Phase I Final Report

Cooling Suit for First Responders

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Grant Number: 1R43OH009349-01

February 3, 2009

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List of Terms and Abbreviations

No special terms or abbreviations are used in this report.

Abstract

This final report was included as part of the Phase II proposal. In Phase I of the *Cooling Suit for First Responders* SBIR project, TDA successfully designed, built, tested and demonstrated the effectiveness of our carbon fiber composite trim cooler heat exchanger (Figure 1) that is part of a system for cooling the air inside of a Level A Hazmat suit. The system effectively and safely cools the air during use in contaminated external environments without exposing the wearer to toxic or other dangerous materials. The trim cooler is the key technological innovation in TDA's Hazmat suit cooling system. It is used to cool clean air inside the suit using indirect heat transfer with external contaminated air that has been cooled by the evaporation of water. The heat exchanger, is made from carbon fiber composite materials and has a large heat transfer surface area making is lightweight and compact. TDA's cooling system also incorporates a desiccant to prevent humidity from building up in the suit. With TDA's system, a first responder in a Level A Hazmat suit can work safely for extended periods of time without danger of heat exhaustion.

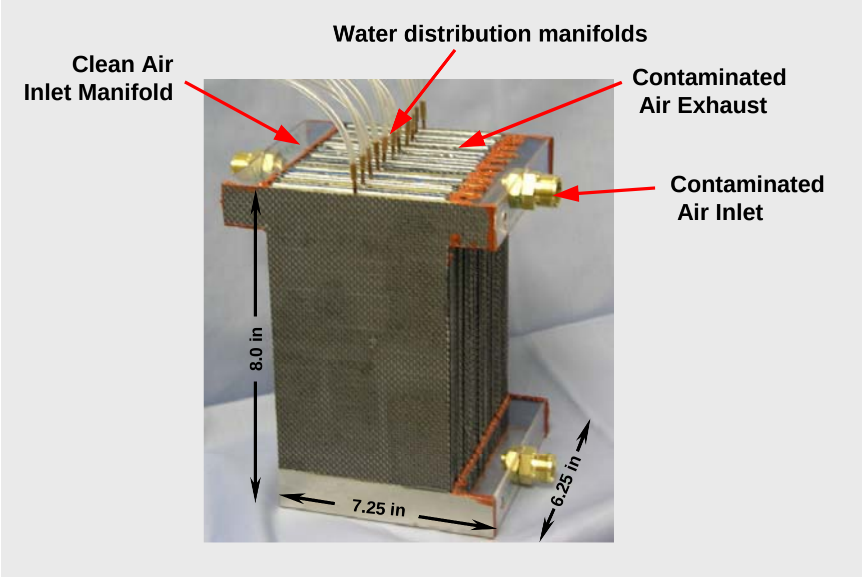

Figure 1. Photograph of the full sized trim cooler designed, fabricated and tested in Phase I.

The trim cooler that we fabricated in Phase I (Figure 1) successfully passed all tests. In these laboratory tests, the "contaminated air" stream was simply room air heated to temperatures between 95°F and 120°F and humidified to a 65°F dew point. For simplicity, no toxic components were added to the "contaminated" air because they do not affect the heat transfer characteristics of the trim cooler. The clean air inlet temperature was varied between 106°F and 140°F. Table 1 summarizes the test results showing the various inlet and outlet air temperatures. The dimensions and weight of the trim cooler were: overall height of 8 inches, depth of 6 ¼ inches, width of 7 ¼ inches, and weight of 2.39 lbs without brass fittings (2.67 lbs with the brass fittings). The sections that follow describe the design, construction and testing of the trim cooler in detail. Even with contaminated air in at a temperature of 122°F, the clean air outlet temperature was 75°F, indicating that the trim cooler was functioning as designed.

Table 1. Summary of trim cooler test results obtained in Phase I.

Clean air IN (°F)	Clean air OUT (°F)	Contaminated air IN (°F)	Contaminated air OUT (°F)	Contaminated air flow rate (SCFH)
130	76	122	88	160
140	75	119	85	160
120	70	120	84	100
106	67	95	75	100

The Phase I project performance period was from 09/01/2007 to 09/30/2008.

Key Personnel

The following key personnel performed the work during the Phase I effort:

Name	Title	Dates of Service	Hours
Dr. Girish Srinivas	Principal Investigator	09/01/07 to 03/31/08	72
Dr. Robert Copeland	Principal Engineer	09/01/07 to 03/31/08	178
Ms. Georgia Mason	Engineering Tech.	09/01/07 to 03/31/08	522
Dr. Steven Gebhard	Senior Scientist	09/01/07 to 03/31/08	7
Mr. Kerry Libberton	Engineer	09/01/07 to 03/31/08	27
Dr. Jeanine Elliott	Senior Engineer	09/01/07 to 03/31/08	68

1. Section 1.

1.1 Highlights/Significant Findings

When responding to a chemical spill or other hazardous cleanup operation, first responders must frequently wear a level A hazardous materials suit. 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, which 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 get very hot and humid. 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 a real danger to their health because of the risk of heat exhaustion. In addition, perspiration condenses on the inside of the faceplate obscuring vision.

* TDA Research, Inc. (TDA) is developing a lightweight, portable system that will both cool and dehumidify the air that is circulated through a hazmat suit. Breathing air is supplied to the first responder inside the suit by the usual SCBA. To cool the wearer, TDA's system circulates clean, dry, breathable air inside the suit. Evaporation of perspiration is the main heat transfer mechanism that cools the first responder in the suit. The water vapor generated by sweat evaporation is removed using a lightweight bed of lithium chloride (LiCl) desiccant. The dry air exiting the LiCl bed is then cooled using a specially designed heat exchanger (trim cooler) that rejects heat to the outside environment. Even though the clean air is heated as it passes through the desiccant (due to the heat of hydration of the LiCl), heat can be rejected to the environment even at hot outside (dry bulb) temperatures because we pass water into an absorbent material that lines the channels on the contaminated air side of the trim cooler, and the contaminated air flow is evaporatively cooled. The clean air is cooled by indirect heat transfer through the walls of the trim cooler (heat exchanger) that are in thermal contact with the passages where evaporative cooling on the contaminated air side takes place. Thus, the heat exchanger transfers heat from the inside of the suit to the dirty environment, while keeping the clean and contaminated air streams completely separate. The clean air is now dry (about 15% RH) and at a temperature of about 77°F. This clean, dry air is returned to the first responder, where it evaporates sweat to cool the wearer. The cool, dry air is distributed to the hands, head, and feet within the hazmat suit using a lightweight internal duct system.

* The key to minimizing the weight of TDA's cooling system is a high performance, lightweight, carbon composite, heat exchanger. For preliminary design purposes, we assumed that the contaminated air was at 120°F and had a relative humidity (RH) of 17% (dew point ~64°F).
* Adding water to the contaminated air reduces its temperature (by evaporation), which provides the heat sink for the system. However, the temperature differences between the air inside the suit and the cooled, humidified outside air that is used for heat removal are not very large, and therefore we need a high effectiveness heat exchanger to ensure that the size and weight of the heat exchanger (trim cooler) is reasonable.

* TDA's trim cooler heat exchanger uses commercially available carbon composite materials to minimize weight. Using carbon composites for both heat exchangers and support structures, a LiCl desiccant, and lightweight internal air ducts, we estimate that the entire cooling system would weigh about 4.9 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 hazmat suits under "ordinary" conditions, but also permits work to be carried out in situations where high temperatures would make work otherwise be impossible. Finally, because the system is made from carbon composites, epoxies and plastics, it is resistant to decontamination chemicals such as soaps, bleach, and assorted solvents.

* The overall objective of the project is to develop 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 will be designed to keep a user cool for about 60 minutes (although, it can easily be used for longer periods of time by carrying more water). The duration of operation of our system is mainly governed by the battery life for the small fan that circulates the air, and the amount of cooling water carried, both of which only add a small amount of weight to the total system — incorporating a larger battery and water reservoir would permit operation for longer times. Ultimately, the SCBA used for breathing air will be the time limiting factor. The key innovation for our cooling system is the lightweight, high efficiency carbon composite heat exchanger that we refer to as a "trim cooler." In order to accomplish the goal of developing a cooling system, we must first develop this heat exchanger. Therefore, in Phase I we focused on developing and demonstrating the carbon composite heat exchanger for the cooling suit.

* All of the Phase I goals were met or exceeded including the design, fabrication, testing and thermal modeling of a full sized trim cooler heat exchanger. Our tests showed that the trim cooler performed exactly as designed and that it was fully capable of meeting all of the design criteria.

1.2 Translation of FIndings

When responding to a chemical spill or other hazardous cleanup operation, first responders must frequently wear a level A hazardous materials suit (Figure 2). These suits protect the first responder from chemical exposure by completely sealing the wearer against hazardous external vapors and liquids. Because the suits are sealed, a fresh air supply is required, which 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, 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, overheating is not just a source of discomfort, but is potentially dangerous to their health. In addition, perspiration condenses on the inside of the faceplate, obscuring vision and potentially causing a dangerous situation, and the heat/humidity buildup in the suit severely limits the time that can be spent in the suit without risking heat exhaustion.

Even thought the first responders carry enough air to operate in a hazardous environment for more than 60 minutes, in most cases the maximum practical time for being in a level A suit is about 30 minutes. Depending on the ambient conditions and the amount of physical exertion, it is frequently even less. For example, a study by Patterson et al. (1998) shows that a 70 kilogram, physically fit individual engaged in strenuous exercise generates about 1000 W of energy of which about 800 W (2732 BTU/hr) is heat. The heat capacity of tissue is about 3.5 kJ/kg°C (0.84 BTU/lb°F, slightly lower than that of water). For a heat generation rate of 800 W, a person's body temperature will rise about 1°C in slightly more than 5 min and reach 41°C (106°F) in about 20 min (Peterson et al. 1998). A core body temperature of 106°F is extremely dangerous (hyperthermia). 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 severely endangering his/her own 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 may be required), especially in hot climates.

Level A: Highest level of protection
- **Positive pressure SCBA**
- **Gas/vapor tight suit**
- **Chemical resistant gloves**
- **Chemical resistant steel toe boots**

Level B: Intermediate protection
- **Positive pressure SCBA**
- **Chemical *resistant* suit**
- **Chemical resistant gloves**
- **Chemical resistant steel toe boots**

Level C Lower level of protection
- **Air purifying respirator**
- **Chemical resistant gloves**

Level D Lowest protection
- **Normal work clothing (gloves, etc.)**
- **PPE for nuisance exposures (e.g. dust)**

Figure 2. Hazmat protection levels and a level A suit (Hamilton Sundstrand Corp. SCAPE suit).

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 are cold pack cooling and liquid cooling. The idea behind cold pack cooling is that the first responder wears a vest with pockets that hold either chemical cold packs (e.g. ammonium salts when mixed with water become cold caused by their endothermic heats of solution) or ice pack type materials that are refrigerated prior to use.

The other approach is for the first responder to wear a vest that has tubes that contain a cooling liquid such as water. The circulating liquid approach is used for space suits and is well suited for applications where the wearer can be attached to the system with an umbilical and a separate cooling unit. One disadvantage of liquid systems is the possibility of scalding, and this has prevented liquid systems from being used for firefighters. In either case, the cooling vests were designed for workers that did not have to wear vapor tight suits, and in such cases (such as working outdoors during hot weather) they work quite well. In the case of the liquid cooling system used for space applications, fresh air and cooling fluid are supplied either by an umbilical or by a large backpack (e.g. during EVA) and moisture from breathing and sweating can be removed externally. In a third approach, ice packs can be used to cool a first responder. This approach requires frequent change outs of the cold packs and a refrigeration system must be close by to chill the cold packs. Also, cold packs do not remove moisture from the air in the suit. Finally, ice and cold packs provide uneven cooling and cold spots. While either of these systems could keep the wearer of a level A hazmat suit cool, *there is currently no* ***portable***

<u>system that dehumidifies the air while simultaneously cooling the first responder that can be used for extended periods of time.</u>

What is needed is a lightweight portable system that can be easily incorporated into a level A hazmat suit that will both cool the wearer and simultaneously dehumidify the air. This will make the wearer more comfortable as well as increase safety by eliminating the deleterious physiological effects of high temperature, and prevent fogging of the faceplate by perspiration.

Figure 3. NASA AVG (NASA 2006).

* TDA Research, Inc. (TDA) is developing a lightweight, portable system that both cools and dehumidifies the air circulated through a hazmat suit. The ducting system would be similar to the air ventilation garments (AVG) used for decades (with appropriate advances) by NASA inside space suits (Figure 3). Air cooling is a proven method for cooling and humidity control inside vapor tight suits. A simple variation of our technology can also be developed that can be used by first responders in non-toxic atmospheres. In the latter application, neither hazmat nor CBD garments are worn, but heavy fire resistant clothing, coveralls, helmets and other hot clothing/equipment are worn that can cause overheating.

* For the cooling system to be effective it must light weight, compact and consume as little power as possible to minimize battery weight. A preliminary design and systems analysis of our technology indicates that the system would weigh about 5 lb and consume about 3 watts when cooling 120°F air down to 77°F during a 60 minute mission. The electricity is used to run a small fan that circulates clean air.

1.3 Outcomes/Relevance/Impact

* In our approach, we use evaporative cooling of water and a desiccant to provide cool, dry air (77°F, 15% RH) to the hazmat suit (Figure 4). To describe the system, we will start at the exit of the clean, warm, humid air from the suit in Figure 4. The air is warm and humid because it has passed over the occupant's body where it has picked up moisture from their breath and from perspiration. This air is pulled by a fan over a bed of anhydrous (dry) lithium chloride (LiCl) desiccant. The humidity of the air is decreased as the water is removed by the LiCl desiccant according to the reaction: $LiCl + H_2O = LiCl{*}H_2O$. In this reaction, the water is incorporated into the crystal structure of the lithium chloride and is not simply adsorbed on the surface of the granules. Other alkali chlorides can be used for moisture removal as well, but LiCl is the most efficient because of the small size of the Li^+ ion (Kohl and Riesenfeld 1985). Additionally, because Li is a low atomic weight element, LiCl has the lowest mass of the alkali metal chlorides for a given mass of water removed. The hydration of LiCl is exothermic, and this increases the temperature of the partly dehumidified air to about 160°F. This air then passes through a main cooler (also a carbon composite heat exchanger) where its temperature is dropped to ~100°F as it is cooled by indirect exchange with ambient, contaminated air that has been cooled by water evaporation. Indirect heat transfer prevents contaminated air from entering the hazmat suit. The 100°F air then passes over a second LiCl bed to further dry the air to about 30°F dew point (ca. 15% RH).

* The adsorption of water in the second LiCl bed again raises the temperature of the air (this time to ~140°C) so it must be cooled again. This is done in a second heat exchanger (the trim cooler in Figure 4). The trim cooler also uses water evaporation on the contaminated air side to cool

the clean air that will eventually go back to the suit. The clean, 77°F, 15% RH air exiting from the trim cooler is supplemented with air from the pressurized breathing air tank (that is normally carried) and is then sent to the suit where it is distributed to flow along the arms and legs and

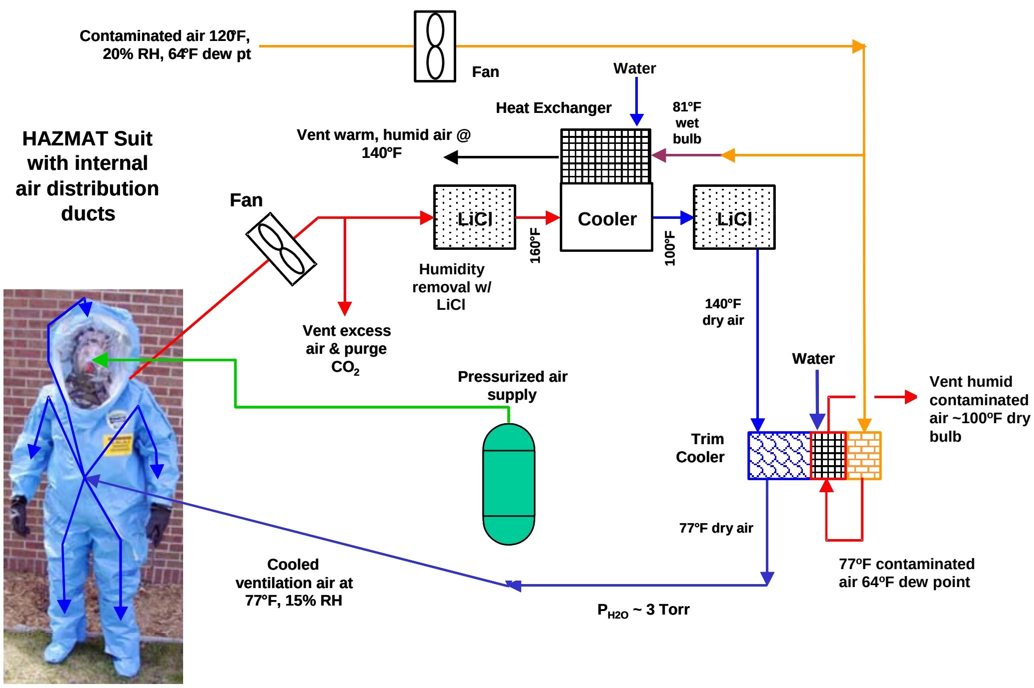

Figure 4. Schematic of TDA suit cooling technology

over the head/neck of the occupant. This cool, dry air then flows from the person's extremities back to the central collection point, cooling the wearer. The LiCl beds are sized to last 60 min.

* Overall, the air that circulates through the hazmat suit is cooled using indirect heat transfer with contaminated air that has been cooled by water evaporation, and we have carried out a preliminary design of the cooling system. First, ambient, contaminated air at 120°F (dew point 65°F) is cooled by water evaporation in the main cooler. The function of the main cooler is to remove the heat added to the clean air stream when its water vapor has been absorbed by the lithium chloride desiccant. The contaminated air is humidified in the process and exits at about 140°F (and has a wet bulb temperature of ~81°F). The other portion of the hot, contaminated air passed through two stages of heat exchange in the trim cooler. It is cooled to 77°F in the first pass (Figure 4). This cooled (but still contaminated) air is then used to remove heat from the 140°F clean dry air exiting the second LiCl bed. This is done on the clean air side of the trim cooler. The clean air is at 77°F and has a relative humidity of only 15%. This cool, dry air is then distributed using fabric tubing over the arms, legs, neck and torso of the occupant, where the evaporation of the perspiration cools the occupant.

* One additional and very important feature in our system is that it is thermally <u>self-.regulating</u>. If the occupant is not doing any strenuous physical activity and therefore not sweating, then they will simply be bathed in 77°F 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 (15% RH). ***Consequently, the occupant will be cooled by the right amount and cannot be overcooled.*** This is not the case with cold packs or cold circulating liquids. There is no way to prevent overcooling with cold

packs, and a complex temperature feedback system is needed with liquid cooling systems. In TDA's system, the wearer's body controls the temperature in a natural manner (by sweating and evaporation of the sweat).

* Another important feature of TDA's approach is that no additional air is needed beyond the amount that needs to be carried for breathing. Also, is it not absolutely necessary (although desirable in very hazardous environments as an added precaution) for the responder to wear an SCBA face mask when using TDA's cooling suit technology because a level A suit will always be at a slight positive pressure. The main reason that first responders wear SCBA face masks in existing hazmat suits is because if the suit gets a small hole in it, there is nothing to prevent contaminants from diffusing into the suit. With TDA's technology, air would blow out of any hole (until it is fixed) preventing contaminants from diffusing in (an SCBA mask can still be easily incorporated into TDA's system for an extra measure of safety if desired). Finally the power requirements are quite small; the two small fans use about 3 W; the 3W-hr are easily supplied by about 0.3 lb of lithium batteries.

1.3.1 Carbon Fiber Composites for Heat Exchangers

* The key to TDA's system is having small highly efficient heat exchangers for the main cooler and the trim cooler. *Heat exchangers are used because they separate clean from contaminated air*. If the heat exchangers are to be compact however, they must be efficient, and this requires that there be good heat transfer through the walls of the device, with poorer heat conduction down the length of the heat exchanger. If heat conduction down the length of the heat exchanger is significant, then the temperatures at each end will approach each other and the driving force for heat transfer will be diminished.

* Figure 5 shows a simplified diagram of a heat exchanger. Note that we are not using a shell and tube geometry, Figure 5 is simply for illustrative purposes. Hot gas enters at T_1 and leaves cooled at a temperature of T_2 . Cool fluid enters at t_1 and leaves heated to t_2. This configuration is referred to as countercurrent flow and is frequently used because it minimizes the contact area required to obtain the desired heat exchange. The circle in Figure 5 is a "close-up" of the interface between the two fluids with the thermal conductivities labeled for heat conduction across the tube (k_A) and along the tube (k_B). For good heat transfer, the tube wall must have good thermal conductivity in the k_A direction so that heat can flow from the hot fluid to the cold fluid. On the other hand, heat conduction down the length of the tube (k_B) is undesirable because it tends to reduce the difference between T_1 and T_2. If the heat exchanger must be small, then a material with a high k_A and low k_B is required, which eliminates the use of most metals.

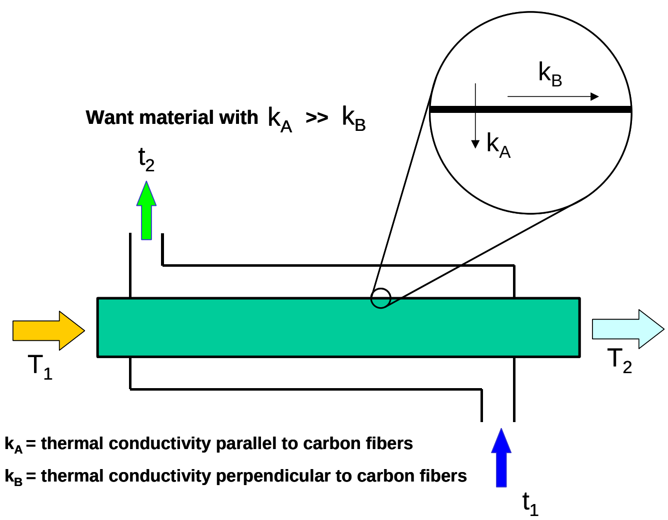

Figure 5. Idealized heat exchanger showing how to minimize axial heat conduction.

* A few carbon fibers composites have very high thermal conductivity and low density, and some carbon fiber composites have significantly lower thermal conductivity in the direction perpendicular to the fibers ($k_\perp$ in Figure 5) than the thermal conductivity parallel to the fibers ($k_{||}$

in Figure 5). Table 2 lists the thermal conductivities of several carbon fiber composites along with typical metals for comparison. The best (but most expensive) materials for our application would be K-1100/Epoxy and K-1100/C. In Phase I, however, we found that we could use a C-fiber/E-glass composite (where $k_{\|}/ k\perp \approx 10$. Importantly a typically lightweight metal such as aluminum is unsuitable because its thermal conductivity is the same in all directions (isotropic). Table 3 shows additional physical properties of K-1100 and other carbon fibers.

Table 2. Thermal properties of heat exchanger materials.

K = thermal conductivity; CTE = coefficient of thermal expansion

Material	K (││) W/m-K	K (⊥) W/m-K	CTE ppm/K	Density g/cc	Specific K(││)(W/m-K)/(g/cc)
Copper	**400**	**400**	**17**	**8.9**	**45**
Al 6061	**218**	**218**	**23**	**2.7**	**81**
K-1100/Cu (46v/o)	**709**	**135**	**1.1**	**5.9**	**117**
K-1100/Al (55v/o)	**634**	**50**	**0.5**	**2.5**	**236**
K-1100/Epoxy (60v/o)	**540**	**1**	**-1.4**	**1.8**	**300**
K-1100/C (53/v/o)	**696**	**52**	**-1.0**	**1.8**	**387**

(││) parallel to fibers, oriented across the tube wall
(⊥) perpendicular to fibers, oriented down the tube

Table 3. Properties of several carbon fiber materials

Property	Value	Fibers only (not composite)							
Material		XAS,HTA,T300	34-700, T650/35	UMS2526	HM	HS40	P25	P100	F180	**K1100**
Coefficient of thermal expansion Longitudinal	$x10^{-6}$ K^{-1}	-0.1to-0.5	-0.6	-0.7	-1.3	-0.5	-	-1.5		**-1.4**
Coefficient of thermal expansion Transverse	$x10^{-6}$ K^{-1}	+26	-	+37	+25					
Density	g cm^{-3}	1.76-1.8	1.77-1.8	1.78	1.86	1.85	1.87	2.15	-	**2.1**
Extension to break	%	1.5-1.7	1.7-1.9	1.2	0.8	0.9	1.0	0.3	-	
Filament diameter	µm	7	7	4.8	8	5	11	10	-	
Precursor		PAN	PAN	PAN	PAN	PAN	Pitch	Pitch	Pitch	**Pitch**
Tensile modulus	GPa	230-40	230-40	380	350-70	450	140-60	720	180	
Tensile strength	GPa	3.6-4	4.5	4.9	2.5-2.7	4.4	1.4	2.2	2.0	
Thermal Conductivity	W m^{-1} K^{-1}	17-24	14	46	105	52	22	520		**1100**
Volume Resistivity	µOhmc m	1400-1600	1500	1000	900	1000	1300	250		

* TDA has designed and fabricated carbon composite heat exchangers in the past when developing lightweight space radiators for NASA (Figure 6). Carbon-based heat exchangers are superior to aluminum heat exchangers primarily due to their lighter weight and the fact that they exhibit much lower rates of heat conduction perpendicular to the fibers (while having good heat transfer along the fibers). Carbon composites are generally made as so-called lay-ups. The starting material is “prepreg,” which is a tape of material with unidirectional fibers in partially cured resin (commonly epoxy). In lay-ups, the prepregs can be oriented in layers so that the fibers are in different directions, which can add mechanical strength or affect other properties such as thermal conductivity. In our heat exchanger, carbon fiber (C-fiber) and epoxy/fiberglass (E-glass) were oriented at right angles in the lay-up to maximize strength and minimize weight. Once the lay-ups are complete, the composite is cured using a combination of pressure and heating, sometimes in vacuum (Ilschner, et al., 2005; Minus and Kumar 2007). There are two heat exchangers in TDA’s hazmat cooling system that are made from carbon composites: 1) the main cooler, which removes the heat added to the system by the LiCl desiccant beds, and 2) the trim cooler that is used to cool the clean, dry air down to 77°F.

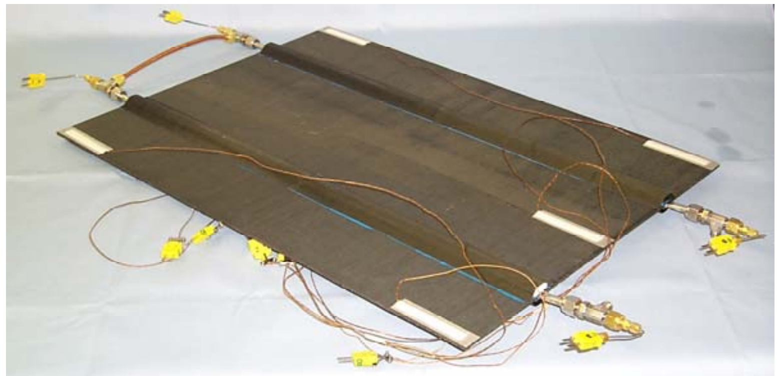

Figure 6. Freeze tolerant radiator made by TDA that uses a carbon fiber fin (approximately 9” x 12”).

1.3.2 Main Cooler

* The main cooler (Figure 4) is located between the LiCl desiccant beds. The heat of absorption of water to form LiCl*H_2O is high (1,490 Btu/lb of water) and therefore, the temperature of the air exiting the LiCl beds is increased. The function of the main and trim coolers is to reject this heat and cool the dry air. Figure 7 is a greatly simplified diagram that illustrates the flow paths in the main cooler. The heat exchanger is divided into two sections. Hot dry air from the first LiCl desiccant bed is cooled in the center channels. Contaminated air that has been cooled by evaporative cooling passes through the upper and lower channels.

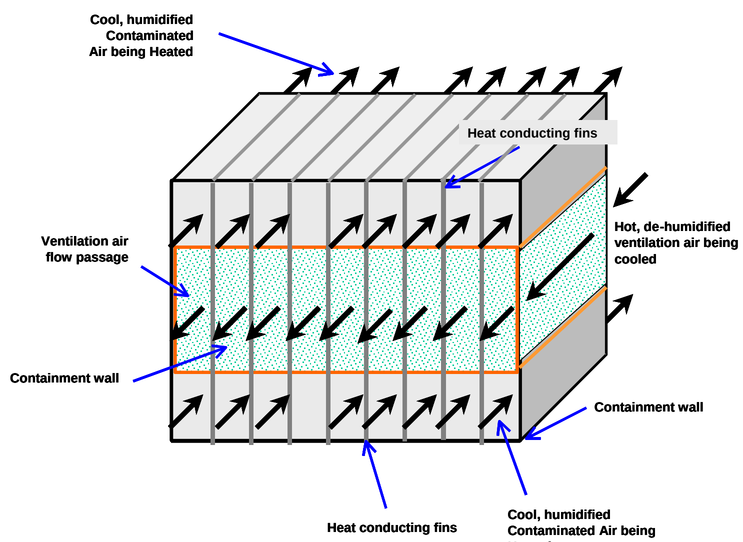

Figure 7. Cross section of the main cooler

1.3.3 Trim Cooler

* Air exiting the main cooler, goes to the second LiCl desiccant bed where the remaining water is removed, which increases the temperature to about 140°F. This air must be cooled, and this is the function of the trim cooler. In Phase I, the trim cooler was made using commercially available, moderately priced (ca. $25/ft^2) carbon-fiber, epoxy resin fiberglass composite (C-fiber/E-glass). Details of the design, fabrication and testing of the trim cooler as discussed in Sections 2.1.1 and 2.1.2.

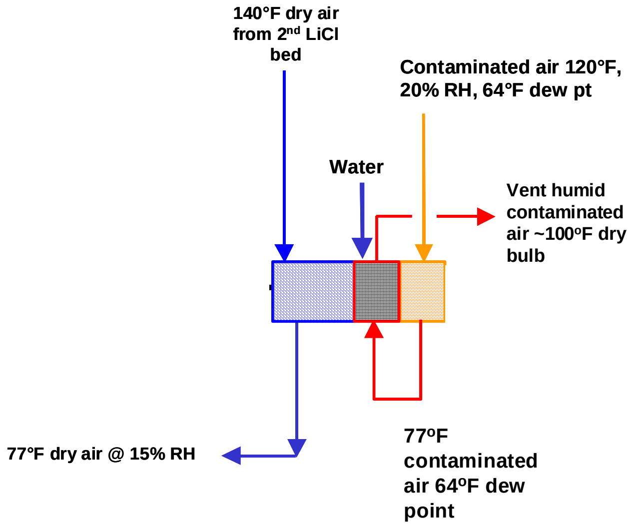

Figure 8. Trim cooler

* The trim cooler also functions by water evaporation (Figure 8). The initial stream of hot (ca. 120°F) contaminated air makes two passes through the trim cooler. At steady state, dry contaminated air enters at 120°F and 20% RH and is cooled to 77°F before entering the second pass of the trim cooler. Water is injected into wick-filled channels in the second pass removing 1000 BTU of heat per pound of water evaporated. This cool (still contaminated) humid air cools the clean, dry 140°F air exiting the second LiCl bed to about 77°F by indirect heat transfer. Because heat transfer between the clean and contaminated air streams is done using a heat exchanger, the occupant of the hazmat suit is never exposed to contaminated air. Finally, the clean dry (77°F, 15% RH) air is directed back to the hazmat suit where it cools the occupant by the evaporation of his or her perspiration. As was the case with the main cooler, the trim cooler needs to be as small as possible to minimize weight and bulk.

1.3.4 Lithium Chloride Desiccant Beds

* 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 the air is dehumidified with TDA's technology. This is not only important from a comfort standpoint, but condensation of perspiration on the inside of the face shields obscures the users vision. Worse, because the level-A hazmat suit is completely sealed, there is no way to wipe the faceplate clean from the inside. Obviously the best solution is to remove this moisture, and the lightest most efficient way for a short duration use (ca. 60 min) is to use a desiccant.

* 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 with water (P_2O_5, concentrated sulfuric acid, CaO etc.). Solid, nontoxic desiccants are more suitable for use in this application, and the criterion then becomes water capacity, dew point, and the weight of desiccant needed to achieve the desired level of dehumidification.

* Lithium chloride is nontoxic and has a very high affinity for water, forming three stable hydrates: $LiCl*H_2O$, $LiCl*3H_2O$ and $LiCl*5H_2O$ (Table 4) (Hart and Beumel 1973). LiCl's affinity for water is so great that when continuously exposed to a humid environment LiCl will absorb water until it

completely dissolves (deliquescence). Because of its' high affinity for water and low toxicity, LiCl *solutions* are used in large industrial air conditioning systems for dehumidification where water is absorbed by a concentrated solution of LiCl, which is subsequently regenerated by heating (ASHRAE 1993). LiCl also lowers the relative humidity to a comfortable level without making the air too dry. TDA's cooling suit system uses *solid* LiCl. The material can be regenerated by heating and reused. Thus, the desiccant beds in the hazmat cooling unit could be used repeatedly. The regeneration would be done in a clean environment after the hazardous waste emergency had passed.

* Because LiCl and its hydrates are powders, they need to be contained in a vessel. The design must physically contain the powder to prevent spillage into the air stream while simultaneously giving good air/solid contact and minimum pressure drop. By containing the LiCl in a polypropylene membrane (such housings are available commercially), water vapor can diffuse into the LiCl where it is dried while the hydrophobic membrane (polypropylene) ensures that any potential aqueous salt solution that might be formed will not leak into the air stream. A polypropylene membrane is lightweight, thin and stable to 302°F (150°C). Figure 9 is a conceptual diagram of how to contain the LiCl in the desiccant.

Table 4. Desiccant 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

1.4 Other Applications

* The main application of TDA's cooling technology is for extending the operating time and enhancing the safety of first responders when they are using completely sealed, level A hazmat suits. While this application is the main focus of our R&D efforts, TDA's technology is so versatile that it could also be used for cooling workers in hot, but otherwise non-hazardous situations. For example, construction workers and others working in hot, dry, but non-toxic atmospheres spend many hours wearing helmets, heavy clothing, gloves, knee and elbow pads, and other heat trapping equipment. TDA's cooling technology can also be applied to various garments such as coveralls and vests designed to keep workers comfortable and at less risk for heat stroke. In fact, the cooling system would be much simpler in this application because there is no need to isolate contaminated and clean air streams. Figure 10 is a schematic of how the TDA cooling system would work for a worker wearing a hard hat and chemically resistant coveralls. As with the hazmat suit system, cool air is distributed in the arms, legs and torso of the wearer and most of the cooling is achieved by the evaporation of perspiration. The cooling unit itself would be much less complex than the hazmat suit system and could be simply carried in a belt pack and would weigh about 3 lbs. The system is lighter than the hazmat application (which would weight about 5 lbs) because there would be no desiccant beds and there would only be one heat exchanger. The heaviest item would be water the amount of which would depend on how long cooling is required. The reason for using a heat exchanger is to avoid bathing the wearer in humid air (as would be the case if the system were just a portable swamp

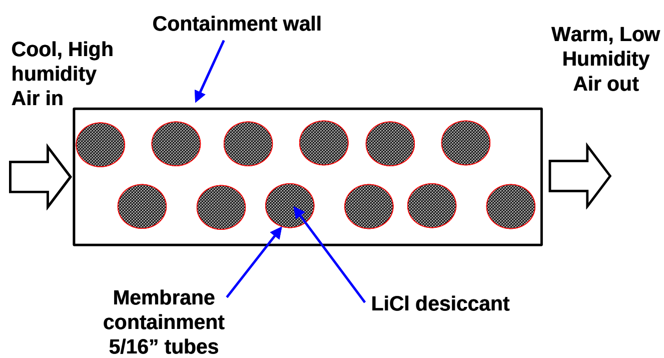

Figure 9. Possible design of a LiCl desiccant bed

cooler). Being bathed in cool and relatively dry air, increases the effectiveness of cooling by the evaporation of perspiration.

* In the case of the not-toxic atmospheres (NTA) unit, there is only one heat exchanger (basically a single pass version of the trim cooler) and a fan to push air through the system. As air is passed through the trim cooler, heat is removed by the evaporation of water at a rate that depends on the air and water flow rates. The heat of vaporization of water is approximately 1000 BTU/lb, and as discussed by Peterson et al. (1998) the rate of heat generation of an active first responder would be about 800 BTU/hr. Thus one pound of water (about one pint) would be required for each hour of cooling. As in the case of the hazmat suit, air ducts would be used to pipe cool air through the first responder’s sleeves, pant legs and neck/helmet area of the cooling garment. These air ducts (most likely made of fabric) are light and weigh only a few ounces, and add little weight to the cooling garment. Flexible lightweight tubing is readily available for this and the hazmat application.

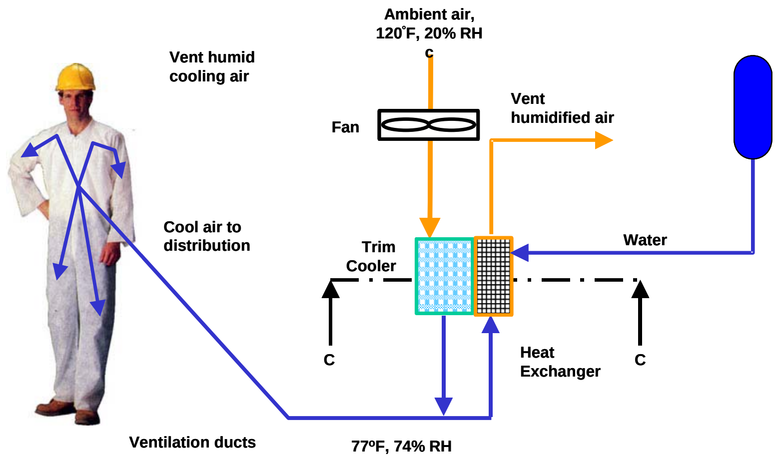

Figure 10. Cooling coveralls for use in not-toxic atmospheres

* Because the cooling garment application is simpler, both the heat exchanger and the overall system are simpler. Water is evaporated into ambient air to cool a stream of ambient air to 77°F. Rechargeable batteries power a circulation fan that delivers about 12.5 ft^3/min (CFM) of air to cool the first responder. An additional 6 CFM of air is required to cool the other stream for a total air flow requirement of 18.5 CFM through the fan. The cool air is delivered under the outer clothes to the head, shoulders, and hip/leg areas in the cooling garment. As in the hazmat application, evaporation of sweat cools the first responder and the unit works best in hot dry environments. The cooling capacity of the system is recharged by refilling the bottle that supplies distilled water to the evaporative heat exchanger and recharging/switching the battery packs. Distilled water is preferred to avoid scale buildup in the heat exchanger, which would eventually lead to plugging. Distilled water is used for both the cooling garment and hazmat systems.

* The NTA system uses the same type of trim cooler as the hazmat application – a lightweight carbon fiber composite heat exchanger. In the NTA case, the trim cooler does all of the work so it will be slightly larger than the trim cooler for the hazmat suit (but smaller than the combination of the main and trim coolers needed for the hazmat suit system). The NTA unit uses a flexible air duct system (just like the hazmat system) but in this case the ductwork can be attached to under various garments Velcro or other convenient attachments (if not part of a specialized cooling garment). The air flows out the end of the sleeves, pant legs, and sides of the helmet.

2. Section 2.

2.1 Scientific Report

* The overall objective of the project is to develop 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 will be designed to keep a user cool for about 60 minutes in a typical hazardous environment. The length of time that our system can operate is mainly governed by the battery life for the fan and the amount of cooling water carried, both of which only add a small amount of weight to the total system. Therefore, incorporating a larger battery and water reservoir would permit operation for more than 60 minutes. Ultimately, the air pack that the first responders carry to supply breathing air (in the hazmat application) will determine the time that can be spent in the suit. The key innovation for our proposed cooling system is a lightweight, high efficiency carbon composite heat exchanger. In order to develop a cooling system, we must first develop the heat exchanger. Therefore, our Phase I work plan was to design, develop and demonstrate this key piece of hardware, the carbon composite trim cooler heat exchanger.

* All of the goals of the Phase I project were successfully met. These goals were to:

- Perform a detailed design of the carbon composite trim cooler
- Fabricate and test the trim cooler.
- Perform a system analysis to determine how the performance of the trim cooler affects the overall cooling system design.

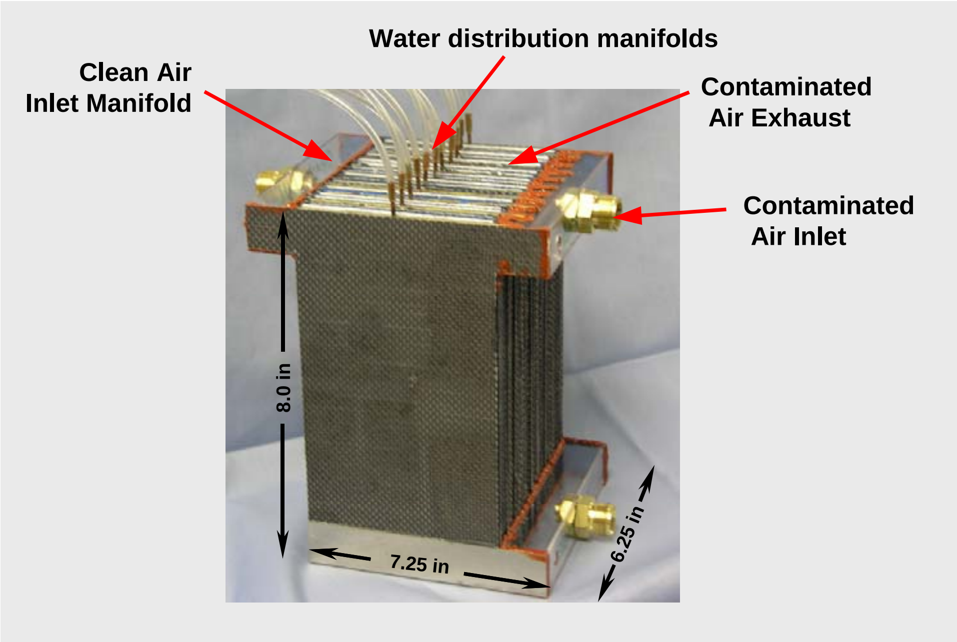

Figure 11. Photograph of *full-scale trim cooler* built and tested in Phase I (8" high x 7.25" wide x 6.25"deep).

* TDA successfully designed, built, tested and demonstrated the effectiveness of a carbon fiber composite trim cooler heat exchanger (Figure 11). The trim cooler successfully passed all tests. The "contaminated air" stream was simply room air heated to temperatures between 95°F and 120°F and humidified to a 64°F dew point. The clean air inlet temperature was varied between 106°F and 140°F. Table 5 summarizes the test results. The dimensions and weight of the trim

cooler were: overall height of 8 inches, depth of 6 ¼ inches, width of 7 ¼ inches, and weight of 2.39 lbs without brass fittings (2.67 lbs with the brass fittings). The sections that follow describe the design, construction and testing of the trim cooler in detail.

2.1.1 Results for Task 1: Design the Heat Exchanger

2.1.1.1 Design Conditions

Table 5. Summary of test results for full scale trim cooler

Clean air IN (°F)	Clean air OUT (°F)	Contaminated air IN (°F)	Contaminated air OUT (°F)	Contaminated air flow rate (SCFH)
130	76	122	88	160
140	75	119	85	160
120	70	120	84	100
106	67	95	75	100

* Because TDA's cooling suit technology uses evaporative cooling of contaminated air to cool the clean air circulated through the hazmat suit, the system is best suited for use in hot, dry climates – one of the best examples in the U.S. being Phoenix, AZ. Figure 12 shows the maximum, minimum and mean temperatures for Phoenix averaged for each months between the years of 1997 through 2000 (ASU 2008). Temperatures as high as 106.6°F have been recorded in the summer.

The right side of Figure 12 shows dew point data for 2007 in Phoenix during their so-called monsoon season. Despite the dry climate, a 64°F dew point is feels quite humid at these temperatures (although it is dry compared with the gulf coast and eastern seaboard). Typically, the highest the dew point gets is during the hottest month of the year (July) is about 65-70°F. Dew point is the temperature to which the air would have to be cooled to obtain the first traces of condensation. Actually, a dew point of 64°F with an ambient temperature near 106°F (77°F wet bulb) is verging on dangerous because it has the same physiological effect as dry 112°F air (Table 6). At heat index values above about 105°F, one is at high risk of heat stroke or heat exhaustion.

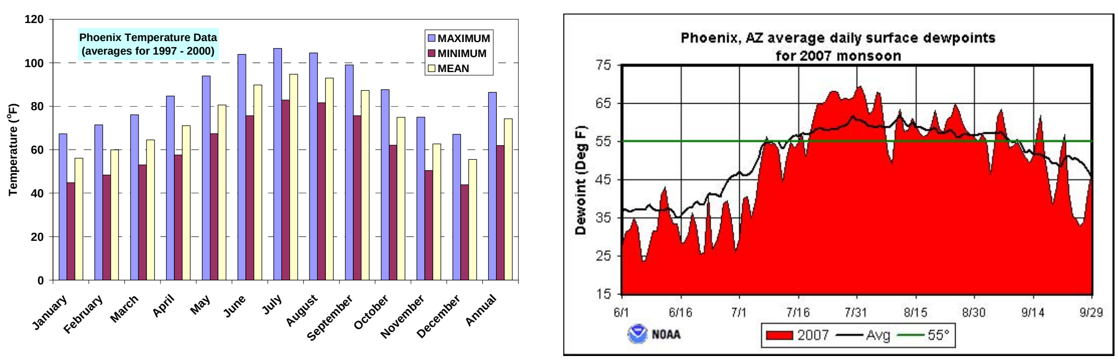

Figure 12. LEFT- High, low and average temperatures in Phoenix, AZ between 1997 and 2000 by month (ASU 2008) and RIGHT - Average dew points during summer months in Phoenix, AZ (NOAA 2008).

* To be conservative, we chose very hot conditions, (a dry bulb air temperature of 120°F) and relatively humid conditions (for Phoenix) of a dew point of 64°F (80°F wet bulb, heat index ~125°F) when designing the trim cooler. The trim cooler is the key part of TDA's innovative cooling system. The trim cooler is used as a final cooling step that removes the heat produced by the second LiCl bed, which dries the air prior to its entering the suit (Figure 8). Water evaporation on the contaminated airside is used to cool the clean air (via. indirect heat transfer)

that goes into the suit. Prior to fabrication, the trim cooler was modeled with the SINDA/FLUINT software package to optimize the design.

* SINDA/FLUINT is a comprehensive, finite-difference, lumped parameter (circuit or network analogy) computer program for modeling simultaneous heat transfer and fluid flow in complex systems. This computer program was chosen because it can simultaneously analyze multiple effects, and can simulate the variation in heat transfer rate down the length of the trim cooler as a function of temperature and humidity of the air stream. Using the SINDA/FLUINT model we predicted the performance of the trim cooler as a function of a wide range of system parameters and designs, and determined the lightest and smallest design that would be able to remove the required heat load. In particular, the length of the flow channels and width of the heat exchanger required to cool the air stream were optimized.

Table 6. Heat index for different dry bulb temperatures and dew points

Dry Bulb (°F)	Dew point (°F)	RH (%)	Heat index (°F)
100	75	45	112
101	74	43	112
102	69	35	110
103	69	34	110
104	68	32	111
105	69	32	113
106	67	29	112
107	66	27	112
108	68	28	116
109	66	26	116

2.1.1.2 SINDA/FLUINT Trim Cooler Model Description

* The air exiting the second LiCl bed and entering the trim cooler is nominally at 140°F due to exothermic absorption of water in LiCl bed. The purpose of the trim cooler is to reduce the temperature of the 140°F dry air to 77°F (15% RH, P_{water} = 3 mmHg). The trim cooler is a heat exchanger that cools the contaminated air by the evaporation of water, thereby cooling the clean air via. indirect heat transfer. As shown in the trim cooler subassembly schematic (Figure 13), the contaminated air makes two passes through the heat exchanger. The first pass pre-cools the contaminated air, and in the second pass it is further cooled (and humidified) by water evaporation. The dimensions of the channels are shown in Figure 14. There are three flow sections in the trim cooler (Figure 8); two for contaminated air and one for clean air. These three heat exchanger channels (clean air, contaminated air and humidified contaminated air) were included in the SINDA FLUINT model.

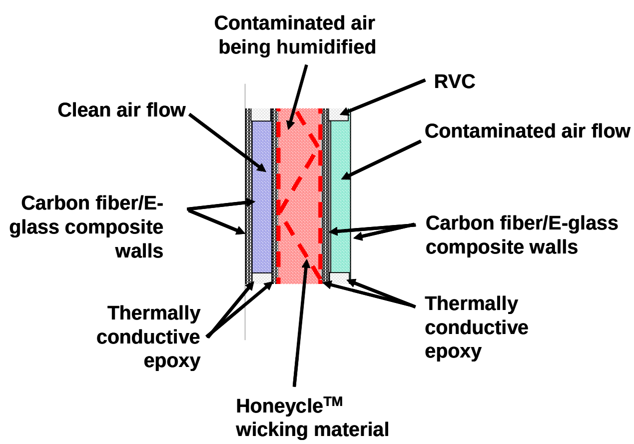

Figure 13. Three flow channels and materials of construction in trim cooler

* The humidified air channel is filled with Honeycle, which is a fibrous, hydrophilic ceramic material that wicks water into the contaminated air channels. In the actual system, water is forced down through Honeycle filled channels using a pump, but for simplicity, a hydrostatic head of 2 ft was used when testing the trim cooler in the lab. The heat transfer surface area of Honeycle was neglected because it has a low thermal conductivity.

* The walls between the channels are made from a composite of carbon fiber and epoxy fiberglass laminate material (C-fiber/E-glass), epoxy glue, and a wall of Honeycle material. This was treated as a single material in the SINDA/FLUINT model with a thermal conductivity perpendicular to flow direction of 0.257 BTU/hr/ft/°F and thermal conductivity parallel to flow direction of 0.1 BTU/hr/ft/°F. Reticulated Vitreous Carbon foam (RVC) spacers were used in the dry air and humidified contaminated air channels for supporting the wall of the channels. The dimensions of the channels are given in Figure 14.

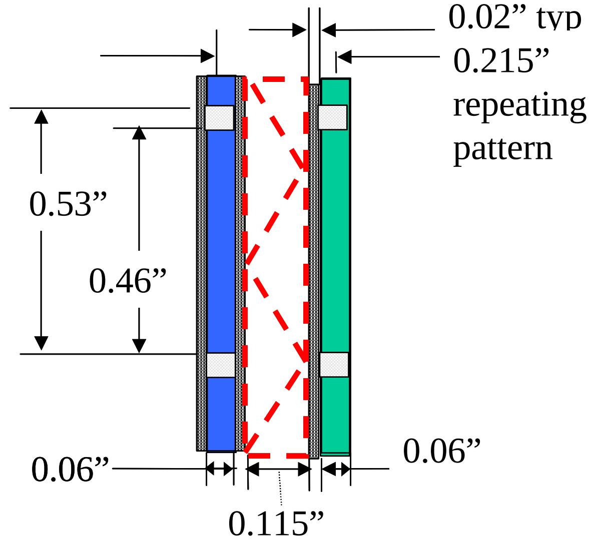

Figure 14. Dimensions of flow channels in trim cooler.

* Our SINDA/FLUINT model predicted the heat transfer between all three channels (clean, contaminated and humidified contaminated). For computational efficiency only a single flow cell repeat unit was modeled. The number of channels required then became one of the variables.
The entire cross-section of the trim cooler (with the flow direction into the page) is shown on the left in Figure 15. There are many repeat units across and down. The flow path down the axial direction is shown on the right side of Figure 15. The contaminated air goes down the heat exchanger in one direction and then splits into two humidifying channels and then flows back up in the opposite direction. The dry and humidified contaminated air streams were entered separately in the model. Water is injected into the humidified side, which immediately lowers the air temperature. The pre-cooled, humidified, contaminated air was assumed to be saturated at a temperature of 68°F at its inlet. The clean air and contaminated air steams were modeled using the thermal and physical properties of dry air in the SINDA/FLUINT fluid database. The humidified, contaminated air was modeled as a "custom" fluid with its heat capacity and thermal conductivity input as an increasing function of temperature.

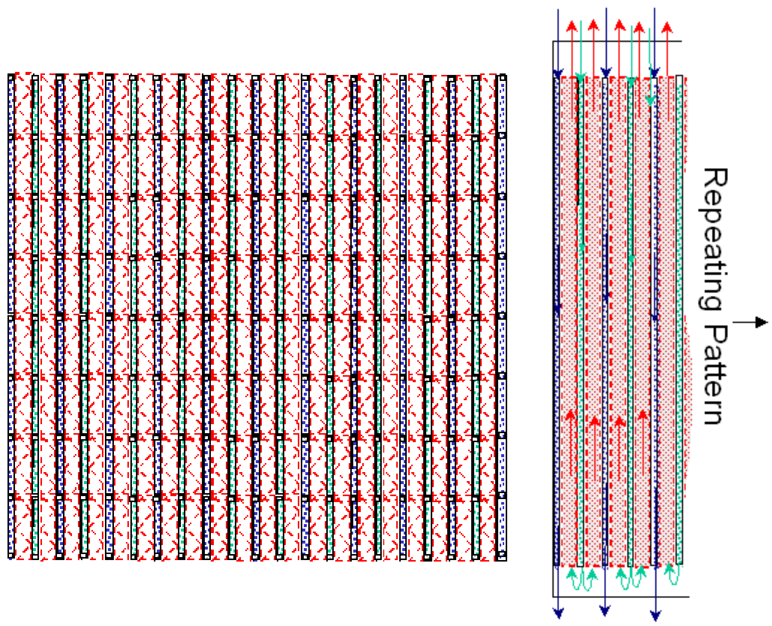

Figure 15. **LEFT** - Cross-section of trim cooler showing repeating flow channels stacked across and down. The flow direction is into the page. **RIGHT** - Cross section of trim cooler down the flow length. Flow direction is across the page.

* The model includes both convective heat transfer from the gases to the walls of the trim cooler, and heat conduction through walls. Radiation heat transfer was neglected because of the low temperatures. A schematic of clean air and humidified air channel showing how it appears in SINDA output visualization program (SINAPS) is shown in Figure 16. The colored output

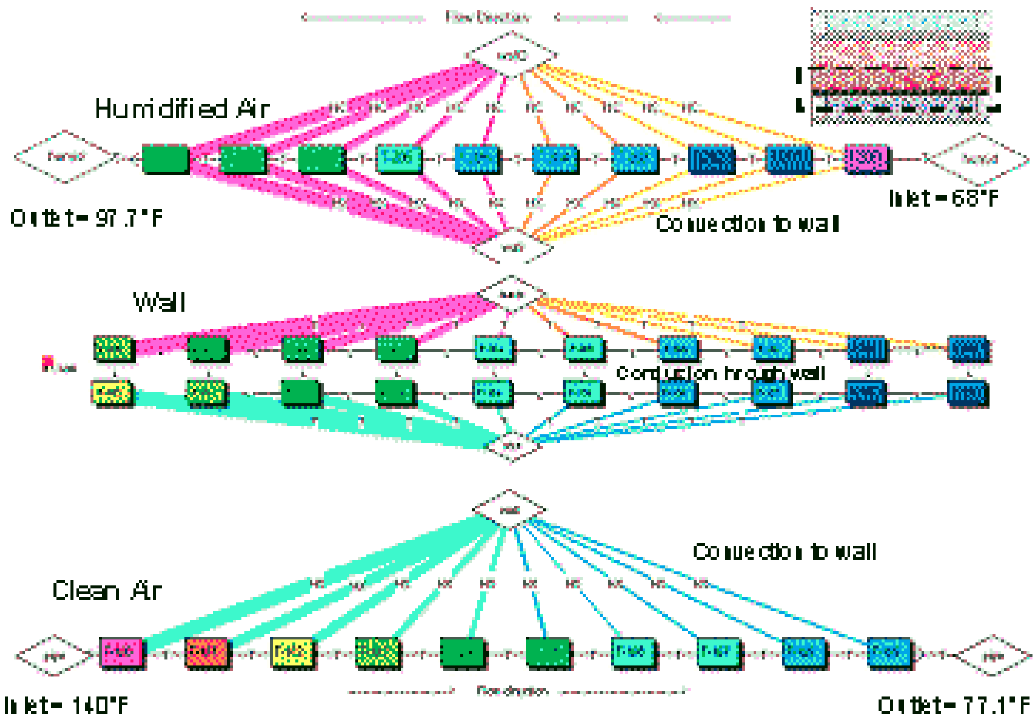

Figure 16. Schematic of SINDA/FLUINT model showing clean air and humidified contaminated air channels in SINAPS viewer.

captures the changes in temperature as function of the path length for the clean and the humidified air channels.

2.1.2 Results for Task 2: Fabricate the Heat Exchanger

* The most critical heat exchanger is the trim cooler because it has the most demanding size, weight and heat transfer surface area requirements. Initially, we planned to use K-1100 carbon fiber because its thermal conductivity is high along the fibers and poor across them. K-1100 is fabricated as very thin sheets (prepreg). The individual prepreg sheets are then glued together with epoxy in a lay-up to obtain the desired thickness. Heating in an autoclave or under vacuum cures the lay-ups. ***Subsequent analysis using SINDA/FLUINT indicated that we could build the trim cooler using the much less expensive and more readily available commercial grade carbon fiber/epoxy-glass (C-fiber/E-glass) laminate that has a*** $k_{//}/k_{\perp}$ ***~10***. While K-1100 fiber has a thermal conductivity along the fibers of about 1,100 W/m/K, it is extremely expensive ($2,964.84 *per lb* with a minimum order of 25 lb or $74,121 for un-formed prepreg material). In contrast, commercial carbon fiber has a $k_{//}/k_{\perp}$ ~10, but costs about $25/ft^2. Since SINDA/FLUINT analysis of the trim cooler indicated we could use the commercial material while still having a reasonable sized trim cooler, we chose to use the less expensive material because this dramatically improves the chances for commercial success by keeping he final cost of the manufactured units reasonable. While we built the flow channels of our Phase I prototype using C-fiber/E-glass lay-ups, we used commercial brass fittings for the inlet and outlet connections because they are inexpensive, readily available, and irrelevant to demonstrating the effectiveness of the carbon composite trim cooler. In a mass production,

however, the fittings, manifolds and other components of the trim cooler would be custom made from plastic or other lightweight, inexpensive materials.

* Figure 17 shows two photographs of the trim cooler during its construction. The white material is the Honeycle, which end on somewhat resembles the cross section of cardboard (i.e. zigzag channels). Honeycle however, is a ceramic/glass fibrous material that is extremely porous (when used in catalyst supports it can be loaded to more than 50 wt% with active material) that is hydrophilic (Figure 18). Each set of channels was built in individual panels that were then assembled by gluing them together using high thermal conductivity epoxy. This method was suitable for the Phase I (and Phase II) efforts, but in commercial production, specific manufacturing techniques will be required. This is one of several areas where our industrial partner, Hamilton Sundstrand Corporation, will be able to provide valuable suggestions. Once complete, the trim cooler is a more or less rectangular prism (Figure 11), to which the air and water manifolds are attached (Figure 19).

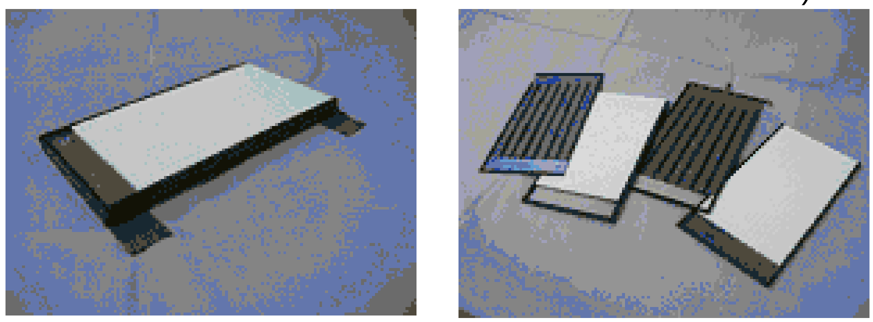

Figure 17. Full scale trim cooler during assembly stage

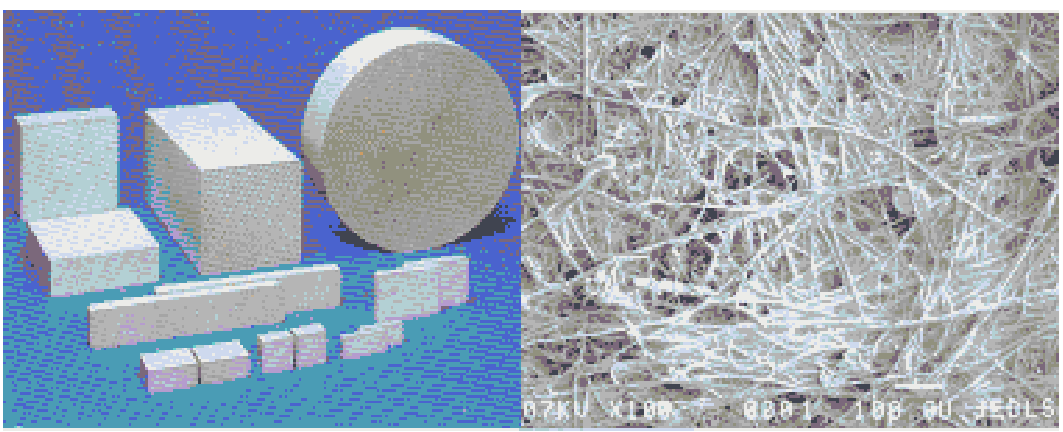

Figure 18. Honeycle® ceramic fiber monoliths (left) and photomicrograph showing fibers (right) www.ncimfg.com/honeycle.htm

2.1.3 Results for Task 3: Test the Full Scale Trim Cooler Heat Exchanger

* Prior to building the full scale trim cooler shown in Figure 11 and Figure 19, we built much smaller unit that contained only a few flow channels to make sure that our SINDA/FLUINT model was correct so that we could confidently use those results to design the full scale unit. Briefly, the subscale unit performed properly and we went ahead with the fabrication and testing of the full sized unit.

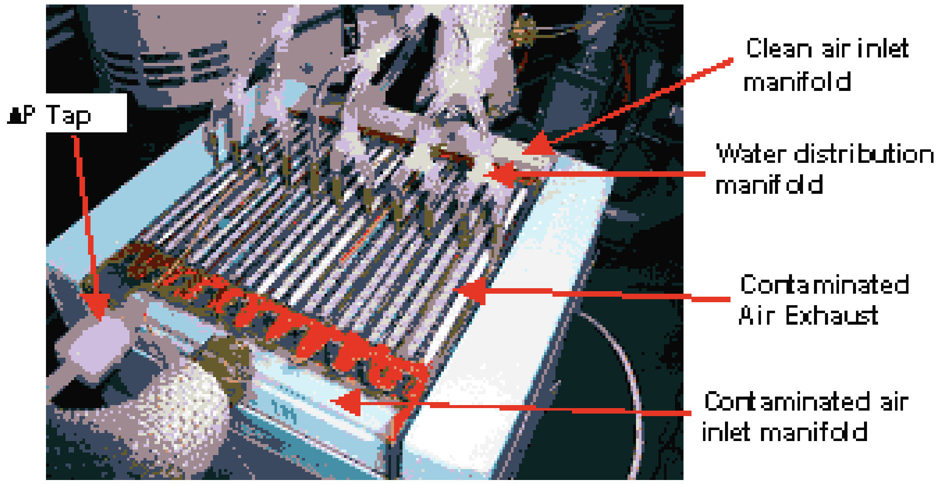

Figure 19. Top of full scale trim cooler in test unit showing details of manifolds

* The experimental apparatus used to test the full scale trim cooler is shown in Figure 20 and Figure 21. The cooler itself is insulated with Styrofoam boards. Air is feed with a blower, preheated and then metered in with a variable area flow meter (rotameter). Distilled water is metered in with a rotameter from a one gallon jug located about 2 ft above the trim cooler assembly. Several thermocouples are in place to measure the inlet and outlet air temperatures and there is a small pressure transducer to measure the pressure drop through the cooler. All of the data are recorded on a PC using Control EG as the process control/data logging program.

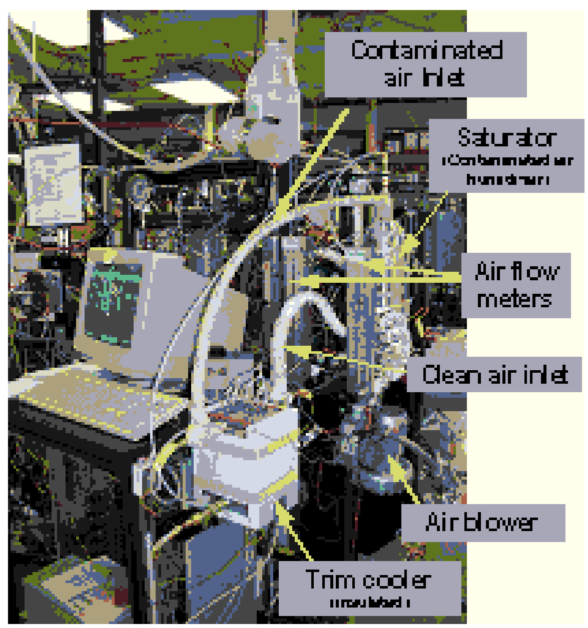

Figure 20. Full scale trim cooler test apparatus.

* Figure 22 shows the results of the trim cooler test. Between time equals zero and 38.73 min, the contaminated air, clean air and water saturators were heating up to their desired operating temperatures. The temperature of the saturator used to humidify the contaminated air stream was maintained at 62°F, so that the contaminated air had a dry bulb temperature of 120°F and a dew point of 62°F. Once the clean air reached the desired operating temperature of 130°F (the approximate temperature of the air stream exiting the second LiCl desiccant bed located just upstream of the trim cooler), the water flow to the Honeycle® wicking material was started. Prior to this time the clean air out temperature was increasing as expected because there was no evaporative cooling occurring. The temperature of the contaminated air immediately fell to about 86°F when the water was introduced due to evaporative cooling. Indirect heat transfer then cooled the clean air, which reached the desired outlet temperature of 76°F about 30 min after the start of the water flow through the wicking material.

*

The reason for the long time lag was discovered to be incomplete wetting of Honeycle® by the water due to some minor plugging in the system. This was discovered at about 70 min, and once resolved (by applying pressure to the water to force it to fill the channels, the clean air outlet temperature quickly fell to 76°F. As part of the Phase II effort, we will investigate methods to improve wetting of the Honeycle® material, which will probably be as simple as treating the Honeycle® with a surfactant (or mixing a surfactant in the distilled water fed to the trim cooler). With the exception of the time lag due to the wetting problem, Figure 22 clearly demonstrates that our trim cooler functioned as designed and that this concept is viable for use in TDA's cooling suit system. The temperature and flow rate results are summarized in Table 5 above.

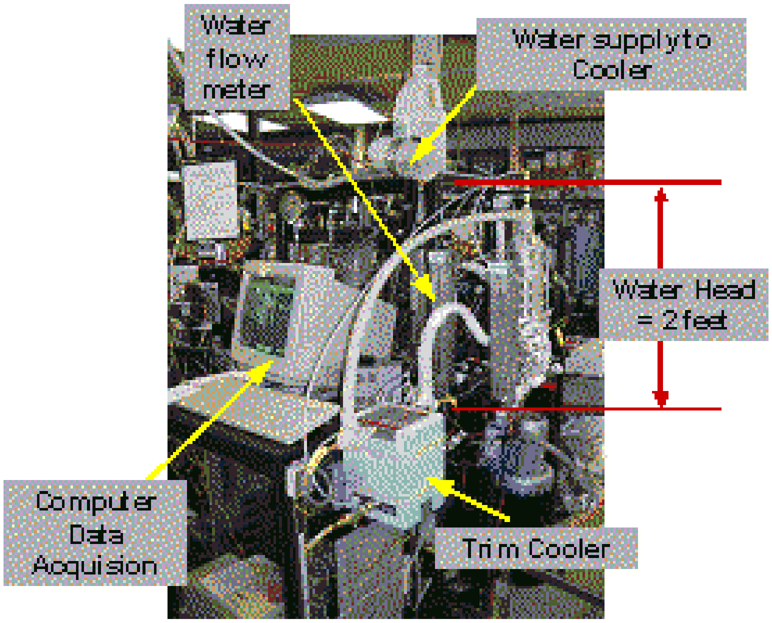

Figure 21. Trim cooler assembled in test apparatus

2.1.4 Results for Task 4: System Analysis

* The goal of the systems analysis was to optimize the trim cooler heat exchanger design and in particular to determine the required length. As discussed in Section 2.1.1, SINDA/FLUINT was used to model the trim cooler. The flow rates through the trim cooler were 34.86 lb/hr of clean air (that flows through the suit) and 24.63 lb/hr of hot, contaminated outside air. The inlet air on the suit side was assumed to be at a temperature of 140°F (the temperature of the air exiting the second LiCl desiccant bed) and the contaminated airside temperature was assumed to be 120°F, with a dew point of 65°F (the Phoenix case as shown in Figure 12). The number of flow cells (size) and length of heat exchanger were optimized to obtain clean air at 77 °F.

* Simulations were run with 80, 120 and 160 clean air channels. For each suit air channel there is one dry contaminated air channel and two humidified air channels (the dry air is split into two channels before it is evaporatively cooled. Figure 16 shows the temperature in the three different channels as a function of the length of the heat exchanger assuming 80 clean suit air channels. Increasing the number of channels decreases the length of heater exchanger. We examined cases for 120 and 160 clean air suit channels with the corresponding increase in the contaminated air side dimensions (Table 7). The savings in the heat exchanger length, however, were not worth increasing the width by 50 to 100%, because making the trim cooler twice as wide, decreased the outlet air temperature by a modest 5°F. With 80 clean suit air channels (80 dry air and 160 humid air) the heat exchanger is approximately 4" x 4". Making the trim cooler 6.0" inches long (and adding 1.0" in manifolds at each end) the outlet temperature of the clean air is predicted to be 77°F (Figure 23).

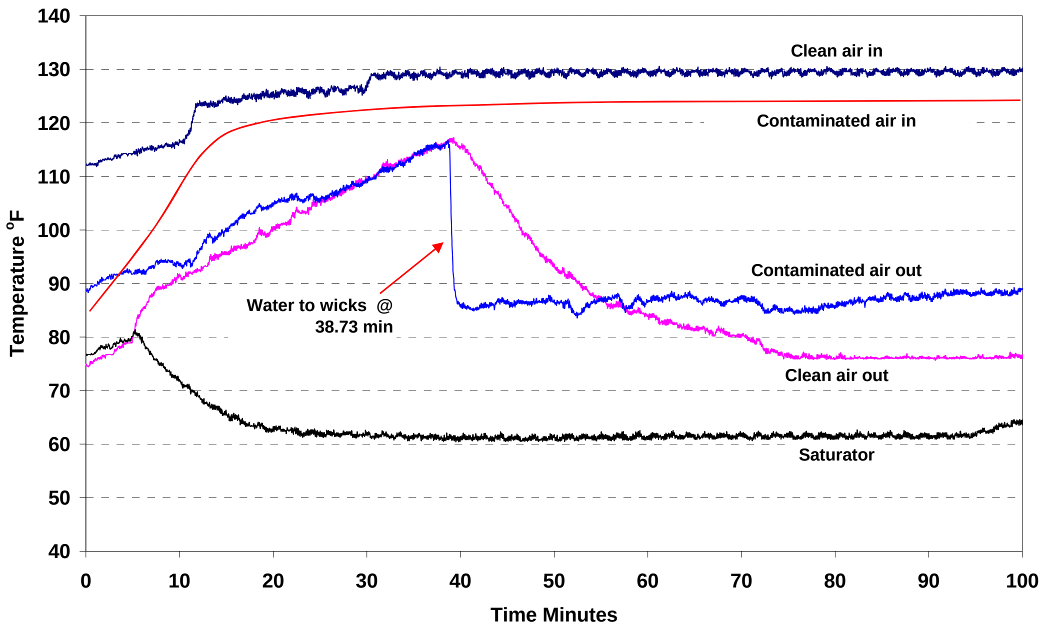

Figure 22. Results of full scale trim cooler test.

* We also considered two designs for the spacers. We examined using Reticulated Vitreous Carbon (RVC) spacers (shown in Figure 13 and Figure 14 as well as aluminum spacers. The RVC spacers have lower thermal conductivity than aluminum and contribute very little to heat transfer between the channels. We evaluated 0.005” thick corrugated aluminum spacers to determine if the would act as fins between the walls of the trim cooler to improved convective heat transfer and improve the efficiency of the unit. On the other hand, the higher thermal conductivity of the aluminum spacers could provides a pathway for axial conduction down the length of the trim cooler, which is undesirable. The SINDA/FLUINT simulations showed that the advantage of the increased heat transfer across the channels with the aluminum spacers was nullified by the increased heat conduction down the length of the trim cooler. Thus, we determined that there was no advantage of using aluminum rather than RVC spacers (Table 7).

* In summary, the SINDA/FLUINT modeling of the trim cooler verified our the basic design and importantly, led us to add 2 inches (from 4” to 6”) to the length of the trim cooler in order to be able to meet the clean air outlet temperature requirement of 77°F. We also found that increasing the other dimensions of the trim cooler would not work as well, and that there was no advantage to using aluminum instead of RVC spacers.

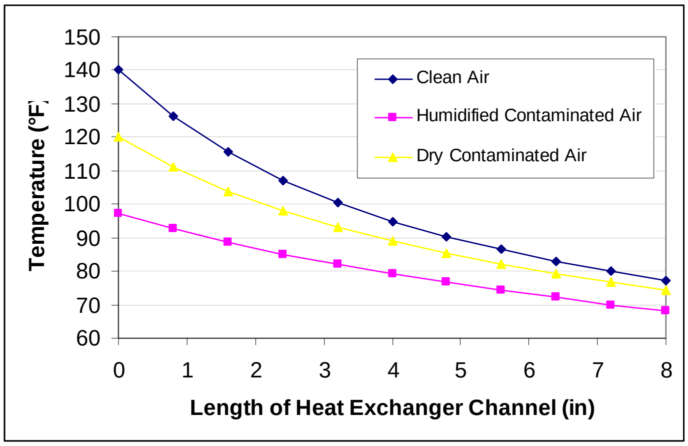

Figure 23. Temperature Profile in heat exchanger as function of length

Finally, we estimated the weight of the entire package for cooling and dehumidification of the air for the hazmat suit application. The only moving parts are the two small fans. The LiCl desiccant beds have a total estimated weight of about 1.4 lb. The two carbon composite heat exchangers would weight about 2.5 lb. The overall unit is expected to weigh about 5-6 lb and would be carried in a fanny or backpack type of arrangement. The heights of the main cooler and trim cooler are about 8 inches, with depths of 6.25 inches and widths of 7.25 inches. The water bottle would be about 1.75" diameter by 7" long (e.g. 500 mL Nalgene Lexan water bottle). The fan is expected to be about 5.8" x 4" x 1" and would run on batteries (e.g. rechargeable lithium type to minimize weight).

2.1.5 Results for Task 5: Reporting

All of the Phase I reporting requirements were met.

2.2 Publications

None

3. Phase I Summary and Conclusions

* The critical component in TDA's cooling suit technology is the C-fiber/E-glass composite trim cooler (the main cooler uses the same technology). Lithium chloride is well established as a desiccant (we will design the LiCl vessels in Phase II). Therefore, the successful demonstration of the trim cooler in Phase I, indicates that the overall cooling suit concept is viable. One of the problems we identified, was wetting of the wicking material (Honeycle®) in the contaminated air channels. A small pump (to force the water into the channels) or possibly treating the Honeycle® to increase its wettability prior to fabricating the heat exchangers may solve this problem. Distilled water is preferred because it prevents water scale buildup; however, water scale deposited from using normal water can be removed using a dilute solution of sulfamic acid (H_2NSO_3H). Having successfully demonstrated the critical component of the system, in Phase II, we plan to focus the effort on the details of the system.

Table 7. SINDA/FLUINT model results

Number channels (clean suit air, humidified suit air, and dry contaminated air)	Outlet Temperature (°F) (7 in length exchanger without manifold)		
	Suit air (°F)	Humidified contaminated air (°F) (runs reverse flow direction)	Dry contaminated air (°F)
80, 160, 80 channels RVC spacers	78.7	97	75.3
120, 240, 80 channels RVC spacers	75.3	95.7	71.6
160, 320, 160 channels RVC spacers	73.9	94.9	70.4
80, 160, 80 channels Aluminum spacers	79.3	96.6	76.4

4. Publications from Phase I Effort

None

5. Patents, Copyrights, Trademarks, Invention Reports

TDA will obtain a patent for the for the cooling suit application and the heat exchanger designs.

6. Current Status of the Technology Developed from this SBIR

* TDA Research has submitted a proposal for continued development of our cooling suit technology under Phase II SBIR funding. TDA has teamed with Hamilton Sundstrand Corporation (HSC) to develop the complete cooling system. Hamilton Sundstrand Corporation (HSC) is a $5.6 billion/yr subsidiary of United Technologies, which is a $43 billion/yr company. Of their many technologies and products, Hamilton Sundstrand's expertise in environmental controls and space life support systems (including space suits) are the most valuable for

successfully developing the hazmat cooling suit technology. Hamilton Sundstrand Corp. is particularly interested in our technology because they have recently entered the hazmat suit market with their SCAPE (Self-Contained Atmospheric Protective Ensemble) suit (Figure 1). Hamilton Sundstrand wrote a letter of support, and provided a task schedule and budget for the Phase II proposal.

7. Other Information

No human or animal subjects were used in this Phase I project. No protocol or software were generated.

8. References

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