. The solution is a highly efficient cooling garment, using a combination of bladders and tubing, rather than just tubing. This combination provides a more substantial surface area for the cooling liquid to remove heat from the skin surface. The increased surface area also allows the garment to operate effectively at a warmer water temperature, decreasing power consumption on the chilling units. It also increases user comfort by decreasing the likelihood of vasoconstriction. If the skin were to get too cold, then the blood capillaries would constrict and the body core would retain even more heat.

Chilled liquid can be supplied to the cooling garment by several methods, provided an appropriate temperature and flow rate is produced. Currently, the cooling garment has been paired with a liquid air breathing apparatus that provides breathing air and cooling liquid. A simpler, but effective, alternative obtains the cool water from an ice based chiller system.

The current firefighter cooling garment prototype will be undergoing further tests for fit and comfort, usability,

cooling efficiency, and adherence to the National Fire Protection Association (NFPA) standards. Though continued critical research is required to develop this prototype liquid cooling garment, it is already known that, with a liquid cooling garment, a firefighter can walk around in the broiling Houston sun, while fully enclosed in the firefighter turnout gear, and maintain a safe core temperature for three hours.

One concern regarding the liquid cooling garment is that it adds weight. However, as the firefighter avoids heat stress, exertion is reduced due to decreased cardiac stress. Another concern is that wearing protective clothing that includes a liquid cooling garment accessory is more costly for each firefighter so equipped, but each of those firefighters will have more time and energy to save a life. Another protective layer will further impair mobility and further remove the firefighter from situation awareness, but other technologies and accessories are being developed and will be implemented to overcome these obstacles.

## **CRYOGENIC LIQUID AIR BREATHING PACK**

Several alternatives for a heat sink (i.e., methods for removing heat from the microclimate within the firefighter's suit) were considered for the Liquid Cooled Garment (LCG). Among the alternatives are: phase change materials, electrical energy, and chemical energy. A balance must be achieved with factors such as weight, cost, ease of use, and complexity of the worn device, as well as of the infrastructure to maintain and replenish the system. We chose a phase change materials system for further development.

One of the technologically more simple solutions involves phase change materials, such as a block of ice or a frozen gel pack that absorbs heat while melting. It would take about 3 kilograms (7 pounds) of ice to provide sufficient cooling for an hour. In an informal demonstration, one of our team members wore a tube-laced shirt under his turnout gear during a fire training exercise. He attached the tube-laced shirt to a small thermos bottle (about half a liter, or one pint) and a miniature circulating pump. We used ice from the cold drink ice chest and switched out thermoses about every ten minutes. It was a typically hot and humid day in Houston. Those of us in shirt sleeves and straw hats were perspiring and uncomfortably hot. The other training firefighters met their limits of endurance, peeling off their coats and seeking shade and water at every opportunity. The cooled firefighter remained buttoned up in his turnout gear for three hours – in the training fire house, in the sunshine, hauling hose – with no visible sweat, and a contented smile on his face.

We are now exploring an experimental technology that uses cryogenic liquid air as a heat sink. Cryogenic liquid air packs have been explored as a low pressure, low profile breathing air source. A key benefit of the liquid air is the ability to contain higher quantities of breathing air without increasing pressure. The thought behind this

innovation is to couple cryogenic air with a liquid cooling garment in a package that will meet safety standards and be robust enough for the fire service. The cooling system works by using the firefighter's body heat to warm the water in the LCG. The water then passes through a heat exchanger to boil off the liquid air. The warmed air is then available as breathing air for the firefighter. The increased air demand and increased cooling requirements are each correlated with increased work levels by the firefighter. The firefighter is not carrying any extra weight, because a breathing air pack is required anyway. An added relief is that, as the air is breathed from the tank, weight is reduced.

At this time, a first generation cryogenic breathing air pack with heat exchangers and controls linking it to a liquid cooling garment has been built, has been demonstrated to work, and is being prepared for further evaluations. Improvements for the next generation unit are already being conceptualized. Before a liquid air pack can be rated for human use in a fire setting, rigorous testing to meet NASA and fire industry safety requirements will be required.

## **FIREFIGHTER SUIT MATERIALS AND FABRICS**

Current requirements state that firefighter protective garments for structural fires must consist of an outer shell, a thermal barrier, and a moisture barrier. Taken together, either as a single layer or as a layup of multiple layers, this composite of fabrics is tested and certified to provide a minimum level of thermal protection while withstanding the physical abuse at a fire scene. The outer shell serves as the first layer of defense against flame and particulates. The moisture barrier function is intended to help keep a firefighter from getting saturated by water and fluid-borne toxins from the outside. The thermal liner provides the bulk of the insulation. The liner includes a face cloth that was designed to wick away perspiration moisture from the skin; however, firefighter experience suggests that the quantity of perspiration is so great that it overwhelms the wicking capacity of the present face cloth.

Protection is reduced when the garment is damaged, worn-out, contaminated, or saturated. Even with a new garment, a firefighter can sustain burns at points where the insulation is compressed, such as at the knuckles or near the air pack straps, or at places where two units of the garment fail to interface effectively, such as at the neck or wrist. Residential fires are typically much hotter than the current fabrics can withstand, and under these conditions, the firefighter also suffers burns through the garment.

In the design of a protective garment, a trade-off among more protection, more weight, and increased cost must be made. Thicker garments would offer a firefighter more time at higher ambient temperatures, but the added bulk would reduce mobility, and the weight of thicker insulation would reduce the work the firefighter could do before becoming exhausted. As long as a firefighter

stays away from direct flame and crawls, down on the floor, current turnout gear for structural fires usually can do an adequate job of protecting a firefighter from the heat transferred by conduction and convection. If the firefighter were to stand up, the temperatures would be too hot for the garment to withstand.

In addition, the current structural firefighter suits offer little protection from radiant heat. In a structural fire, the current aluminized or coated fabrics get scraped and soiled so badly that any radiant heat protection can be lost immediately. Putting a radiation shield inside the outer shell is not practical because this would subject the outer shell fabric to a multiple impact of the infrared radiation. The actual amount of increased infrared radiation would depend on the transmissivity and reflectivity of each of the materials involved.

Another concern is that, with current suit designs, super insulating a garment from outside heat must be balanced with the need to eliminate the metabolic heat produced by the firefighter's work that is then contained within the micro-climate between the firefighter's skin and the insulation of the suit.

NASA has participated in developing various textile fibers and polymeric structures for use in space suits and other crewmember applications. The purpose of the current materials development effort of this project is to apply the space related softgoods materials technology towards improving materials selection and design for application to commercially available firefighter turnout gear. Fibers and fabrics can be engineered for strength, thermal properties, chemical resistance, and wear resistance. The goal is to find advanced materials and processes to produce turnout gear with superior comfort, reduced weight, improved mechanical performance (tear, abrasion, tensile strength, etc.), higher thermal damage tolerance, advanced thermal insulation, and radiation heat flux protection.

## **OUTER SHELL ADVANCED FABRICS**

The outer shell provides protection from abrasion and other mechanical action, as well as providing the first line of defense against high temperatures and heat flux. This layer has very high requirements on strength, chemical, thermal, and wear properties. Since this layer is exposed to the elements, it should also be stable under ultraviolet radiation from the sun.

Poly-phenylene benzobisoxazole (PBO) fibers were developed and tested, with NASA participation, for applications, including shielding from high velocity orbital debris. PBO properties include superior flame resistance, tear and puncture resistance, lighter weight, and extremely high thermal damage tolerance. A twill weave blend of PBO and Kevlar has been woven for evaluation and demonstration as a candidate for firefighter garment outer shell material.

Poly-benzimidazole (PBI) and Kevlar blends are

currently the fabric of choice for outer shell material for commercially produced firefighter turnout gear. PBI is characterized as having no melting point, not igniting, retaining fiber integrity and suppleness upon flame exposure, having a high char yield, providing mildew and age resistance, and being abrasion resistant.

On preliminary tests, a PBO/Kevlar blend had superior performance on all measures when compared with a PBI/Kevlar blend. For example, in tests conducted at NASA JSC, on a burst strength test after exposure to direct hot flame for 17.5 seconds, a PBO/Kevlar blend required 143 kilograms (316 pounds) force before fabric rupture, while a PBI/Kevlar blend burst at 22 kilograms (48 pounds). On the vertical flammability test resulting in a limiting oxygen index (LOI), the PBO/Kevlar blend required 70% oxygen before sustaining a flame, while the PBI/Kevlar blend ignited at 38% oxygen.

There is still the problem of reducing the heat transfer from thermal radiation. Sometimes this is referred to as infrared radiation. One candidate solution would be a fiber coating that could withstand abrasion and that would shed contamination. Another candidate, a metal fiber, is being studied for its applicability to firefighter turnout gear. Chromel R is a high performance nickel alloy metallic fiber developed by NASA for Gemini and Apollo suits. Chromel R has superior heat flux reflection, high flame resistance, and good abrasion resistance. A composite, using Chromel R as the outer shell, was compared with a similar composite using PBI/Kevlar as the outer shell on an infrared emittance test. This test was designed to determine the radiation heat that is reflected from a fabric. The Chromel R composite reflected 57% of the infrared, while the PBI/Kevlar reflected 12.6%. Chromel R is no longer being produced. Because many firefighter burns are the result of infrared heat, protection from radiation heat is an area that NASA JSC will continue to pursue.

## MOISTURE BARRIER

Current moisture barrier fabrics are adequate and do a good job of keeping external moisture away from direct contact with the thermal liner, so NASA is not pursuing improvements of this layer. However, if the Liquid Cooling Garment is implemented inside firefighter garments, then sweating will be reduced, and alternate face cloths, comfort layers, and moisture barriers may be introduced. Under these conditions, there may be continued emphasis on keeping the insulation fibers dry from the water sprayed from the hoses at the fire scene, and more emphasis on comfort on the fabric layer next to the skin.

## INSULATION FIBERS AND INNOVATIVE LAYUPS

The thermal liner provides the firefighter protection from conducted and convected heat. Ideally, this layer will continue to provide superior protection when wet or compressed, but this is where improvements still need to be made. The insulation effect is a result of the loft or of

the trapped air pockets in the insulation layer. Since the fibers are in close proximity to the heat outside the suit, it is important that they must be stable under high temperature conditions, while not conducting this heat along the length of the fiber. Fiber tensile strength does not play an important role, but the insulation still has to be robust due to the flexion and compression of the garment. One of the major contributors to the degradation of a firefighter turnout is the mechanical action that occurs during laundering. Investigation is underway to develop a thermally stable fiber with low weight, and a compromise of compression that will not impede mobility at the firefighter's joints, while still maintaining the loft required for thermal insulation.

Evaluations are being made to compare the thermal insulation batting used in Houston firefighter turnout gear, as a baseline for comparison, with alternate batting materials including: a carbon fiber blended with Nomex, polyimide (P84) microfibers, a Nomex mesh thermal enhancement, and a composite flexible blanket insulation developed by NASA Ames. So far, the results on thermal protective performance (TPP) tests on these alternates are similar to those obtained by the batting being used in the Houston firefighter turnout gear. A TPP of about 44 was obtained on the alternate samples and on the baseline sample, each of comparable thickness. The TPP number, if divided by two, gives a rough approximation of how many seconds the fabric layup would provide protection before the firefighter would sustain a second degree burn in a very hot fire condition called flashover. A high TPP protects the firefighter from higher temperatures and heat outside the suit for a longer time, but subjects the firefighter to increased risk of heat stress from the metabolic heat load inside the suit.

## CONTAMINATION

The firefighters on our team expressed some concern about the contamination on their turnout gear. The first question they asked was "How dirty is my gear?" "How dangerous is this fire debris?" Later meetings raised the questions of how to adequately clean the gear, and how to determine how clean is clean enough. Even house fires can contain dangerous toxins and carcinogens from solvents, plastics, fabrics, wiring, and so on.

We obtained used coats, pants, and gloves and cut samples from these articles of clothing, as well as from new samples of the same fabric. Residues were removed from the samples using thermal extraction at 270 degrees Celsius for 15 minutes, and cryogenically trapped and analyzed by gas chromatography / mass spectrometry (GC/MS). Medium (1% to 5%), high (5% to 10%), or very high (10% and higher) relative areas are considered to be at dangerous levels, especially if the exposure is continual over a period of years.

In the new fabric samples, we found medium concentrations of 1-octadecene; 1,4-Dioxane (carcinogen); and n,n-dimethyl acetamide (moderately

toxic by skin contact); and a high concentration of 2,4-disocyanato-1-methyl benzene (carcinogen). In the used fabric samples, we found medium levels of 1-octadecene; 1-chloro octadecene; 1,4-Dioxane (carcinogen); acetic acid (toxic and severe skin irritant); propanal (moderately toxic by skin contact); 4-toluene sulfonamide (poison by ingestion, when heated emits very toxic fumes); 2-(2-methoxyethoxy ethanol (moderately toxic by skin contact); 1,2-benzene dicarboxylic acid (moderately toxic by ingestion); and a very high level of n,n-dimethyl acetamide (moderately toxic by skin contact).

Clearly, the debris on the used suits indicated they had not been washed after their last use, but even the new sample of the same fabric was contaminated. Wet turnout gear is not supposed to be worn to a fire because it is known to provide little thermal protection when wet. It takes from 3 hours to over a day to dry a turnout gear. It is typical for a firefighter in Houston to make five or more runs each shift. Several shifts in a rotation can occur before having a day off and the opportunity to wash or hose down the turnout gear. Firefighters are reluctant to take their turnout gear home to wash, and few fire stations have washing machines. So, it is usually months between washes. Many firefighters just hose down their turnout gear when they can. The residual contaminants present a safety concern to anyone handling the garments on a regular basis.

We plan to do a series of controlled studies. We plan to subject turnout gear fabric samples with known contaminants and quantities. Then we will measure the residual contaminants after brushing the fabric, after rinsing the fabric with water, and after washing the fabric with detergents.

## DETERIORATION

Chemical action from residual contamination may cause fabric deterioration, but there are other, more obvious, sources of fabric deterioration. Ultraviolet radiation from sunlight and fluorescent lighting is known to break down the fibers used in turnout gear. A history of abrasion, wear, high heat, and thermal cycles also contributes to the degradation of thermal and strength properties of turnout suit materials.

We obtained some discarded suits from the Houston Fire Department. We took samples of outer shell fabric from these old suits and compared them with identical fabric from new suits. We performed two mechanical property tests. On the tongue tear strength test, a new suit tore at 35 pounds, while an old suit tore at 7.7 pounds. On the tensile strength test, a new suit failed at 300 pounds per square inch, while an old suit failed at 85 pounds per square inch. In each test of mechanical strength, the old suit fabric retained only about one-fourth the strength of the new suit fabric. On thermal conductivity tests, the old suit had a five percent reduction in thermal resistance when compared with the new suit.

Currently, there are no written standards or nondestructive tests for determining the level of protection still offered by a used firefighter turnout gear. After a suit shows visible tearing that requires more than just a small patch, it is replaced. That tear means the firefighter was already subjected to a reduction in protection. In addition, the less visible effects of high heat, thermal cycling, and ultraviolet radiation exposure are not measured on suits as they are being used by the firefighters. As a result, further compromise of firefighter safety is likely.

## CONCLUSION

We believe that the next step towards improving firefighter protective clothing must be the reduction of metabolic heat and the resulting rise in body core temperature. If the body core temperature can be kept within safe levels, then more insulation can be provided to protect the firefighter from the ambient fire temperatures and heat. With protection from both internal and external heat sources, the firefighter will be able to extend the time available to perform the tasks of saving lives and property.

At NASA JSC, the goal is to apply space technology products and processes to develop an integrated, modular firefighter suit. The elements discussed here are but the first steps in a multi-block approach to address the firefighter protection and productivity issues as a system. Members of the NASA JSC FireFighter Suit and Gear Team are addressing alternatives, including: the design of a helmet that will incorporate built-in digital quality communications with noise canceling headsets; clothing elements to reduce burns from compressed insulation and injuries from structural collapse; built-in sensors and imaging devices to help the firefighter and scene commander evaluate the fire environment, as well as continuously monitor the health status of each individual firefighter. We have developed a digital communications system model block diagram architecture that will allow each firefighter voice, video, and data links with any other emergency personnel. Functional requirements for the advanced helmet are being reviewed. Infrared imaging devices have been ordered for evaluation, not only for structural fires on the ground, but also for availability on the Space Shuttle and the Space Station. The science and technology exists; it is past time to bring firefighter protective gear into the twentieth century.

Current space suits are designed for optimal use in micro-gravity conditions in the relatively clean environment of orbital space. However, a planetary or lunar suit may be more like firefighter protective clothing. The planetary or lunar suit will be faced with very similar requirements as an advanced firefighter turnout gear in the areas of fiber strength, chemical resistance, thermal stability, and wear resistance.

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