PHASE II FINAL REPORT

Title:	Cooling Suit for First Responders
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Sponsor:	NIH
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Technical Monitor:	Dr. Maria Lioce
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1. List of Terms and Abbreviations

(in the context of TDA's hazmat suit cooling system)

Anhydrous – A chemical compound that is in a completely dehydrated state, desiccants are commonly used in their anhydrous form.

Coefficient of Performance (COP) – The amount of heat removed from the body (in watts) divided by the power required to operate the cooling system (also in watts). The greater the COP, the more efficient the cooling system.

Desiccant – A material (in our case a solid) that has a high affinity for water that is used to remove water vapor from air, thus decreasing its humidity.

Dew Point – The temperature at which water vapor in the air just begins to condense. The lower the dew point, the drier the air.

Dry Bulb Temperature – Air temperature measured with a bare thermometer

Evaporative Cooling – Heat removal from the body where the body's heat is used to evaporate water (in this case, sweat to cool the first responder, or water evaporated by contaminated air in the heat exchanger to cool the dry air).

Endothermic – A process that requires (absorbs) heat, such as the vaporization of water.

Exothermic – A process that releases (generates) heat, such as when a desiccant (e.g. anhydrous lithium chloride) absorbs water.

First Responder – Firefighter, law enforcement, emergency medical, or other personnel using a level A hazmat suit.

Heat Exchanger – The device for transferring heat through aluminum walls that isolate the contaminated (outside) air from the clean, dry air that circulates inside the suit that cools the first responder. A compact heat exchanger refers to a highly efficient heat exchanger that requires a minimum of space.

Heat of Vaporization – The amount of energy required to evaporate a given quantity of a liquid (in this case water); the heat of vaporization of water is ΔH_{vap} ~ 1000 Btu/lb.

MET – Metabolic Equivalent– an amount of heat generated due to exertion equal to 1 kcal/kg/hr.

NIOSH – National Institute for Occupational Safety and Health

NPPTL – National Personal Protection Technology Laboratory

Phase Change Cooling Vest – A vest with pockets that hold ice, wax or other material that removes heat by melting

SCBA – Self-Contained Breathing Apparatus

Wet Bulb Temperature – Temperature that air would have if adiabatically cooled (i.e. no heat added) to 100% relative humidity. The lower the wet bulb temperature compared to the dry bulb temperature, the drier the air.

2. Abstract

Title: Cooling Suit for First Responders
Principal Investigator: Dr. Girish Srinivas (gsrinivas@tda.com)

When responding to a chemical spill or other hazardous cleanup operation, first responders must frequently wear a level A hazardous materials (hazmat) suit to protect them from chemical exposure. The level A suit is completely sealed against external vapors and liquids, and because it is completely sealed, they internal environment quickly becomes very hot and humid because body heat and water vapor from sweating (and exhaling air) are trapped inside the suit. Given the fact that a first responder can be in the suit from 30-60 min, overheating is not just a source of discomfort, but is dangerous because of the risk of heat exhaustion and/or heat stroke. In addition, perspiration frequently condenses on the inside of the faceplate, obscuring vision.

TDA Research, Inc. (TDA) has developed a lightweight, portable system that both cools and dehumidifies air that is circulated through (inside) a level A hazmat suit to cool the first responder. As in the case without cooling, the first responder's breathing air is supplied by a SCBA. To cool the occupant, TDA's system bathes the user in dry, clean air supplied by our cooling device. The evaporation of sweat (water) into the dry air stream is the primary heat transfer mechanism that cools the first responder. Heat from the body evaporates water in the sweat, which removes approximately 1000 Btu per pound of water evaporated.

If the water vapor generated by sweat evaporation were not removed, then eventually, evaporative cooling would stop and the occupant inside the suit would overheat. Water vapor (from sweat evaporation) is prevented from accumulating in the suit because TDA's system uses a lightweight bed of solid desiccant. The hot, dry air exiting the desiccant bed (the remove of water by the desiccant gives off heat) is then re-cooled using a specially designed compact heat exchanger that rejects heat to the outside environment. This is done by evaporating *liquid* water (that is carried separately outside the suit) into the contaminated outside air. This cools the contaminated air side of the heat exchanger, which allows heat to flow from the hot dry, clean inside air (that circulates through the suit) to the cooler external side of the heat exchanger, lowing the temperature of the dry clean air. Cooled, dry, clean air now bathes the first responder inside the suit allowing them to be cooled by sweat evaporation. The desiccant beds are changed out and the external water bottle is refilled prior to each use of the cooling system.

TDA's hazmat cooling system is the first completely portable system that permits the user to remain in the suit for up to 60 min without overheating. TDA's cooling system has been demonstrated at the National Personal Protection Technology Laboratory (NPPTL) to remove approximately 850 Btu/hr (250 watts) of metabolic heat during tests with NPPTL's thermal sweating manikin. The resulting *core* body temperatures measured with the manikin were consistently 2-3°F lower compared to not using cooling or to cooling the manikin with a phase change cooling vest. TDA has applied for a patent for our cooling system technology and is currently working with a major hazmat suit manufacturer to commercialize it.

3. Section 1 – Overview of the Project

3.1. Significant (Key) Findings

TDA Research, Inc. (TDA) has developed a lightweight, portable system that both cools and dehumidifies air that is circulated through a level A hazmat suit to cool the occupant via sweat evaporation. (Figure 1) shows our system being tested on a sweating thermal manikin at NPPTL (the hazmat suit is clear). Breathing air is supplied to the first responder by the SCBA, which is worn inside the suit. To cool the user, TDA's system bathes the first responder in dry, clean air supplied by our cooling device. The evaporation of perspiration (sweat) is the primary heat transfer mechanism that cools the first responder in the suit. Heat is supplied by the body to evaporate the water in the sweat, which removes approximately 1000 Btu/lb of sweat evaporated. Figure 2 illustrates the concepts behind TDA's level A hazmat suit cooling system.

Figure 1. TDA's 2nd generation cooling device being tested at NIOSH.

Figure 2. Concept used in TDA's hazmat suit cooling technology.

In TDA's system, water vapor from sweat evaporation does not accumulate inside the suit because it is removed by a lightweight bed of anhydrous lithium chloride (LiCl) desiccant. Removing the water vapor with the LiCl bed heats the air because the heat of hydration is exothermic. Hot, dry air exiting the LiCl bed is then re-cooled using a specially designed, compact heat exchanger that rejects heat to the outside environment. TDA's cooling system is designed so that it is possible to reject heat even when the outside temperature is high (high dry bulb temperatures). This is done by evaporating *liquid* water inside of the contaminated air side of the heat exchanger and rejecting that vaporized water to the outside environment (Figure 2). Evaporative cooling of this externally carried water makes use of the same evaporative cooling mechanism that cools the wearer inside the suit when his/her sweat evaporates. Importantly, however, *the two systems are <u>completely isolated</u> from each other by the heat exchanger* so there is no risk of contaminated air entering the suit (Figure 2). The clean air is cooled by indirect heat transfer through the walls of the heat exchanger that are in thermal contact with the passages where evaporative cooling of externally carried water occurs on the contaminated air side (a small fan blows contaminated air through the heat exchanger). Thus, the heat exchanger transfers heat from the inside of the suit to the contaminated environment outside the suit, while *keeping the clean and contaminated air streams <u>completely separated</u>.* For example, if the outside air temperature is 86°F with 50% relative humidity, then the clean air is now dry (about 14% relative humidity – RH) and at a temperature of about 80°F. This cooled, clean, dry air is then returned to the suit where it bathes the first responder, evaporates sweat, and causes cooling. The cooled, dry air is distributed to the hands, head, and feet inside the hazmat suit using lightweight, crush resistant tubing.

Figure 3 shows the results of testing TDA’s 2nd generation cooling device using the NPPTL thermal sweating manikin (Figure 1) where the outside air was simulated for two conditions: a heat index of 125°F (very hot but dry) and a heat index of 88°F (hot and humid). In both cases, *TDA’s cooling system significantly outperformed all other cooling methods* (except for not wearing the suit, which was run as a benchmark) and importantly was able to reduce the extremely important *core body temperature* by 2-3°C. None of the other methods including a phase change vest were able to cool the body’s core temperature. We are currently designing a 3rd generation cooling system based on the results from our 2nd generation system testing.

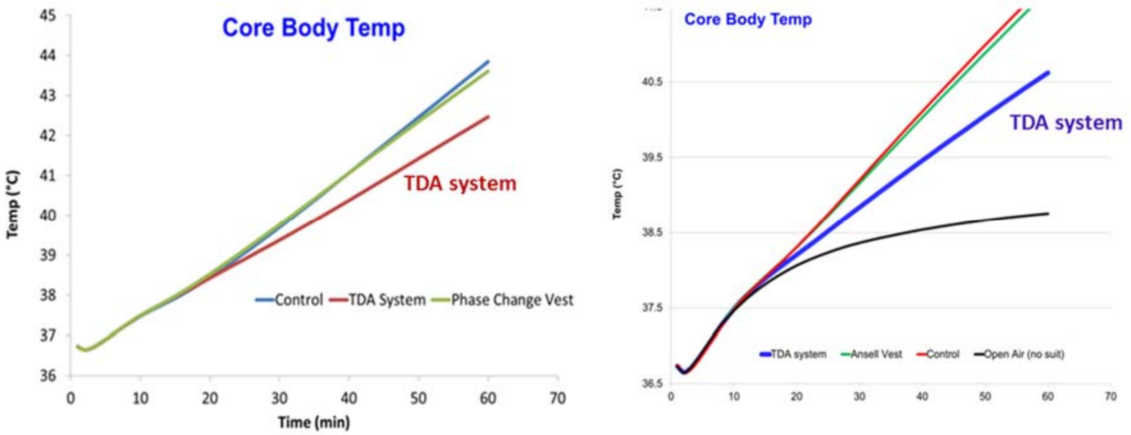


Figure 3. Test results for TDA’s 2nd generation level A hazmat cooling system; testing done with the sweating thermal manikin at NIOSH (Figure 1). Test conditions: 50°C (122°F) and 15% RH (left) and 30°C (86°F) and 50% RH (right).

3.2. Translation of Findings

During the Phase II project TDA successfully developed a cooling system that can be used by first responders to enable them to wear level A hazmat suits for more than 20 minutes without overheating. The system is designed to keep a user cool for about 60 minutes. This amount of time allows for donning and doffing along with time spent inside the suit. *The key innovation for our cooling system is using dry air to cool the first responder via their own sweat evaporation that is made possible by our lightweight, integrated desiccant bed/high efficiency compact heat exchanger. We are currently applying for a patent for the technology*.

3.3. Outcomes/Impacts

Currently, overheating is an extremely important concern when using level A hazmat suits. Not only is overheating uncomfortable, but also potentially very dangerous due to the increased likelihood of the first responder experiencing heat related illness. TDA’s hazmat suit cooling system represents the first truly portable system that can *keep the users core body temperature from rising to dangerous levels*, thus providing an unprecedented level of protection against heat exhaustion and heat stroke for users of Level A hazmat suits. TDA Research Inc. (TDA) is now teamed with Ansell Protective Solutions AB to commercialize the technology, and we are currently discussing marketing options.

4. Section 2 – Scientific Report

4.4. Executive Summary

When responding to a chemical spill or other hazardous cleanup operation, first responders must frequently wear a level A hazardous materials (hazmat) suit (Figure 4). These suits protect the first responder from chemical exposure by completely sealing the wearer against external vapors and liquids. Because the suits are sealed a fresh air supply is required, and this is typically provided by a self-contained breathing apparatus (SCBA). In total, the SCBA/impermeable suit provides contaminant free air and a barrier to the chemical hazard. Unfortunately, because the suits are sealed, they quickly become very hot and humid because the water vapor from sweating (and breathing) is trapped inside the suit. Given the fact that a first responder can be in the suit from 30-60 min, overheating is not just a source of discomfort, but is dangerous because of the risk of heat exhaustion/stroke. In addition, perspiration frequently condenses on the inside of the faceplate obscuring vision, which is an additional hazard.

Figure 4. Trellchem level A hazmat suit manufactured by TDA's partner Ansell Protective Solutions, AB.

Level A hazmat suits are mainly used in two types of situations: 1) when the substances dealt with are known to be extremely hazardous and 2) when the nature of the substances are unknown. The use and requirements for level A suits were studied at length by (Branson et al. 2005) and cooling was identified to be vitally important to prevent heat exhaustion of users of level A hazmat suits (Branson et al. 2005).

TDA Research, Inc. (TDA) has developed a lightweight, portable system that both cools and dehumidifies air that is circulated through a level A hazmat suit (Figure 1). Breathing air is supplied to the first responder inside the suit by the SCBA. To cool the wearer, TDA's system bathes the wearer in dry, clean air supplied by the cooling device. The evaporation of perspiration is the primary mechanism that removes heat from, and cools, the first responder in the suit. Heat removed from the body evaporates the water in the sweat, which removes approximately 1000 Btu/lb of water evaporated (the heat of vaporization of water). Figure 2 illustrates the concepts behind TDA's level A hazmat suit cooling system.

In TDA's system water vapor (from sweat evaporation) is prevented from accumulating using a lightweight bed of lithium chloride (LiCl), which is a desiccant. The dry air exiting the LiCl bed is then re-cooled using a specially designed heat exchanger that rejects heat to the outside environment. When the clean but humid air (water vapor from the occupant sweating) passes through the LiCl desiccant bed it is heated due to the exothermic heat of hydration of the LiCl. TDA's cooling system is designed so that it is possible to reject this heat even when the outside temperature is high (high dry bulb temperatures). This can be done by evaporating *liquid* water in the contaminated air side of the heat exchanger and rejecting that vaporized water outside environment (Figure 2). Evaporative cooling of this externally carried water makes use of the same evaporative cooling mechanism that cools the wearer inside the suit when his/her sweat evaporates; however, *the two systems are completely isolated from each other by the heat* *exchanger* (Figure 2). The clean air is cooled by indirect heat transfer through the walls of the heat exchanger that are in thermal contact with the passages where evaporative cooling occurs the contaminated air side. Thus, the heat exchanger transfers heat from the inside of the suit to the contaminated environment outside the suit, while *keeping the clean and contaminated air streams completely separated.* For 86°F, 50% RH outside air, the clean air can be cooled to 80°F and 14% RH. This clean, dry air is returned to the first responder, where it evaporates sweat to cool the occupant. The cool, dry air is distributed to the hands, head, and feet within the hazmat suit using a lightweight tubing. Dry 80°F air is capable of fully cooling a person even when they are working hard.

For our initial design, we assumed that the contaminated air was at 120°F and had a relative humidity of RH = 20% (dew point ~68°F). Adding water to the contaminated air reduces its temperature (via evaporation), which provides the heat sink for the system. Because the temperature difference between the air inside the suit and the cooled, humidified outside air that is used for heat removal is not very large, we need a high efficiency heat exchanger to ensure that the size and weight of the heat exchanger is reasonable.

TDA's heat exchanger is made from aluminum to minimize weight. Adding in the lithium chloride (LiCl) desiccant, lightweight internal air ducts, and a plastic housing parts, the total weight is about 5 lbs (not counting the water, which adds another 2 lbs). This small amount of additional weight not only permits more comfortable and longer duration use of level A hazmat suits under "ordinary working conditions," but also allows work to be carried out in situations where high temperatures might otherwise make work in a level A hazmat suit impossible. Finally, because the housing is made from plastics, it is resistant to decontamination chemicals such as soaps, bleach, and assorted solvents.

The overall objective of the Phase II project was to develop a cooling system that could be used by first responders to enable them to wear level A hazmat suits for more than 20 minutes without overheating. ***We have met (and exceeded) this objective in this NIH Phase II project***. Our system is designed to keep a user cool for about 60 minutes. This amount of time allows for donning and doffing along with time spent inside the suit. Although, our system could be used for longer periods of time by carrying more/replenishing the water used for evaporative cooling on the contaminated air side of the heat exchanger, the amount of time the user can remain inside the suit is also limited to 60 min by the capacity of the SCBA. *The key innovation for our cooling system is using dry air to cool the first responder via their own sweat evaporation that is made possible by our lightweight, integrated desiccant bed/high efficiency compact heat exchanger. We are currently applying for a patent for the technology*.

In Phase II we teamed with Ansell Protective Solutions AB, makers of the Trellchem EVO (Figure 4) and Flash level A hazmat suits to commercialize the cooling system technology. Ansell Protective Solutions AB (formerly Trelleborg Protective Products) is one of the world's leading producers of protective clothing and related products, including chemical protective suits and dry diving suits, along with inflatable shelters, dock seals and a range of custom-made products for various industries.

Trellchem has customers worldwide including: FDNY (Trellchem VPS Flash); Tokyo Metropolitan Department, Japan (Trellchem HPS, Trellchem EVO);Hamburg Fire Brigade, Germany (Trellchem EVO); BMI - Service Public Fédéral Intérieur, Belgium (Trellchem Super); SWEDEC - Swedish EOD and Demining Center, Sweden (Trellchem HPS); US Army Demilitarization Program; Japan Ground Self Defence Force, Chemical Division, Japan (Trellchem HPS); Royal Thai Army, Chemical Division (Trellchem HPS); NYPD Emergency Services Unit; FBI Chemical Response Team; Centraldienst der Polizei, Germany (Trellchem VPS); Tokyo Police Agency, Japan (Trellchem HPS); Lanxess, Belgium (Trellchem Splash 600); Statoil, Norway (Trellchem Super); British Nuclear Fuels, UK (Trellchem Super) and the A.P. Møller - Maersk Group, Denmark (Trellchem Super). In 2014, Ansell had total sales growth of $1.6 billion (a 16% increase over 2013) with Earnings Before Interest and Tax (EBIT) of $206 million (up 20%), earnings per share (EPS) of $1.10 (up 3%) with a cash flow of $178 million (up from $130 million in 2013).

We also worked with Dr. W. Jon Williams, a Research Physiologist and Principal Investigator who has 19 years of experience studying the human physiological responses to environmental stresses, first at the NASA Johnson Space center, and now for the National Personal Protective Technology Laboratory (NPPTL) at NIOSH, where he is the lead investigator for the Research Physiology Laboratory. He graciously agreed to serve as an advisor on the project and assisted us by carrying out several tests of our cooling system on NPPTL's sweating thermal manikin (Figure 1). Dr. Williams has conducted or supported a total of 16 major human research studies either as a PI or co-investigator. Dr. Williams received his Ph.D. in Physiology from the University of Illinois at Urbana-Champaign, completed three-years as a NASA/National Research Council Resident Research Associate at the Johnson Space Center in Space/Cardiovascular Physiology, and is currently a senior physiologist at the NPPTL. Dr. Williams areas of expertise include the effects of environmental and micro-environmental heat stress on human physiology, efficacy of cooling systems used in conjunction with personal protective ensembles (PPE), and the effects of atmospheric carbon dioxide and oxygen changes on human physiology as related to PPE.

Figure 3 shows the results of testing TDA's 2nd generation cooling device using the NPPTL thermal sweating manikin (Figure 1) where the outside air was simulated for two conditions: a heat index of 125°F (very hot but dry) and a heat index of 88°F (hot and very humid). In both cases, TDA's cooling system significantly outperformed *all* other cooling methods except for not wearing the suit, which was run as a benchmark. Significantly, our cooling system was able to reduce the extremely important CORE body temperature at the end of one hours of use by 2-3°C (3.6-5.4°F) compared to the use of an uncooled suit. None of the other methods including a phase change vest were able to cool the body's core temperature. We are currently designing a 3rd generation cooling system.

4.5. Background, Significance and Specific Aims

When responding to a chemical spill or other hazardous cleanup operation, first responders frequently wear level A hazardous materials (hazmat) suits. These suits protect the first responder from chemical exposure by completely sealing them against hazardous external vapors and liquids. Breathing air is supplied by a self-contained breathing apparatus (SCBA). The SCBA is worn inside the level A suit, which provides the highest possible level of protection.

Because the suits are completely sealed, the environment inside quickly gets very hot and humid. Given the fact that a first responder can be in the suit from 30-60 min (depending on the capacity of the SCBA air tank), overheating is not just a source of discomfort, but can be dangerous to their health. In addition, perspiration frequently condenses on the inside of the faceplate, obscuring vision, which is also hazardous. The heat and humidity buildup in the suit severely limits the time that can be spent inside the suit without risking heat exhaustion.

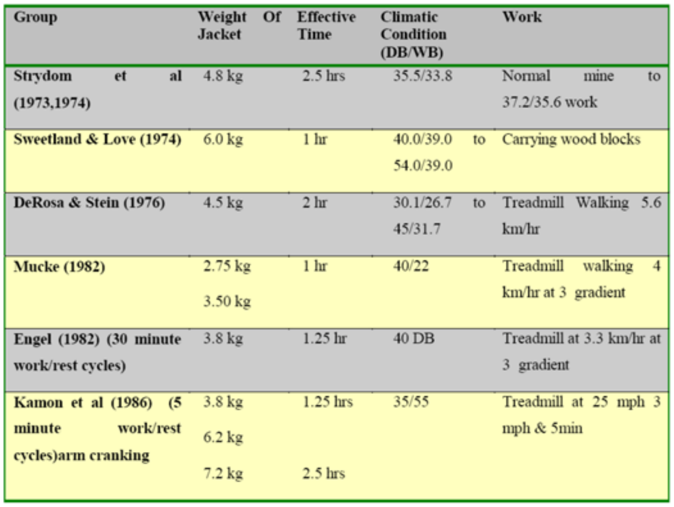
Even though first responders can carry enough air to operate for 60 minutes, in most cases the maximum practical time in a level A suit is about 30 minutes. Depending on the ambient conditions and the amount of physical exertion, it is frequently less. For example, a study by Patterson et al. (1998) shows that a 70-kilogram (154 lb), physically fit individual engaged in strenuous exercise generates about 800 Btu/hr of heat (234 W). The heat capacity of tissue is about 3.5 kJ/kg/°C (slightly lower than that of water). A heat generation rate of 234 watts, will result in a 70 kg person's body temperature rising from about 37°C to 41°C (106°F) in about 20 min (Peterson et al. 1998). A core body temperature this high (106°F) is dangerous. Since this core body temperature can be reached within 30 min in a level A hazmat suit, the first responder will be more than just uncomfortable, but will be unable to work more than 20-30 min without endangering their health. The fact that overheating can easily occur in less than 30 min essentially prevents the responder from staying in the suit for 60 min (as might be desirable in some situations), especially in hot climates. Even in ambient temperatures as low as 65°F, overheating is a common problem (Branson et al. 2005).

The ideal solution to the overheating problem is to have some type of cooling inside the suit, and this is an active area of research and development. The two main approaches used so far have been cold pack/phase change cooling and liquid cooling. The idea behind cold and phase change pack cooling is that the first responder wears a vest with pockets that hold either chemical cold packs (e.g. ammonium salts that when mixed with water become cold because of their endothermic heats of solution), ice packs, or other phase change materials that are refrigerated prior to use. In ice and phase change pack cooling, the heat of fusion (melting) of the material removes heat. Since this approach requires frequent change outs of the cold packs, a refrigeration system must be close by to regenerate the packs. Additional deficiencies of cold packs include not removing moisture from the air in the suit, giving uneven cooling and cold spots, and when expended, are dead weight. Table 1 shows that cold pack systems can be surprisingly heavy, weighing up to 7.2 kg (~16 lb), with the lightest one being 2.75 kg (6 lb).

The other approach is to wear a vest that has tubes through with a cooling liquid such as water circulates. Even with a portable refrigeration system, an umbilical is needed between the cooling vest and the refrigerator (Ernst 2005). In these systems, the water filled tubes are in direct contact with the wearer's skin to maximize heat transfer. Circulating liquid cooling has been used in space suits and works well when the wearer can be attached to the system using an umbilical that is connected to the separate cooling unit and when the use of a complex temperature controlled refrigeration systems is acceptable. Even then, the system is still very cumbersome. One interesting disadvantage of liquid systems that has prevented their use by firefighters (in addition to poor portability) is that there is a risk of scalding if the liquid filled tubes are accidently exposed to high temperatures.

Cooling vests designed for outdoor workers and deep underground miners that use cold packs work reasonably well, but as mentioned before are heavy, need to be frequently recharged, and are dead weight when thawed (Chauhan 1998). Cold packs, refrigeration systems, and cool liquid circulation systems are the most widely used technologies and there are many patents in these areas (Farnworth and Dacey 2006; Almqvist 2006; Steinert 2005; Parrish and Scaringe 1992a&b; Blackstone 2008; Smith et al. 2006; Uglene 2000; Smith and Roderick 2005; Isherwood et al. 2007; Kiwak 1982; Kuramarohit 1993; Parrish and Scaringe 1994; Harvie, 2005; Wise and Aaron 1991; Frustaci and Dominiak 1997; Siegel 1993; Roderick 2003; Horn 2000) however, there are no patents covering indirect heat transfer using heat exchangers as in TDA's technology. As a result, we are currently applying for a patent for our hazmat suit cooling technology.

Table 1. Summary of findings from cold pack cooling vest studies for workers in deep, hot mines (Chauhan 1998)



Group	Weight Of Jacket	Effective Time	Climatic Condition (DB/WB)	Work
Strydom et al (1973,1974)	4.8 kg	2.5 hrs	35.5/33.8	Normal mine to 37.2/35.6 work
Sweetland & Love (1974)	6.0 kg	1 hr	40.0/39.0 to 54.0/39.0	Carrying wood blocks
DeRosa & Stein (1976)	4.5 kg	2 hr	30.1/26.7 to 45/31.7	Treadmill Walking 5.6 km/hr
Mucke (1982)	2.75 kg 3.50 kg	1 hr	40/22	Treadmill walking 4 km/hr at 3 gradient
Engel (1982) (30 minute work/rest cycles)	3.8 kg	1.25 hr	40 DB	Treadmill at 3.3 km/hr at 3 gradient
Kamon et al (1986) (5 minute work/rest cycles)arm cranking	3.8 kg 6.2 kg 7.2 kg	1.25 hrs 2.5 hrs	35/55	Treadmill at 25 mph 3 mph & 5min

While any of the aforementioned cooling systems could keep the wearer of a level A hazmat suit cool for a limited time, what is really needed is a lightweight portable system that can be easily incorporated into a level A suit that will both cool the wearer a*nd simultaneously dehumidify the air*. This will make the wearer more comfortable and increase safety by eliminating the deleterious physiological effects of high temperature, while simultaneously preventing fogging of the faceplate by condensed perspiration.

TDA's hazmat cooling suit technology, is the only portable system available that simultaneously dehumidifies and the air and cools the first responder that can be used for extended periods of time. TDA's system uses a ducting system similar in principle to the ventilation garments used for decades by NASA to circulate cooled dry air over the occupant of the hazmat suit so that they can be naturally cooled by the evaporation of their sweat. Circulating air is a proven method for cooling and humidity control inside vapor tight suits, and a simple variation of this approach is used in our technology to cool and dehumidify air in the hazmat suits worn by first responders. Our technology would also work for first responders that wearing normal garments, such as the heavy fire resistant clothing, helmets and other hot clothing/equipment worn by firefighters. In those cases however there would be no need for humidity control, just cooler air to circulate for sweat evaporation.

For our cooling system to be effective it must be lightweight, compact and consume as little power as possible to minimize battery weight. Our design weighs about 5 lb and consumes about 20 watts of battery power when cooling 120°F air (exiting the LiCl desiccant bed) down to 80-85°F during a 60-minute mission. A weight of 5 lb has been identified as about ideal by a focus group of first responders and other hazmat suit users (Branson et al. 2005).

4.6. TDA's Approach

4.6.1. Metabolic Heat Removal via Sweat Evaporation Using Dry Air

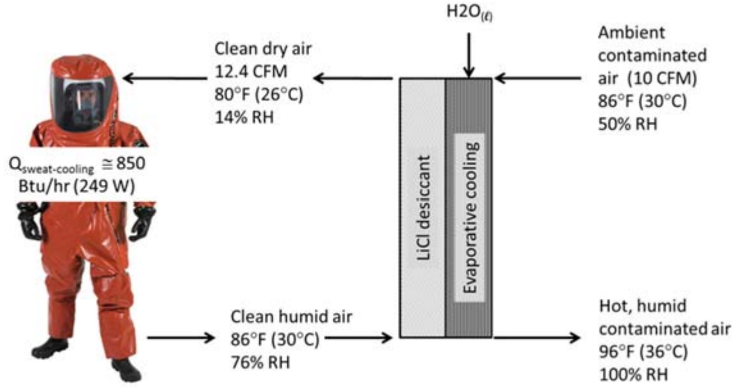


Figure 5. TDA hazmat suit cooling concept.

In TDA's approach, we use evaporative cooling of water and a desiccant to provide cool, dry air (80°F, 14% RH) to the occupant in the hazmat suit (Figure 5). To describe the system, we will start at the exit of the clean, warm, humid air from the suit in Figure 2. The air is warm and humid because it has just passed over the occupant's body where it has picked up moisture from their breath and from sweat evaporation. This air is pulled by a fan over a bed of anhydrous (dry) lithium chloride (LiCl) desiccant. While all alkali chlorides exhibit some desiccant behavior, LiCl is the most efficient desiccant because of the small size of the Li^+ ion, which binds water more tightly than the other alkali cations (Kohl and Riesenfeld 1985). Additionally, because Li is a low atomic weight element, LiCl has the lowest molecular mass of the alkali metal chlorides for a given mass of water removed, which reduces the weight of the desiccant bed. The hydration of LiCl is exothermic and this raises the temperature of the dehumidified air. This heat is removed using a compact aluminum heat exchanger that is integrated with the LiCl desiccant bed and lowers the air temperature to about 80°F. Because the cooling is done with a heat exchanger, evaporating water with contaminated air is carried on one side of the heat exchanger, and the clean dry air is cooled on the other side. This indirect heat transfer prevents contaminated air from entering the hazmat suit (the heat exchanger isolates the air streams). The clean, 80°F, 14% RH air exiting the heat exchanger is then distributed with flexible tubing so that it flows along the arms and legs and around the torso of the occupant. Sweat evaporation cools the occupant, and the now humid air is extracted and the cycle is repeated. Overall, the air that circulates through the hazmat suit is cooled using indirect heat transfer where the cold fluid (heat sink) is contaminated outside air that has been cooled by evaporating externally carried water.

One very important feature in our system is that it the occupants body temperature is thermally *self-regulated*. If the occupant is not doing any strenuous physical activity, and therefore not sweating, then they will simply be bathed in comfortable 80°F dry air. On the other hand, if they sweat heavily, they will be cooled by the evaporation of their own sweat because the air is dry (14% RH). ***Consequently, the occupant will be cooled by the right amount and cannot be overcooled or undercooled.*** This is in contrast to the case with cold packs or cold circulating liquids, especially with ice packs that overcool at first and do not provide enough/any cooling after they have melted.

Another important feature of TDA's approach is that no additional air is needed beyond the amount that is normally inside the suit (along with the air exhaled into the suit as the first responder breaths with the SCBA; this occurs anyway, even without a cooling system. Finally the power requirements are quite small (ca. 20 W) that is easily supplied by rechargeable lithium batteries.

4.6.2. Lithium Chloride Desiccant Beds to Dry the Air that Cools the First Responder

Table 2. Drying bed capacities.

Desiccant	Capacity (lb H_2O/lb dry desiccant)
Molecular Sieves	~0.2
Silica gel (low humidity)	~0.1
Silica gel (high humidity)	~0.3 – 0.5
$LiCl + H_2O \rightarrow LiCl*H_2O$	0.42
$LiCl + 3H_2O \rightarrow LiCl*3H_2O$	1.27
$LiCl + 5H_2O \rightarrow LiCl*5H_2O$	2.12

One of the advantages of the TDA system compared to other cooling options such as cold packs and circulating water (or other liquid coolant) is that *TDA's technology dehumidifies the air inside the suit*. This is not only necessary to make our technology work but as an added benefit, prevents perspiration from condensing on the inside of the face shields in level A suits. This is especially important because there is no way to wipe the faceplate from the inside if fogging occurs.

Desiccants remove water by either physical adsorption (e.g. molecular sieves, silica gel), hydration of anhydrous salts such as calcium chloride, calcium sulfate (Drierite), lithium chloride, sodium sulfate, or by chemical reaction (P_2O_5, concentrated sulfuric acid, CaO etc.). Solid, nontoxic desiccants are most suitable for this application, and the most important variables are water capacity per unit weight of desiccant and what dew point can be obtained (different desiccants give different levels performance).

Lithium chloride has low toxicity and has a very high affinity for water, forming three stable hydrates: $LiCl*H_2O$, $LiCl*3H_2O$ and $LiCl*5H_2O$ (Table 2) in (Hart and Beumel 1973), and in fact, the affinity of LiCl for water is so great that when continuously exposed to a humid environment LiCl will absorb water until it completely dissolves (deliquescence phenomenon). Because of its' high affinity for water and low toxicity, LiCl (and LiBr) *solutions* are used in large industrial air conditioning systems for dehumidification. In LiBr-based air conditioning systems, water vapor is the working fluid that is absorbed by a concentrated solution of LiCl or LiBr (ASHRAE 1988, 1989). In TDA's cooling suit application, solid LiCl lowers the relative humidity to a comfortable level without making the air too dry.

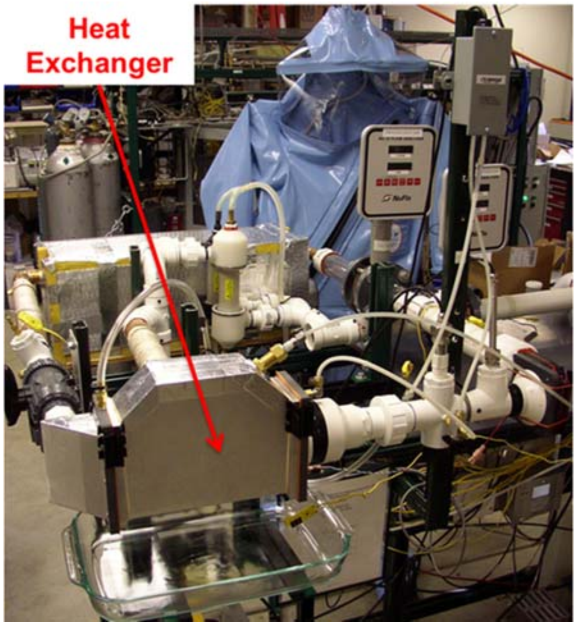


Figure 6. Laboratory bench scale apparatus used prior to prototype design.

Because LiCl and its hydrates are powders, they need to be contained (Mylar bags are used in our 2nd and 3rd generation cooling systems). The Mylar bags physically prevent the desiccant from leaking out (including when it is wet) while simultaneously giving good air/solid contact and minimum pressure drop. By containing the LiCl in Mylar bags that are in direct contact with the heat exchanger, the heat of hydration can be efficiently removed.

4.7. Phase II Results

In Phase II, TDA first developed a laboratory scale cooling system used for initial testing (Figure 6). Based on the laboratory apparatus, we then designed and built two generations of cooling system that were tested with NIOSH using the sweating thermal manikin at the NPPTL. Finally, we have recently designed a 3rd generation cooling system based on what we learned from the manikin testing with the 2nd generation prototype.

4.7.1. Laboratory Bench Scale Test Unit

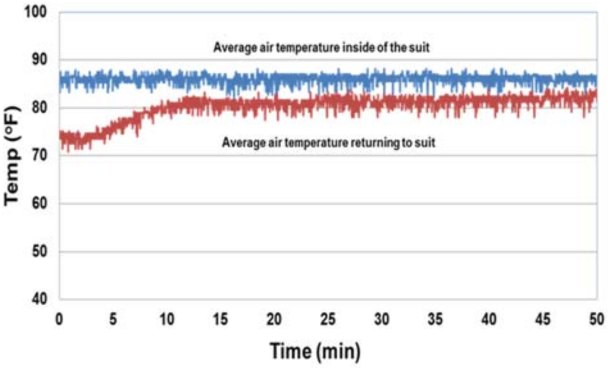


Figure 7. Heat removal from laboratory bench scale apparatus

In Phase II, TDA started the development of the cooling system using a standalone laboratory unit where the components were simply mounted on a Unistrut frame (Figure 6). This apparatus was used to test different methods for integrating the LiCl desiccant bed with the compact heat exchanger. Figure 7 shows test results from the laboratory unit. Importantly, the temperature of the air returning to the suit was approximately 80°F with a relative humidity (RH) of approximately 14% indicating that the cooling system was functioning as designed. For comparison, 14% RH is about the same level of humidity present in most semi-arid climates, which is dry but not uncomfortably dry. The laboratory unit was also capable of removing approximately 852 Btu/hr (250 W) of heat (Figure 8) based on the rate of evaporation of water (a humidification module that was used to simulate occupant sweating). Humid air entering the cooling system was at 86°F and 75% RH, which corresponds to 3.2 vol% water vapor. The dry air at 80°F and 14% RH contains about 0.49 vol% water vapor. Therefore, the laboratory system demonstrated that our approach to hazmat suit cooling was viable, so we proceeded to make a portable 1st generation unit (Figure 9).

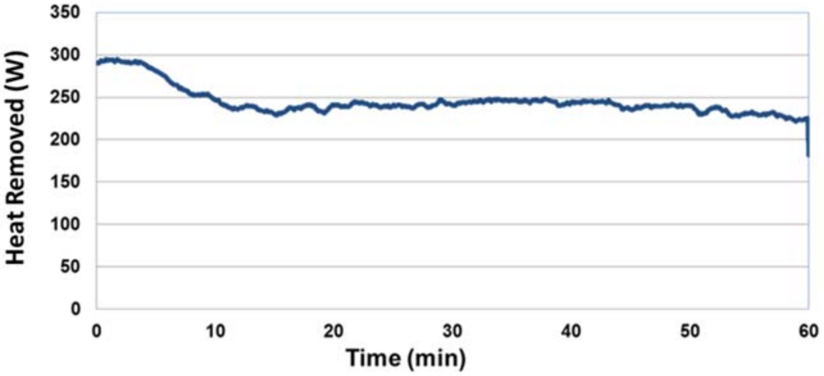


Figure 8. Heat removal rate from laboratory scale cooling system shown in Figure 6.

4.7.2. First Generation Design and Testing

Figure 9 is a 3 dimensional, SolidWorks computer aided design (CAD) drawing of the first generation portable hazmat cooling suit unit. The drawing shows the portions that are both inside and outside of the suit. The portion inside the suit includes the clean dry air distribution manifold and return air fitting (lower right hand corner). The parts outside of the suit include the fan, desiccant cartridge housing (which it integral to the heat exchanger) and water bottle that are used for evaporative cooling of the heat exchanger on the contaminated air side. In this design the suit penetrations are sealed with o-rings and compression nuts. The apparatus is mostly made from plastic.

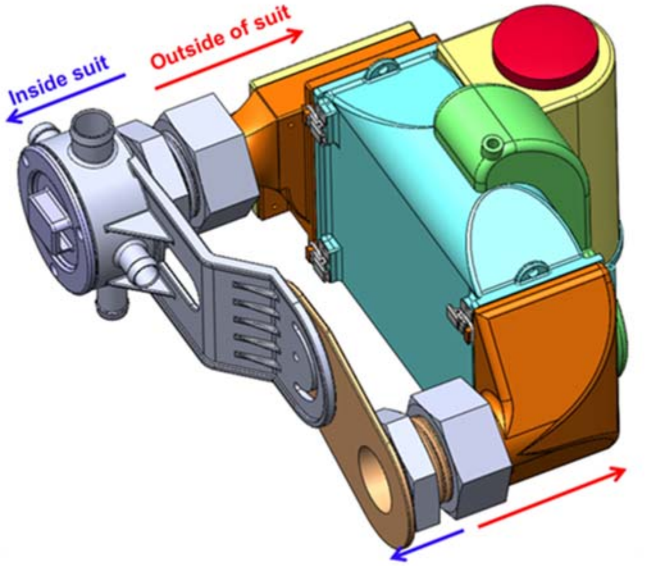
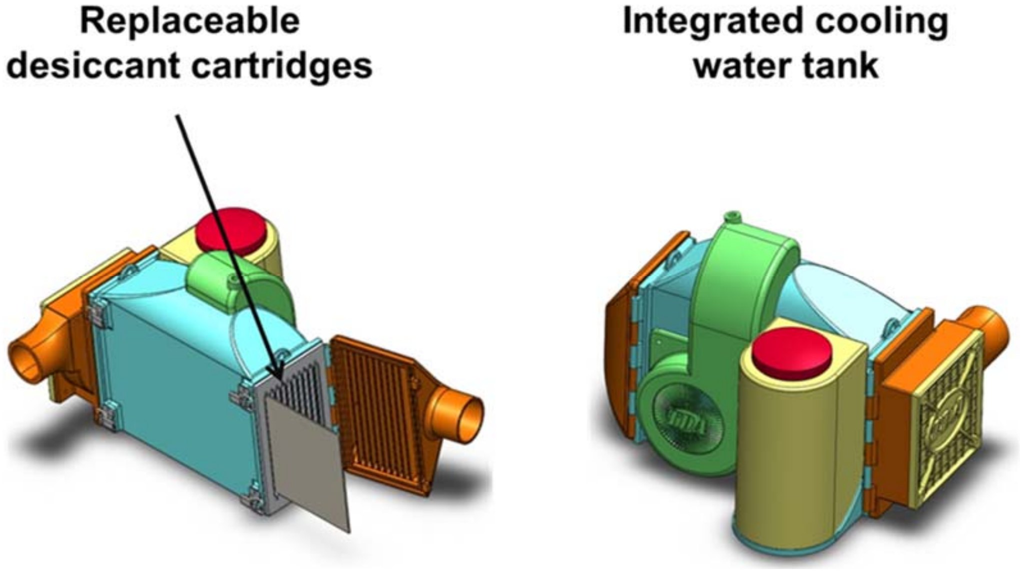


Figure 9. First generation prototype cooling system design showing how it attaches through suit penetrations.

Figure 10 shows some of the details of the 1st generation cooling system. On the left the small door is open to reveal where the desiccant bed cartridges are loaded into the heat exchanger. The desiccant (LiCl) is contained in a series of replicable cartridges that slide into the cooling device much like one replaces furnace filters. Thus, once exhausted, the LiCl cartridges are simply removed and replaced with fresh cartridges, the water bottle is refilled, (yellow cylinder with the red cap) and the unit is put back into service.


Replaceable desiccant cartridges

Integrated cooling water tank

Figure 10. First generation prototype cooling system design.

Figure 11 shows a working prototype of the 1st generation cooling system attached to a level A hazmat suit. In this design, the cooling system is suspended by two wires that were attached to the SCBA harness inside the suit to carry the weight. Figure 12 is a close up photograph of the cooling device showing its component parts. Warm, very humid, air (ca 75% RH) enters the device labeled "air from suit" (partly hidden). The humid air then passes through the LiCl desiccant bed and heat exchanger where the humidity is reduced while the heat of hydration is simultaneously removed. The contaminated air side of the heat exchanger uses evaporative cooling with water (from the water bottle). Contaminated air is forced through the "outside air" side heat exchanger using a small battery powered fan. The clean dry air stream is cooled by the heat exchange to about 80°F and it now at 14% RH. It then passes back into the suit ("air to suit" in Figure 11) to cool the occupant via sweat evaporation. A separate small fan circulates the clean air through the suit.

Figure 11. First generation prototype cooling system mounted onto manikin wearing a level-A Hazmat suit.

Figure 13 shows the "suit occupant" for these tests, which was the NPPTL thermal sweating manikin. The sweating manikin is designed to simulate a human and can sweat at rates similar to those possible by humans (up to about 2 mg/cm^2/min). Distilled water is pumped into the manikin and exits via a multitude of small holes to simulate sweating. The manikin wears a wicking fabric ensemble to spread the water out evenly. The computer inputs a work load in Metabolic Equivalents (METS, where 1 MET = 1 kcal/kg/hr of heat) and the skin temperature, core body temperature and sweating rate are measured at various points.

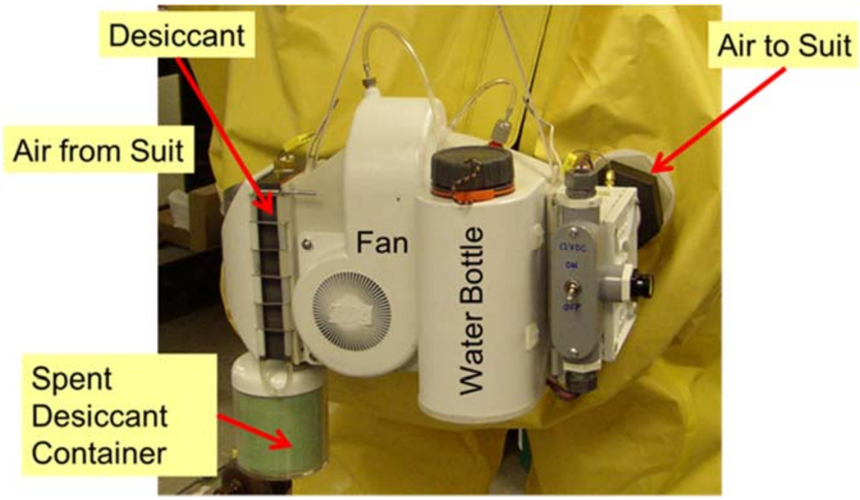


Figure 12. Close up of first generation cooler.

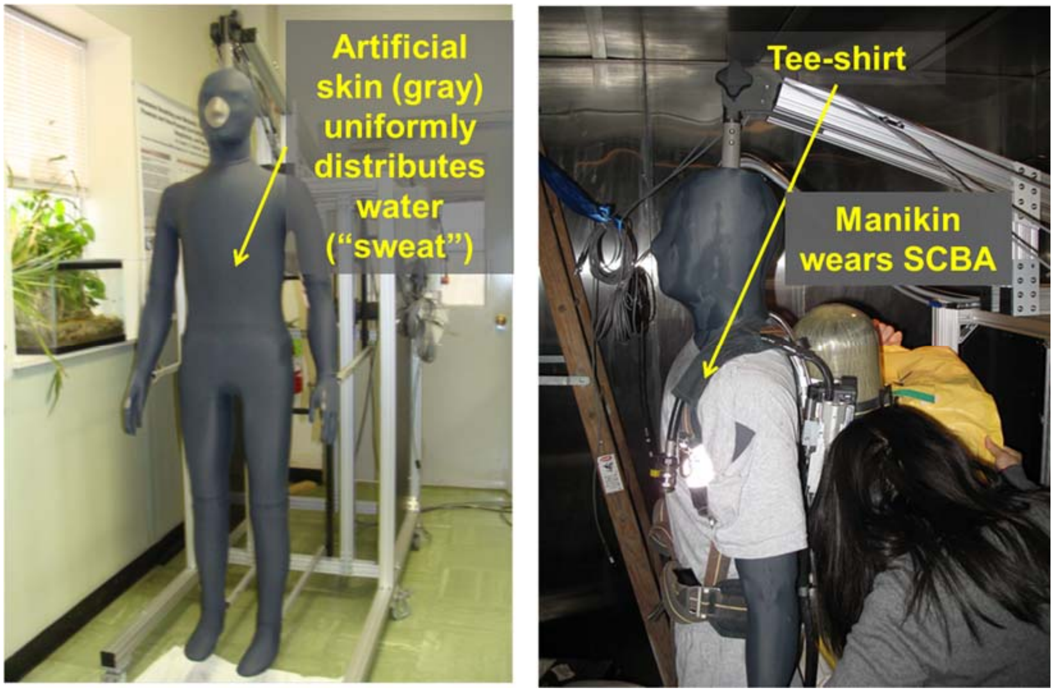


Figure 13. NIOSH thermal sweating manikin used to test first generation cooling system (left) and level A suit and cooling system being installed (right).