ASHRAE Applied Engineering Challenge, 2015

Collapsible, Portable and Conditioned Shelter

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Introduction

The risk of heat illness from high temperatures is one of the most serious challenges to the safety and health of workers according to the Occupational Safety and Health Administration (OSHA) [1]. Every year thousands of workers become ill, and approximately 175 Americans die from heat related illnesses [34]. Heat illnesses vary in severity, with the four most well-known illnesses being heat stroke, heat exhaustion, heat cramps and heat rash. OSHA requires that employers implement prevention methods on the job site to reduce the number of workers who succumb to heat illnesses. Although treatments and prevention methods are widely recognized, there is no existing system in place to treat heat illnesses on a construction site. For the ASHRAE Applied Engineering Challenge, a collapsible, portable, conditioned shelter was designed to assist in the treatment of construction workers who fall victim to heat illnesses. To ensure that the shelter could successfully be utilized in many construction sites, the shelter was designed based on climate data from Atlanta, Georgia and Sacramento, California.

Heat Illnesses: Symptoms and Treatments

The four heat illnesses examined are heat stroke, heat exhaustion, heat cramps and heat rash.

Heat Stroke

Heat stroke is the most severe of the heat illnesses and results in the largest number of deaths. Heat stroke occurs when the victim's body can no longer regulate its internal temperature. This results from the victim's body temperature rising quickly, reaching temperatures of 104°F or higher, which prevents the body from sweating and effectively cooling itself [3]. According to Dr. Suneel Shurman, Co-Founder of ATD Health Network Inc., there is no established treatment for heat stroke and only supportive care can be provided to a victim – even in hospitals [2]. Due to the severity of heat stroke and the medical supervision required to effectively treat a heat stroke victim, the conditioned, portable structure will not successfully treat a heat stroke victim. Instead, the structure will provide an enclosure that will allow the victim to be removed from the heat stroke-inducing environment and allow the victim to be supervised until paramedics arrive. The designed portable, conditioned shelter would provide temporary care by cooling the victim; however it should not be used to treat heat stroke.

Symptoms include red, hot, dry skin, very high body temperature, dizziness, nausea, confusion, strange behavior or unconsciousness, rapid pulse and throbbing headache.

Treatments are provided at a hospital since lowering the body's internal temperature safely requires diligent monitoring and medications provided by medical personnel. Treatments performed include; submersion in an ice bath, evaporative cooling and peritoneal and thoracic lavage for extreme cases [4].

Heat Exhaustion

Heat exhaustion is the most common heat related illness and is caused by loss of water and salt in the body. If left untreated, heat exhaustion can develop into heat stroke [3].

Symptoms include heavy sweating, cramps, headache, nausea or vomiting, tiredness, weakness, dizziness and fainting.

Treatments include resting, lying down, taking a cool shower or bath and drinking juices or sports beverages.

Heat Cramps

Heat cramps include muscle pains and muscle spasms as a result of heavy activity and typically occur in the stomach or legs [3]. Heat cramps are early indicators of heat exhaustion [5].

Symptoms include muscle pains and muscle spasms.

Treatments include resting, sitting, and drinking juices or sports beverages.

Heat Rash

Heat rash is a skin irritation cause by excessive sweating and clogged pores [3]. Heat rash may become uncomfortable to sleep with and becomes more difficult to treat if the rash becomes infected.

Symptoms include red clusters of pimples or small blisters. Heat rash may become uncomfortable to sleep with and becomes complicated if infected.

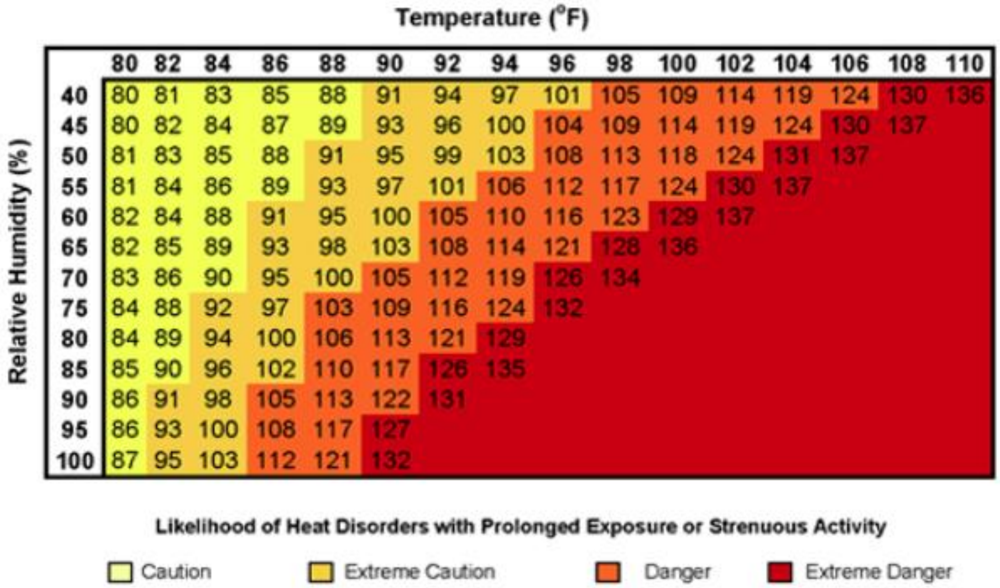
Treatments include placing the victim in a cool environment, providing cooling or applying medication to affected areas.

Prevention

A variety of prevention methods are available for heat illness, however the most common methods are incorporated into OSHA's campaign slogan of "Water, Rest and Shade." According to OSHA, sanitation standards must potable water must be provided to workers and it is recommended that workers drink roughly one quart of water per 8 hour shift [6]. Workers should also be allowed to take breaks in the shade hourly when temperatures reach 85°F and above. 80% of reported heat illnesses occurred within the first four days of employment. Therefore, resting is encouraged when an individual is not acclimated to the weather or work conditions [6]. Knowledge of heat illness symptoms and communication are vital in prevention.

Humans sweat to maintain homeostasis and an internal temperature of approximately 98.6 °F. Typically, sweating lowers one's body temperature due to the evaporation, transferring heat to the air. On dry days, sweat evaporates faster, which reduces body temperature, but when the air has a higher relative humidity or moisture content, sweat cannot evaporate as quickly. Sweat evaporation stops entirely when the relative humidity of the surrounding air reaches about 90%. At these conditions, the body temperature rises without an effective method of cooling, causing an individual to be very susceptible to heat illnesses.

There are two types of heat exposure limits that are often used to regulate workers in unsafe work environments: occupational exposure limits and thermal comfort limits. The occupational exposure limits are implemented to protect construction workers from heat related illnesses. The U.S. National Oceanographic and Atmospheric Administration (NOAA) developed a heat index system which provides alerts based on weather conditions that indicate an increase in the chances for heat illnesses to affect workers. The heat index provides apparent temperature that is affected by air temperature and relative humidity, see Figure 1. As the heat index increases, the environment will feel hotter and there is an increased risk that outdoor workers will experience heat related illnesses. NOAA warns that the heat index values were devised for shady, light wind conditions and that exposure to full sunshine can increase heat index values by up to 15°F [7].



Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution | Extreme Caution | Danger | Extreme Danger

Figure 1. NOAA national weather service heat index [8].

Workers must be cautious when working in apparent outdoor temperatures of less than 91°F since they may experience heat cramps. At these temperatures, basic heat safety must be implemented by employers [35]. At apparent temperatures of 90-105°F, which require extreme caution, workers are susceptible to heat cramps and heat stroke. Starting at extreme caution conditions, precautions to protect workers from heat illnesses must be implemented. Temperatures from 105-130°F are dangerous to workers. If workers are in dangerous conditions for prolonged amounts of time, heat stroke is likely. Extremely dangerous conditions occur at 130°F and above. Heat stroke is imminent for workers in extremely dangerous conditions [35].

Weather Design Conditions

The portable, conditioned shelter was designed to effectively treat heat illnesses for construction workers in both Sacramento, California and Atlanta, Georgia. During the summer months, Sacramento is generally dry and hot, whereas Atlanta is humid and hot. Since an individual's ability to cool itself through sweating is lessened in a hot, humid environment, when compared with a hot, dry environment. Therefore, the difference in climate conditions between Atlanta and Sacramento allows for the design of two unique systems to treat workers with heat exhaustion.

Figure 2 shows the variation in temperature throughout a year in Sacramento, California. In contrast to the weather data throughout a year, the 1% ASHRAE design conditions dictate that the system be designed to function at a 98.2°F dry bulb temperature and a 69.6°F mean coincident wet bulb temperature.

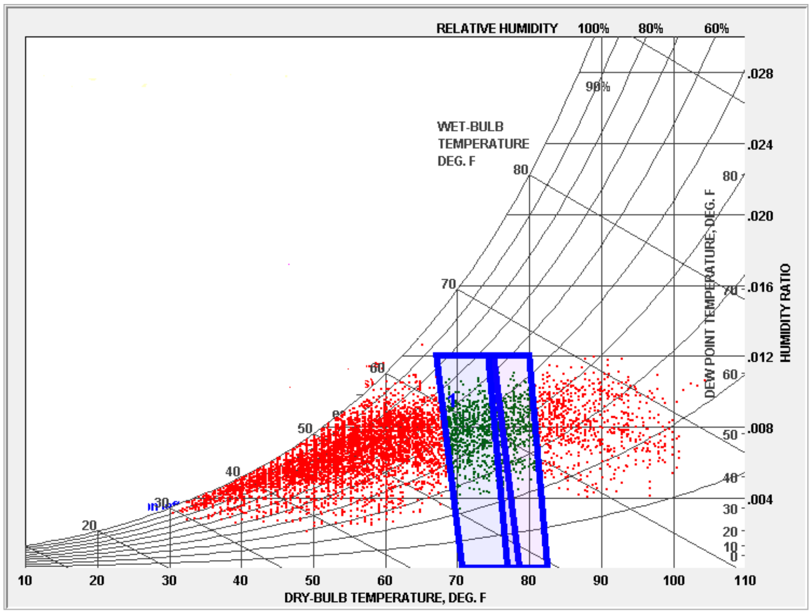


Figure 2. Psychrometric chart demonstrating weather variations for Sacramento, California [36].

Figure 3 shows the variation in temperature throughout a year in Atlanta, Georgia and demonstrates that Atlanta characteristically experiences a higher relative humidity than Sacramento. The 1% ASHRAE design conditions dictate that the system be designed to function at a 91.7°F dry bulb temperature and 73.9°F mean coincident wet bulb temperature. The boxes outlined in blue on the psychrometric chart denote

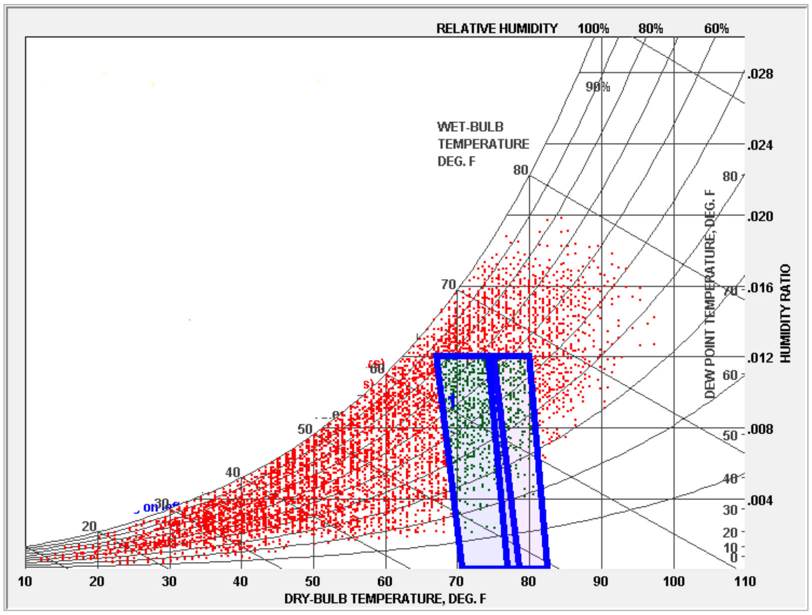


Figure 3. Psychrometric chart demonstrating weather variations for Atlanta, Georgia [36].

ASHRAE Standards

Standard 55

ASHRAE Standard 55, thermal environmental conditions for human occupancy, prescribes occupant characteristics and thermal conditions based on expected worker clothing and activity levels [37]. Information on expected occupant was used in the Transient Analysis on Heat Illness Victim, seen below. ASHRAE Standard 55 dictates summer and winter comfort zones based on clothing thermal resistance and space temperature and humidity. To successfully treat heat illness victims, the portable, conditioned shelter must operate outside of the comfort zones shown in Figures 2 and 3.

Standard 62.2

ASHRAE Standard 62.2, ventilation and acceptable indoor air quality in low-rise residential buildings, dictates that the minimum ventilation air required in a one-bedroom house that is fewer than 500 ft^2 is 30 cfm. This value is the lowest ventilation rate recommended by ASHRAE Standard 62.2 and was used in the energy-model analysis of the system [10].

Standard 90.2

ASHRAE Standard 90.2, energy-efficient design of low-rise residential buildings, recommends thermal resistances for the wall and roof construction and prescribes the need for temperature and ventilation control of the inside environment and applies to residential buildings that are for non-transient residents. The portable, conditioned structure was designed to treat heat illness victims for up to an hour. This function designates the structure as transient; therefore, it does not need to adhere to ASHRAE Standard 90.2 as it is designated for non-transient residences. The portable, conditioned structure meets specific requirements defined in ASHRAE Standard 90.2 by providing temperature and humidity control, insulating the duct to and from the conditioned space, and implementing an air-conditioning unit that adheres to federal guidelines [38].

Existing Products

Although no existing, enclosure-type products were found to treat heat illnesses outside of a hospital; OSHA suggests employers utilize water, shade, fans and misters to help prevent heat illnesses. There are existing portable air-conditioners that are used to cool workers and athletes during activity in hot environments. One example is the Port-A-Cool Hurricane, an evaporative cooler, which has a low operating cost of less than $1 per day and an initial cost of about $3,000 [11]. The Port-A-Cool Hurricane is an evaporative cooler that can deliver up to 14,500 cfm of cool air and includes a 64 gallon water reservoir. Although it efficiently cools a space, the Port-A-Cool Hurricane evaporative cooler was too large to be used for the ASHRAE Applied Engineering Challenge. Another product which employs evaporative cooling is misting tents. Misting tents are often used at work sites and have misters that cool the air around the tent perimeter through evaporation. Similarly to the Port-A-Cool Hurricane, these misting tents only effectively cool in dry climates.

There are many clothing products for construction workers that incorporate conductive or convective cooling. There are Phase Change Material (PCM) and renewable PCM cooling vests that use petroleum byproducts or bio-based phase change materials for cooling. However, these products could not be successfully incorporated into the system because they require 3 to 4 hours for the PCM to freeze before implementation [12]. Products such as HyperKewl are soaked in water and cool via evaporation when worn [13]. Another product worn is the Cool Shirt-- which cools the body through conduction by having a non-flammable freezing agent flow through medical grade capillary tubing that is stitched throughout the garment [14].

Cooling structures utilize passive cooling techniques like extra shading and reflective materials. Surface color has the largest effect on solar absorptivity, and according to Engineering ToolBox, white to light gray surfaces have an absorptivity of approximately 0.25 – 0.40 compared to 0.80-0.90 for dark blue to black [15]. Build it Solar has a list of passive cooling projects that include external misting and reflective surfaces for roofs and walls [16].

To minimize cost and manufacturing time, existing products were utilized in the final design of the portable conditioned shelter. As shown in Figure 5, 6, 7, and 8, various types of existing portable air-conditioners, additional conductive cooling products, inflatable mattresses, and evaporative cooling systems were evaluated using decision matrices.

Design Process and Considerations

Structures and system components were researched and compared using weighted decision matrices to select the optimum components for the portable, conditioned shelter. A list of characteristics were developed for each component of the shelter, and given weighted values based on importance. The datum product in each decision matrix was selected because it had average characteristics when compared to the other products in that category. For each characteristic in the decision matrices, the other products were rated with respect to the datum. For a given characteristic, a product received a rating of +1 if it outperformed the datum product, a 0 if its performance was equal to the datum's performance, or a -1 if it performed worse than the datum. After all characteristic points were multiplied by the weighted values for each characteristic and totaled for each product; the product with the highest total was selected for implementation in the portable, conditioned structure.

The component specific design matrices were used to evaluate: 1) potential structure designs, 2) air-conditioning units, 3) mattresses, 4) additional cooling products, and 5) evaporative cooling systems. Each component was evaluated for cost, weight, ease of assembly, packed dimensions, and thermal resistance to ensure that the ASHRAE Applied Engineering Challenge constraints were satisfied.

Structure

Five unique structure concepts, as shown in Figure 4, were evaluated. To compare the structure concepts, nine characteristics were rated in a decision matrix. Thermal resistance was deemed important because a low cooling load could only be achieved by creating an effective barrier using materials with high thermal resistances between the inside and outside environment. In order to ensure the system complied with the packed-size requirement set by the ASHRAE Applied Engineering Challenge prompt, it was important to compare the packed size of the structure concepts. After rating each individual structure idea using a weighted decision matrix, seen in Table 1, the best components from the top designs were combined into the final structure design.

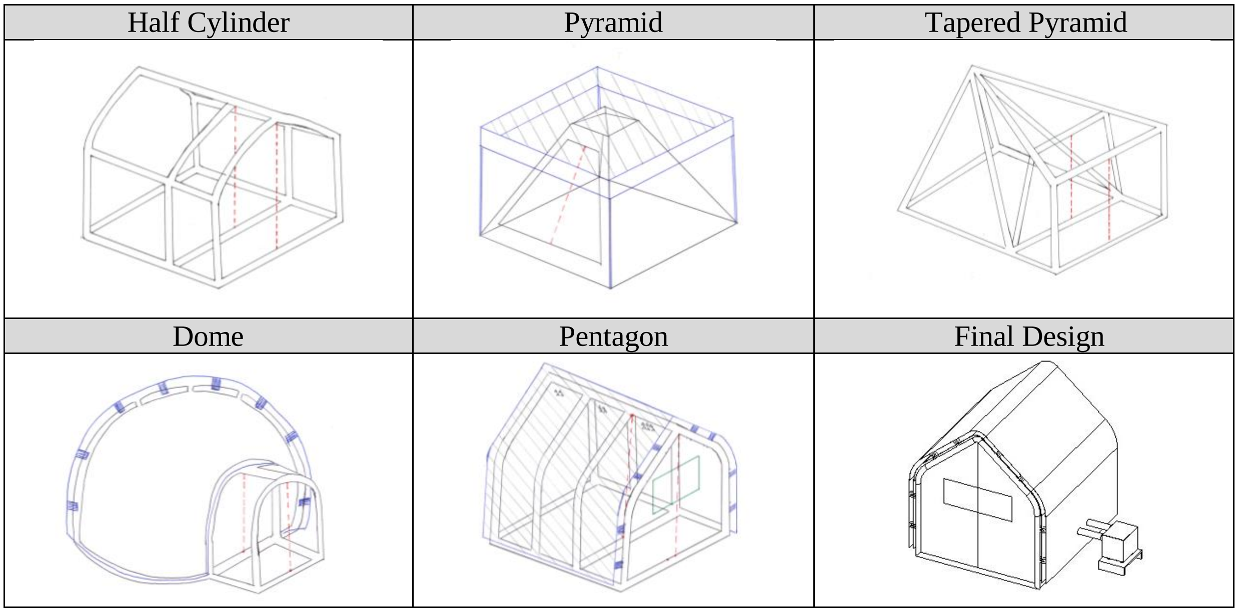


Figure 4. Structure concepts.

Table 1: Structure Decision Matrix

		STRUCTURE DESIGN				
CHARACTERISTIC	Weight	Dome	**DATUM** Half-Cylinder	Tapered Pyramid	Pyramid	Pentagon
Cost	1	-1	0	-1	0	0
Weight	6	-1	0	0	1	0
Ease of Assembly	5	0	0	0	-1	0
Assembly Speed	7	-1	0	1	-1	0
Dimensions	2	1	0	1	-1	1
Packed Dimensions	9	-1	0	-1	0	0
Additional Shading	5	1	0	-1	1	1
Thermal Resistance	9	1	0	0	1	0
TOTAL SCORE	-	-7	0	-6	6	7

Both the pyramid and pentagon received positive scores, which resulted in the final structure design combining characteristics of both these structure concepts. The final structure design features a pentagonal prism with inflatable supports and an extended vestibule. This design was deemed best, relative to the other structure concepts, because it provided a compact shelter-- incorporating the vestibule within the design, a flaw the pyramid design lacked. Additionally, the selected structure's vestibule did not protrude out like the dome vestibule, which allowed for the easier entering or exiting of the structure. The pentagon design also included an additional layer of fabric to allow for shading from the solar radiation. This feature was incorporated into the final structure design since the additional shading will help reduce the cooling loads that the air-conditioning unit must meet. The structure walls of the final design are made of one layer of insulating fabric, two air gaps, and exterior shading material; more details regarding the wall construction can be found in the Building Load Analysis. The insulating fabric selected is modified fabric foam made of 3M Thinsulate. It was developed for extreme outdoor conditions with a thickness of 0.28 inches and an R-value of 1.1 [17]. The inflatable supports allow for fast and easy assembly; inflated with an air compressor. In addition, the design includes a large viewing window in the door between the vestibule and the main room and a small viewing window in the door between the vestibule and the outside, enabling observation of the patient. Similar to the walls, doors and roof, the bottom of the structure is also made of Thinsulate to reduce radiation coming from the ground.

Air-Conditioning Unit

Five different air-conditioning units, shown in Figure 5, were evaluated. The most important characteristics to consider when selecting an air-conditioning unit from the decision matrix, seen in Table 2, were the packed dimensions and weight. Selecting an air-conditioning unit which minimized its packed dimensions and weight ensured the system satisfied the ASHRAE Applied Engineering Challenge weight and size requirements. The cooling load was calculated using TRACE 700 and the air-conditioning unit was sized to meet a load of 8000 Btu/hr. See Building Load Analysis for more information.

EdgeStar Ultra Compact [18]	AMANA AP077R [19]	WindChaser SC7DLX [20]
 Capacity: 8,000 BTU Weight: 56 lbs Cost: $280 Dim: 24.75"x19.25"x13.25"	 Capacity: 7,000 BTU Weight: 61.4 lbs Cost: $286 Dim: 24.25"x18"x13.25"	 Capacity: 7,000 BTU Weight: 47.3 lbs Cost: $650 Dim: 19.75"x11"x22.75"
ClimateRight CR8000 [21]	**Honeywell MF08CESWW [22]**	
 Capacity: 8,000 BTU Weight: 50 lbs Cost: $480 Dim: 17.75"x18.5"x12.5"	 Capacity: 8,000 BTU Weight: 52 lbs Cost: $280 Dim: 14.25"x24.5"x19.5"	

Figure 5. Air-conditioning units.

Table 2: Air-conditioning Unit Decision Matrix

		PRODUCT				
CHARACTERISTIC	Weight	EdgeStar Ultra Compact	AMANA AP077R	WindChaser SC7DLX	**DATUM** ClimateRight CR8000	Honeywell MF08CESWW
Cooling Capacity	5	1	-1	-1	0	1
Weight	7	-1	-1	1	0	-1
Cost	1	0	1	1	0	1
Electrical Connection	4	0	0	0	0	0
Dimensions	7	-1	-1	-1	0	-1
Efficiency	3	0	0	0	0	0
Minimum Supply Air Temperature	8	0	0	0	0	0
Maintenance	2	0	0	0	0	0
Ducted Inlet	6	-1	-1	-1	0	-1
TOTAL SCORE	-	-15	-24	-10	0	-14

The ClimateRight CR8000 was the datum in the decision matrix, but received the highest score of the five air-conditioning units. Though the WindChaser SC7DLX weighed less and cost less, the ClimateRight CR8000 was ultimately chosen for its smaller packing dimensions and its inclusion of supply and return ducts. Implementation of other air-conditioning units would require the unit be placed inside the conditioned space, whereas the ClimateRight CR8000 can be placed outside the structure to optimize internal space and provide air using insulated supply and return ducts. It was determined that all the air-conditioning units had approximately the same minimum supply air temperature, required the same amount of maintenance and could be powered by the provided electric spider boxes.

The ClimateRight CR8000 requires modification to ensure minimum ventilation air requirements are met for the structure. The structure was assumed to act similarly to residential buildings, per ASHRAE Standard 62.2. The minimum ventilation required for the shelter was determined to be 30 cfm. In order to meet the correct ventilation requirements, the return duct will contain openings to allow additional outside air to enter the return air duct. This mixed air will be cooled in the air-conditioning unit before entering the structure.

Mattress

Research showed that individuals suffering from heat illness need to be able to sit and lay down for treatment. As shown in Figure 6, inflatable mattresses were to ensure the design complied with the ten-minute set up time and weight limit requirement as specified by the ASHRAE Applied Engineering Challenge. Additionally, packed dimensions and weight were considered the most important characteristics and received the highest weight in the decision matrix in Table 3.

EZ Bed Inflatable [23]	AeroBed [24]	Serta Airbed [25]
 Inflation Time: 3 minute Weight: 46 lbs Cost: $250 Dim: 78"x39"x24"	 Inflation Time: 1 minute Weight: 8.8 lbs Cost: $60 Dim: 74"x39"x8"	 Inflation Time: 3 minutes Weight: 9.5 lbs Cost: $70 Dim: 74"x19"x18"

Figure 6. Air mattress products.

Table 3: Air Mattress Decision Matrix

		PRODUCT		
CHARACTERISTIC	Weight	EZ Bed Inflatable	**DATUM** AeroBed	Serta Airbed
Collapsed Size	5	-1	0	0
Weight	4	-1	0	0
Inflated Size/Comfort	3	1	0	1
Ease of Assembly	2	-1	0	0
Cost	1	-1	0	-1
TOTAL SCORE	-	-9	0	2

The Serta Airbed was selected as the best mattress to place inside the portable, conditioned structure because of its inflated size relative to its weight. When inflated, the Serta Airbed mattress height is eighteen inches from the ground, which allows an individual to both sit upright and lie down comfortably. Although the EZ Bed Inflatable provided an even taller surface for the victim to rest on, the bed was excessively large and weighed a lot more than both the Aerobed and Serta Airbed, making it undesirable due to the size and weight constraints of the ASHRAE Applied Engineering Challenge. The AeroBed reached an inflated height of nine inches from the ground, making it difficult for a construction worker to sit upright comfortably on the mattress. Furthermore, the Serta Airbed includes its own air compressor which will also be used to inflate the structure.

Additional Cooling

In extreme cases of heat illness, it is recommended that victims are exposed to a cool environment and additional cooling to ensure that their core temperature decreases. Recommended treatments for a victim experiencing severe cases of heat illness included submersion of the victim in a water or ice bath. Due to the constraints on water usage and thermal comfort analysis seen in Transient Analysis on Heat Illness Victim below, submersing the victim in a water bath, a form of convection cooling, was not feasible. As shown in Figure 7, cooling mattress pads were evaluated because of the mattress pads efficiently cooled via conduction and had small packed sizes. The collapsed dimensions of the additional cooling methods were most heavily weighted because the system needed to satisfy the packed-size requirements set by the ASHRAE Applied Engineering Challenge. In addition, air and water temperatures of the chosen system needed to have adjustable conductive temperature to comply with Standard 55. Three different cooling products were analyzed in the decision matrix: the ChiliPad, BedJet and Cooling Mattress Pad. The ChiliPad circulates cooled water through silicon coils embedded in a mesh pad. The BedJet provides cool air under a comforter. The Cooling Mattress Pad provides cooling through thin coils of Phase Changing Material embedded in a mesh pad.

ChiliPad [26]	BedJet [27]	Cooling Mattress Pad [28]
 Weight: 12.8 lbs Cost: $500 Pad Dim: 30"x75"x0.5" Unit Dim: 24"x12.5"x12"	 Weight: 12.8 lbs Cost: $400 Unit Dim: 11"x10"x8"	 Weight: 4 lbs Cost: $90 Pad Dim: 39"x75"x0.75"

Figure 7. Additional cooling products.

Table 4: Additional Cooling Decision Matrix

		PRODUCTS		
CHARACTERISTICS	Weight	ChiliPad	BedJet	**DATUM** Cooling Mattress
Cooling Capacity	5	1	1	0
Dimensions	3	0	-1	0
Weight	7	-1	-1	0
Cost	1	-1	-1	0
Comfort	2	1	-1	0
Collapsed Dimensions	10	-1	-1	0
Circulating Fluid	10	1	1	0
Built-in Pump	8	1	1	0
Conduction	6	1	1	0
TOTAL SCORE	-	13	6	0

Based on the results presented in Table 4, the ChiliPad was selected as the additional conductive cooling product because it provided the highest cooling capacity. Both the ChiliPad and BedJet circulate some form of fluid through the mattress while the Cooling Mattress does not. Unlike the BedJet, which only blows air under mattress pad, the ChiliPad circulates cool water through the mattress pad. The fluid circulating through the ChiliPad is cooled using its own cooling unit and built-in pump, thus providing a larger cooling capacity than the BedJet. The water flowing through the coils in the ChiliPad can reach temperatures as low as 45°F and, unlike the other cooling products, the ChiliPad operation can be monitored via remote control. Calculations verified that the ChiliPad would provide the most effective cooling of a victim through conduction, seen in Transient Analysis of on Heat Illness Victim below.

Evaporative Cooling System

A separate evaporative cooling system was selected for the structure to be used in Sacramento, California. Since Sacramento is characterized as dry and hot, the implementation of evaporative cooling with the air-conditioning unit will reduce the energy consumed by the air-conditioning unit to meet the structure load. Additionally, because the Sacramento climate characteristically has a low relative humidity, the outside air temperature can be lowered significantly with evaporative cooling. The evaporative cooling system would be used to precool the ventilation air used by the air-conditioning unit. Important characteristics considered for evaporative cooling products included the dimensions, cooling capacity and water tank capacity. As shown in Figure 8, four evaporative cooling products were examined: The Big Fogg Handimist, the Misty Mate Cool Camper 6, the Misty Mate 16 Classic Personal Mister and the Humidibreeze. The Big Fogg Handimist uses an outdoor, rated fan to provide a fine mist of water and high speed air movement. The Misty Mate Cool Camper 6 uses pressurized water to deliver a fine mist of water. The Misty Mate 16 Classic Personal Mister, additionally uses pressurized water to deliver a fine mist of water, however, at smaller doses in comparison of the Misty Mate Cool Camper 6. The Humidbreeze provides a fine mist of water and high speed air movement with the use of a large fan.

Big Fogg Handimist [30]	Misty Mate Cool Camper 6 [31]	Misty Mate 16 Classic Personal Mister [32]	Humidibreeze [33]
 Weight: 47 lbs Cost: $550 Dim: 24"x19"x46" Tank Capacity: 14 gal.	 Weight: 4 lbs Cost: $70 Dim: 7.25"x21"x7.25" Tank Capacity: 2 gal.	 Weight: 2 lbs Cost: $15 Dim: 3.6"x8"x11.75" Tank Capacity: 16 oz.	 Weight: 20 lbs Cost: $169 Dim: 11"x23.6"x16.5" Tank Capacity: 1 gal.

Figure 8. Evaporative cooling products.

Table 5: Evaporative Cooling Decision Matrix

		PRODUCTS			
CHARACTERISTICS	Weight	Big Fogg Handimist	**DATUM** Misty Mate Cool Camper 6	Misty Mate 16 Classic Personal Mister	Humidibreeze
Cooling Capacity	6	1	0	-1	1
Weight	4	0	0	1	-1
Cost	1	0	0	1	-1
Electrical Connection	2	0	0	0	0
Dimensions	7	0	0	1	-1
Optimum Tank Capacity	5	-1	0	1	0
Maintenance	3	0	0	0	0
TOTAL SCORE	-	-1	0	11	-6

Based on the results presented in Table 5, the Misty Mate 16 Classic Personal Mister was chosen as the evaporative cooling system because of its optimum water capacity and small dimensions. Most of the evaporative cooling products were too large, and were designed for misting an area much larger than required for the air-conditioning unit. The Building Load Analysis showed that the other evaporative cooling products over-saturated the incoming air in the air-conditioning unit. The Misty Mate 16 Classic Personal Mister has a sixteen ounce water reservoir and mists intermittently for up to three hours. The three-foot mister tubing will attach to the air-conditioner duct near the air intake.

Final Design

The final portable condition shelter design, seen in Figure 9, consists of a pentagonal structure with the Serta Airbed and ChiliPad inside, and the ClimateRight CR8000 and Misty Mate 16 Classic Personal Mister placed outside. The tent walls, doors and roof are comprised of a layer of Thinsulate, and air gap, a layer of nylon, a second air gap and an additional layer of nylon shading material. The observation window is clear plastic called Precision Urethane. The inner material of the inflatable tubes is Thermoplastic Polyurethane, a material typically used for inflatable tubing in larger tents; the outer material of the tubes is the nylon fabric used for shading the structure. The air compressor included with the Serta Airbed will also be able to inflate the tubing. The fitting for the air compressor is near the supply and return duct inlets into the tent. In addition to the practicality of the design, the portable, conditioned shelter is also aesthetically pleasing to the environment. The pentagonal structure resembles a common house, and neutral colors allow it to integrate well with any construction environment. The bill of materials is listed in Table 6.

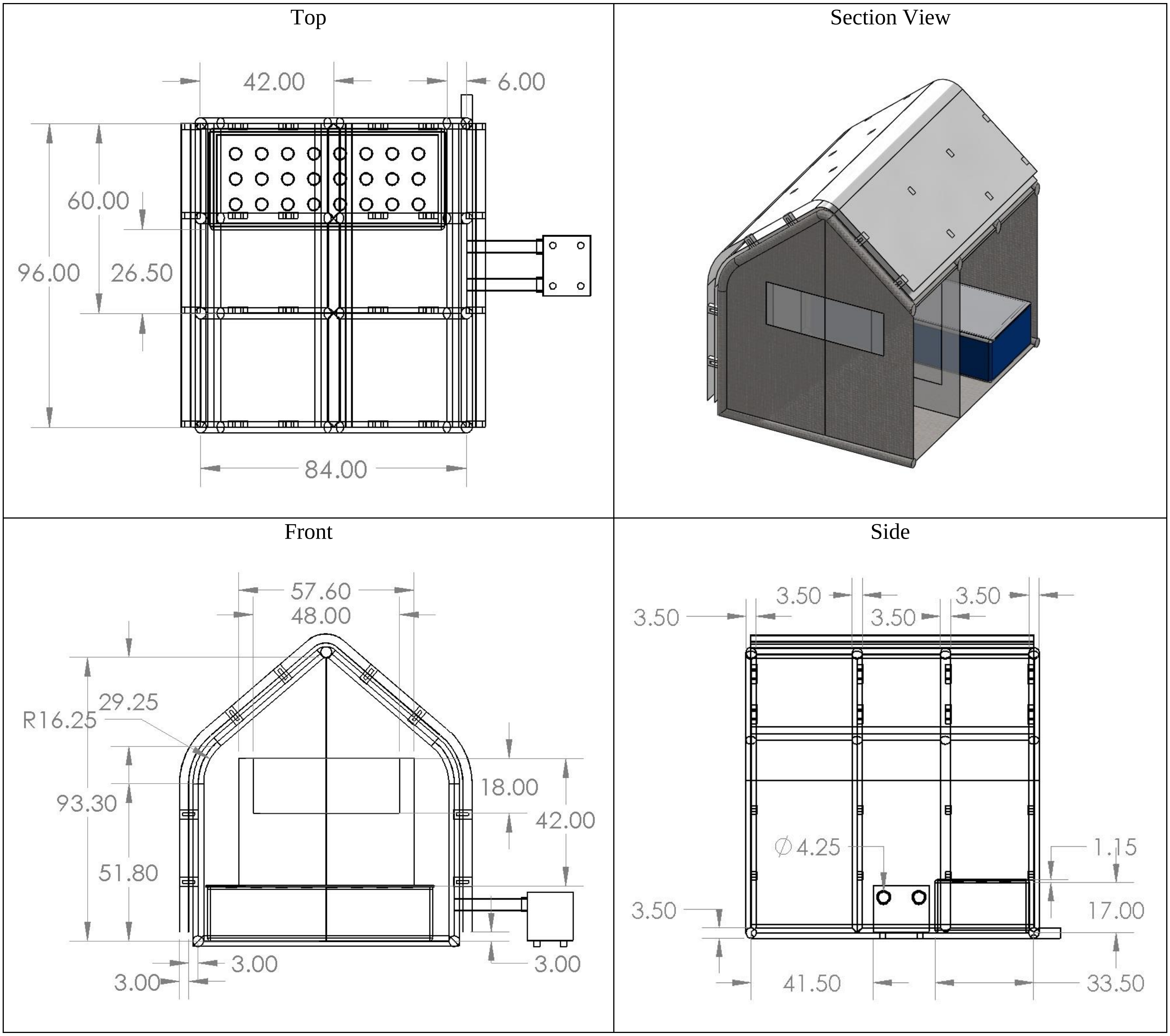


Figure 9. Final portable, conditioned shelter design.

Table 6: Bill of Materials

Part	Description	Part Number	Vendor	Quantity	Price
Inflatable Tent	Tent Insulation, 3M Thinsulate	CS100	The Rain Shed Inc.	85 yards	$510
	Shading, White 70 Denier FR/UV Nylon Ripstop Fabric	RIPDWHI	Online Fabric Store	100 yards	$665
	Window & Vestibule, Precision Urethane 0.031"	FCS24080-60	PSI Urethanes	1	$780
	Tube Interior Material, Nationwide Plastics, Inc. Thermoplastic Polyurethane	7701780075D	ePlastics	1	$1,800
	Aluminum Extra-Long Heavy Duty Separating Zipper	ZIPAL10-100 -0580-Y-108IN	Zipper Shipper	2	$24
Air Conditioning Unit	ClimateRight Portable Air-Conditioning Unit	CR 8000	Endless Horizon Expedition Outfitters	1	$499
Inflatable Bed	Serta 18" Twin External AC Pump Airbed	-	Target	1	$60
Conductive Cooling	ChiliPad Cube 1.1 Twin - Single Zone	1.1	ChiliTechnology	1	$499
Ground Tarp	Sigman Heavy Duty Silver Tarp, 8' x 10'	SPT008010	Home Depot	1	$9
Evaporative Cooler	Misty Mate 16 Classic Personal Mister	-	Misty Mate	1	$33
				Total	$4,879

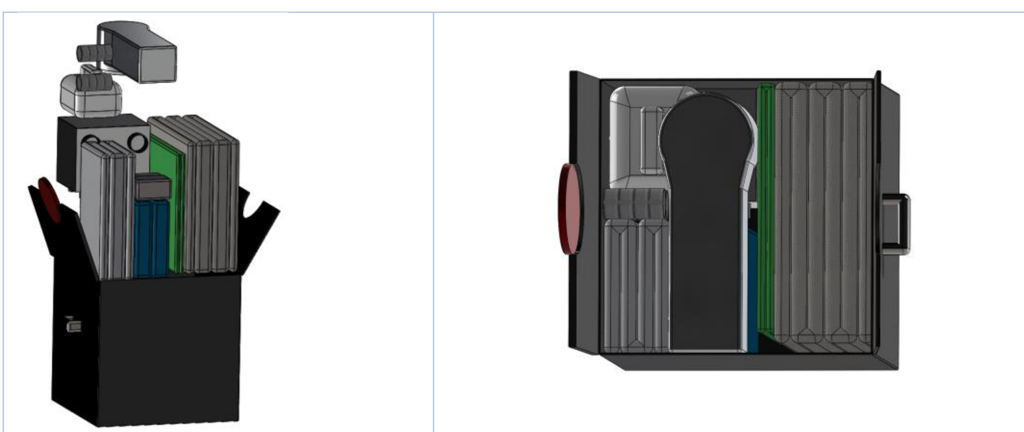
Portability

Table 7 contains tabulated data detailing the packed volume and weight of the separate components of the system. All together, the components of the portable conditioned shelter weighted 147 lbs and fit in a compacted volume of 17 ft^3. This is below the required weight and volume requirements of 150 lbs and 27 ft^3, respectively. Figure 10 shows the packed size and dimensions of the portable conditioned shelter.

Table 7: Weight and Volume Summary

Part	Description	Volume Required (ft^3)	Weight (lbs)
Inflatable Tent	Tent Insulation, Thinsulate	7.19	12.8
	Shading, White 70 Denier FR/UV Nylon Ripstop Fabric	1.66	8.4
	Window & Vestibule, Precision Urethane 0.031"	0.06	5
	Tube Interior Material, Thermoplastic Polyurethane	0.57	43
	Aluminum Extra-Long Heavy Duty Separating Zipper	0.006	0.5
Air-conditioning Unit	Portable Air-Conditioning Unit	2.38	50
Inflatable Bed	18" Twin External AC Pump Airbed	0.61	9.5
Conductive Cooling	ChiliPad Cube 1.1 Twin - Single Zone	2.08	12.8
Ground Tarp	Heavy Duty Silver Tarp, 8' x 10'	1.67	3.3
Evaporative Cooler	Mister	0.64	2
	Total	16.9	147

Figure 10. Packed portable condition shelter.



Sustainability

The portable conditioned shelter includes reusable components to minimize its environmental impact. Insulation surrounding the portable conditioned shelter further decreases the energy consumption of the air-conditioning unit. In addition, the use of the evaporative sprayer in a hot-dry climate reduces the load on the air-conditioning unit, further decreasing the energy consumption of the system.

Analysis

EES (Engineering Equation Solver) and TRACE 700 models were created to model the heat flow through the individual and structure.

Transient Analysis on Heat Illness Victim

Heat transfer from a victim experiencing heat illness was modeled with EES using equations found in 2013 ASHRAE Fundamentals Handbook – primarily chapter 9, Thermal Design – and occupant characteristics found in ASHRAE Standard 55, such as garment insulation values [29]. The two-node model was used to solve differential equations with respect to skin (T_{sk}) and core (T_{cr}) temperature of an individual. The model assumes the body is composed of core and skin layer each assumed to be isothermal. The resulting differential equations are:

$$\frac{dt_{cr}}{d\theta} = \frac{(M - W - q_{res} - \left(K + SkBF * C_{pbl}\right) * (T_{cr} - T_{sk}))}{m_{cr} * C_{cr}} \qquad \text{(Eqn. 1)}$$

$$\frac{dt_{sk}}{d\theta} = \frac{(- q_{dry} - q_{evap} - q_{cond} - q_{conv} + \left(K + SkBF * C_{pbl}\right) * (T_{cr} - T_{sk}))}{m_{sk} * C_{sk}} \qquad \text{(Eqn. 2)}$$

Descriptions of each variable may be found in the Glossary in the Appendix. The model was run at two different initial skin and core temperatures: 100°F and 104°F for skin and core temperature respectfully to represent an individual experiencing a heat stroke; and 95°F and 99°F for skin and core temperature respectively to represent an individual experiencing a heat exhaustion. Additionally, each case was simulated three times to represent the individual being air cooled, being placed in a water bath, and air cooled with the addition of a conductive cooling element. Figures 8 and 9 graphically demonstrate the results of each trial simulation.

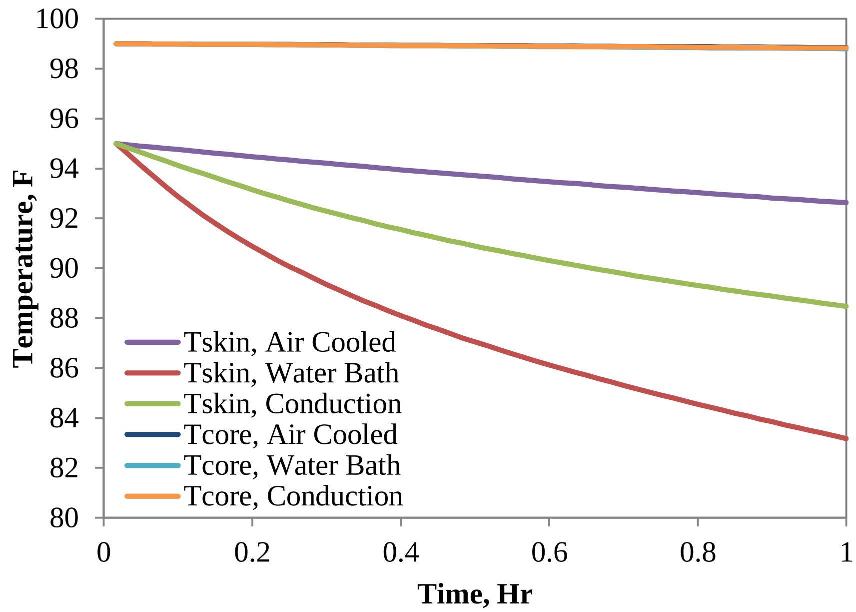


Figure 11. Skin and core temperature as a function of time for an individual experiencing heat exhaustion.

Figure 11 shows the results for the skin and core temperature as a function of time for an individual experiencing heat exhaustion with the addition of three cooling methods. All three methods successfully cooled the person down to a normal core temperature, showing almost no difference among the different trials. When an individual is placed in a water bath, however, their skin temperature drops below 86°F. When the skin temperature of an individual decreases below 86°F, the individual experiences shivering causing their body to heat up [29]. Additionally, the individual feels thermal discomfort from the rapid temperature change [3].

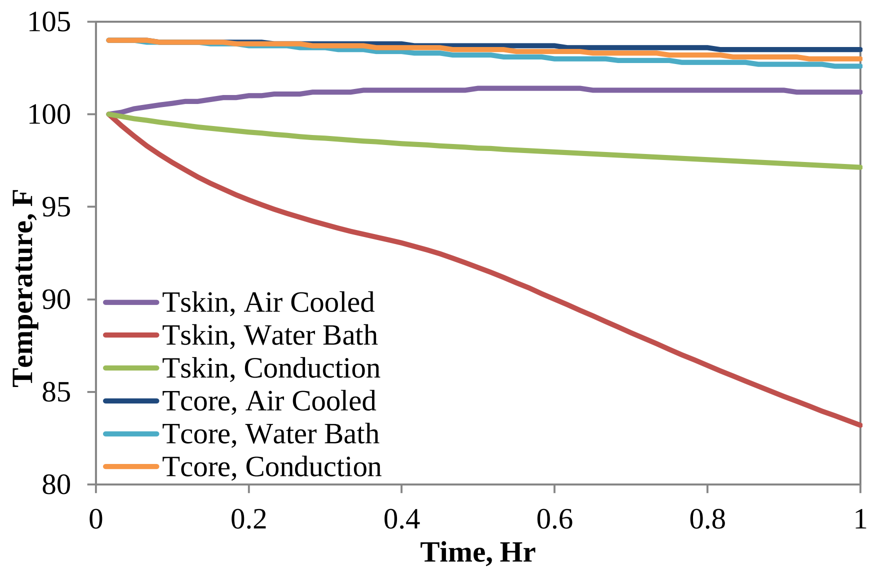


Figure 12. Skin and core temperature as a function of time for an individual experiencing heat stroke.

Figure 12 shows the results for the skin and core temperature as a function of time for an individual experiencing heat stroke using three different cooling treatments. During a heat stroke an individual can no longer regulate his or her temperature, which can be demonstrated by a consistent rise in skin temperature when an individual is placed in an air-conditioned room. For this reason, additional cooling is needed in order to temporarily cool the person down prior to taking them to the hospital. Again, placing an individual in a water bath causes their temperature to change too drastically. Additional conduction cooling was proven to be a successful cooling method, while not resulting in any thermal discomfort for the victim.

Building Load Analysis

The structure was modeled in TRACE 700 to determine the peak cooling loads of the system. The results of the TRACE 700 model allowed for the selection of an air-conditioning unit for the system. The TRACE 700 model detailed the occupant, ventilation and space loads on the structure. The occupant loads were gathered from the victim analysis since a construction worker experiencing heat exhaustion produces higher sensible and latent heat than an employee working at an office. The sensible occupant load is 514 Btu/hr and the latent occupant load is 298 Btu/hr. The ventilation rate was specified by ASHRAE Standard 62.2 as 30 cfm. The space loads were calculated using the thermal resistances of materials comprising the structure walls and the structure dimensions.

The structure was modeled as a two-room building with the roof and building sides made of the same material. The door between the vestibule and the conditioned room was modeled as a partition. The thermal resistances of the wall material are included in Table 8. The construction of the wall material includes a layer of Thinsulate, a 3” air gap, a layer of nylon, a secondary 3” air gap and layer of nylon to allow for shading from the solar radiation on the structure. Figure 13 depicts a section view of the wall construction.

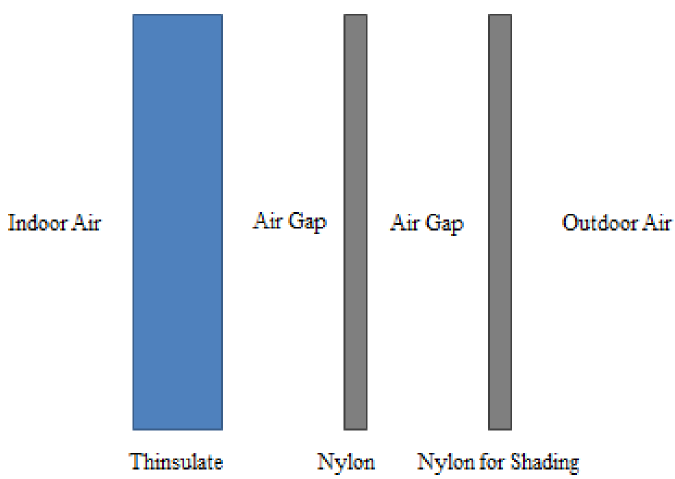


Figure 13. Section view detailing construction of wall, roof, door material.

Outside and inside film resistances, as well as thermal resistances for the air gaps were determined from chapter 26 of the 2013 ASHRAE Fundamentals Handbook. The thermal resistance of the Thinsulate was obtained from the manufacturer’s specifications.

Table 8: Summary of Thermal Resistances of Structure [9]

Resistance	**hr ft^2 F/Btu**
Outdoor Film Resistance	0.25
Air Gap 1 (with Nylon on either side)	0.77
Air Gap 2 (with Nylon and Insulation on either side)	0.77
Insulated Fabric	1.1
Inside Film Resistance	0.68

The cooling load for the structure in Sacramento for the given 1% design conditions was 5,254 Btu/hr. The cooling load for the structure in Atlanta for the given conditions was 5,261 Btu/hr. Table 9 summarizes the results from the TRACE 700 analysis and a secondary EES analysis for verification. The component loads from the TRACE 700 analysis are summarized in Table 9.

The cooling load was calculated separately using methods outlined in the 2013 ASHRAE Fundamentals Handbook to verify the TRACE 700 results. The solar radiation was determined using the clear-sky model from (chapter 4) and the load was calculated using a simplified formulation of the Heat Balance Method (chapter 18).

Table 9: Summary of TRACE 700 Cooling Loads on Structure and Load Verification

	Atlanta, Georgia		**Sacramento, California**	
	TRACE 700 Results	**EES Results**	**TRACE 700 Results**	**EES Results**
Cooling Coil Peak	June, 3 PM		August, 3 PM	
Ventilation Load (Btu/hr)	1,836	1,790	1,974	1,102
Sensible Human Load (Btu/hr)	514	514	514	514
Latent Human Load (Btu/hr)	298	298	298	298
Space Load (Btu/hr)	2,613	3,346	2,468	3,832
Total Load (Btu/hr)	5,261	5,948	5,254	5,746

The EES results confirm TRACE 700 results with 90% confidence, confirming the proper selection of an air-conditioning unit meet the load requirements of the structure.

These cooling loads do not account for the transient load on the system, which result from the large temperature difference between the outside air and inside air, at 65°F, that must be overcome within ten minutes to allow for most effective treatment of the victim. Additional analysis was performed to account for the transient loads on the structure.

$$q_{transient}(Btu/hr) = m_{air}C_{p,air} * \frac{T_{outside} - T_{inside}}{\Delta\theta} \quad \text{(Eqn. 3)}$$

Where m_{air} and $C_{p,air}$ are the mass and specific heat of the air in the structure, and $T_{outside}$ and T_{inside} are outside and inside temperatures for both the Atlanta and Sacramento design criteria, 91.7, 98.2 and 65 ^{o}F, respectively. The heat capacity of the structure was neglected since the structure walls are made of lightweight nylon and insulation. The added load on the air-conditioning system was estimated to be an additional 1000 Btu/hr over the peak cooling loads provided by the TRACE 700 analysis.

The TRACE 700 analysis verified that the selected systems, for both the Atlanta and Sacramento design conditions, would effectively cool the structure's interior to allow for a heat illness victim's internal body temperature to lower. The TRACE 700 analysis employed the results of the analysis performed solely on the heat illness victim to account for the additional load on the system caused by the victim overheating. The sensible load caused by the victim is 514 Btu/hr and the latent load caused by the victim is 298 Btu/hr. These values are significantly larger than the typical sensible and latent loads caused by a person in a space; the expected loads caused by an employee in an office space are 250 Btu/hr (sensible) and 200 Btu/hr (latent). No other internal loads were taken into account, the heat added to the room by the ChiliPad pump is deemed negligible compared to the heat produced by the victim.

The unique structure material was also specified in the TRACE 700 analysis. The resistances of the materials in the wall are listed in Table 8. Using these material properties and the dimensions selected, TRACE 700 determined the building envelope load.

The ventilation requirement of the structure was specified as a minimum of 30 cfm of outside air, as dictated by ASHRAE Standard 60.2. This is also accounted for in the TRACE 700 analysis. The TRACE 700 analysis approximates that the cooling load resulting from the ventilation, envelope and internal loads is 5,254 Btu/hr for Sacramento and 5,261 Btu/hr for Atlanta.

Psychrometric Depiction of System Operation

The system process is based on the 1% design data provided in the 2013 ASHRAE Fundamentals Handbook. For the Atlanta design data, the 91.7°F outside air is mixed with the return air from the space and passed through the air-conditioning unit to be cooled before entering the space. The space temperature is set at 65°F, which is the minimum room air temperature that the air-conditioning unit can produce, to allow for more rapid cooling of the victim. This space temperature of 65°F dictates that the supply air temperature leaving the air-conditioning unit must be 50°F. Testing performed on a similar portable air-conditioning unit verified that the temperature difference between the supply and room air temperatures is approximately 15°F. The return air is then mixed with 30 cfm of outside air. Figure 14 depicts the air-conditioning process of the system.

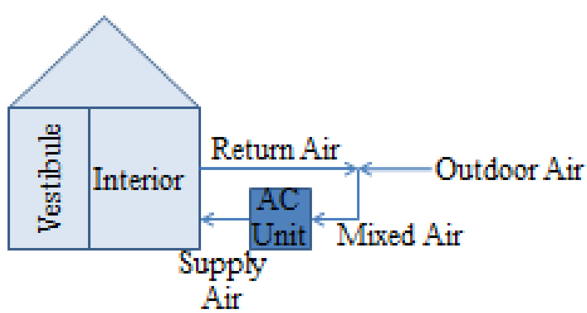


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Figure 14. Schematic detailing air flow of air-conditioning system for hot, humid climates.

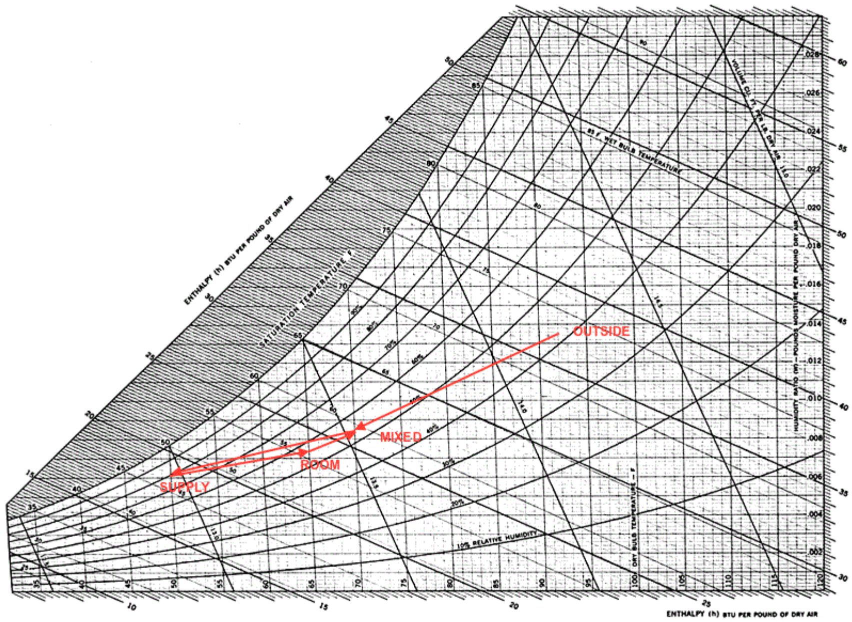

Figure 15. Psychrometric chart detailing the cooling process with an air-conditioning unit in Atlanta, Georgia.

The additional evaporative cooling implemented in the system designed to operate in hot, dry climates modifies the mixed air conditions entering the air-conditioning unit. The outside air, estimated to be 98.2°F, per the Sacramento design conditions, is cooled and dehumidified using a personal mister. The mister specifications estimate that the mister can cool the outside air to approximately 30°F through evaporation. To allow for a more accurate representation of the energy savings associated with the use of added evaporative cooling for a large range of hot, dry climates, the evaporation with decrease the temperature of the outside air by 15°F. The return air is mixed with 30 cfm of this modified outside air, per the ASHRAE Standard 62.2 ventilation requirements, and then cooled to the 50°F supply air temperature. This supply air temperature allows the space to maintain a 65°F room temperature to cool the victim off. Figure 15 details the psychrometric process for the air-conditioning system including the evaporative cooling of the outside air before it is mixed with return air.

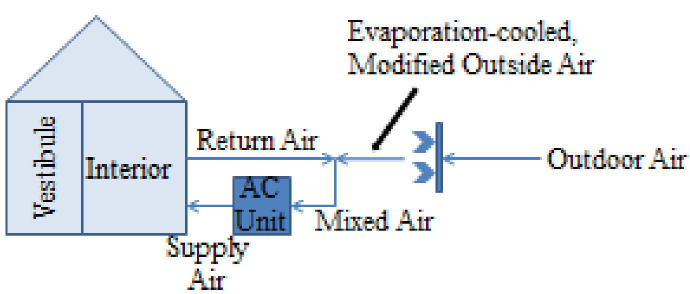

Figure 16. Schematic detailing air flow of air-conditioning system, including evaporative cooling for hot, dry climates.

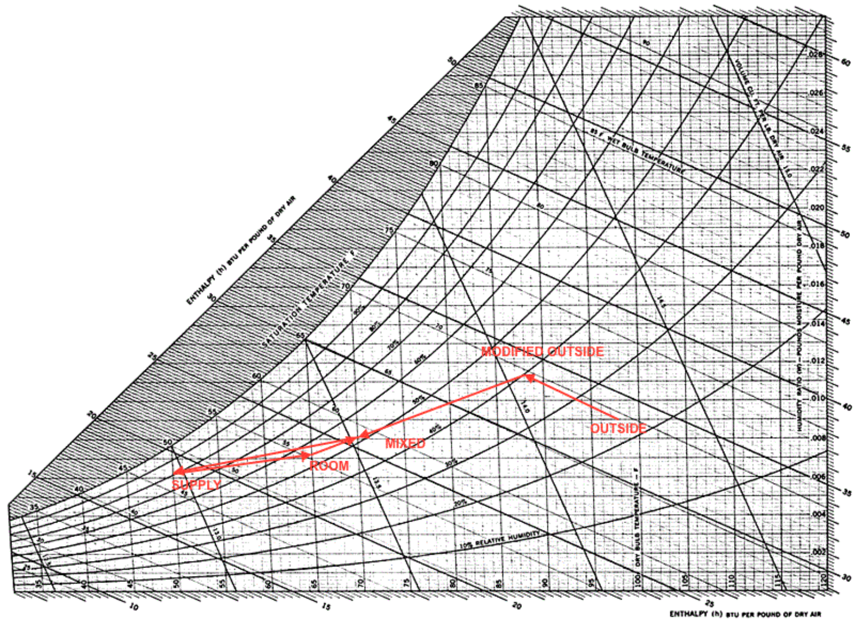

Figure 17. Psychrometric chart detailing the cooling process with an air-conditioning unit and evaporative cooling in Sacramento, California.

Conclusion

The portable, conditioned structure designed for the Applied Engineering Challenge will effectively treat victims of heat exhaustion, heat cramps and heat rash on the job site. Design criteria were developed to ensure that construction workers, the target audience would be comfortable in the structure for an extended period of time. The portable air-conditioning unit will meet the peak building loads for both Atlanta and Sacramento. However, to offset the energy costs in Sacramento, a portable mister will be included in the system to reduce the energy required for the peak load.

Operations Manual

This operations manual details the stages of assembly of the conditioned shelter and instructs users on how to assist in the treatment of a victim of heat illness.

Structure Assembly

1. Identify 10’x10’ flat ground near an electrical outlet on construction site to deploy system.
2. Clear ground of large or hazardous debris and lay out tarp.
3. Unfold the tent on tarp and orient so direct sunlight is not entering the observation window and that an individual is able to supervise victim through the observation window.
4. Connect air compressor (also used to inflate mattress) to inlet of the tent. This connection is found on the bottom right corner of the right side of the tent.
5. Turn on compressor and wait 3-4 minutes for tent to fully inflate. Tent should be in full upright position. Seal connection to compressor.
6. While the tent is inflating, place air-conditioning unit on left side of the tent and attach air-conditioning unit ducts to the duct connections on the air-conditioning unit and the tent. Also connect air-conditioning unit to power system.
7. Enter the tent and connect air compressor to deflated air mattress. Feed power cord through the tent’s electricity port - bottom right corner of the right side of the tent - connect to electricity switch. Wait 3-4 minutes for mattress to fully inflate. Remove air compressor once completed.
8. Fill water-cooled mattress pad control unit with 14 ounces of water.
9. Place water-cooled mattress pad and its respective pump inside tent. Connect the tubing of the mattress pad to the pump. Feed power cord through tent’s electricity port.
10. Adjust water-cooled mattress pad to cover air mattress.

If the shelter is to be used in a hot, dry climate, complete the following steps as well.

11. Fill mister tank reservoir with water.
12. Connect mister tubing to specified connections on the ducting to the air-conditioner.
13. Pump water tank until sufficient mist begins to leave nozzles on tubing.

Air-Conditioning System Activation

1. Turn on the air-conditioning unit by using the power button on the power pad of the air-conditioning unit.
2. While inside the tent, set the air-conditioning unit for maximum cooling using the remote control. Select the following; cool mode, high fan, and a temperature of 64°F- the lowest set temperature.
3. Turn on the water-cooled mattress pad control unit using the remote control.
4. Set water-cooled mattress pad control unit for maximum cooling using the remote control. Select the following; cooler, enter, and a water temperature of 46°F.
5. Exit tent and close interior and exterior doors upon exit.
6. Allow system to cool inside air for 10 minutes before allowing victim or operator to enter the tent.

Victim Treatment Process: Heat Exhaustion

1. Allow victim to sit or lay in cool, shaded area during shelter set-up if possible.
2. Encourage victim to drink water and apply moist towel to forehead, neck or affected heat rash area during shelter set-up.
3. After the air-conditioning unit has been on for 10 minutes and the tent interior has reached the desired internal temperature of 64°F, allow victim to enter structure.
4. Monitor victim periodically.
5. After 1 hour of use, the victim can return to work as he or she desires.

Victim Treatment Process: Heat Stroke

1. Call 911 and inform dispatcher that victim is suffering from heat stroke.
2. Allow victim to enter structure and observe through viewing window until paramedics arrive.
3. Upon arrival of paramedics, direct them to victim and inform them of the condition of the victim.

Structure Disassembly

1. After the victim has left the shelter, turn off the water-cooled mattress pad and air-conditioning unit using the respective control devices.
2. Disconnect the power cords of the water-cooled mattress pad unit, air-conditioning unit and misting unit.
3. Enter the shelter and remove the water-cooled mattress pad unit, including pump.
4. Use water release key to purge water from water-cooled mattress pad control unit.
5. Deflate the mattress pad inside the tent and remove any foreign objects (including water bottles, towels and dirt/sand).
6. Deflate the tent structure and allow 3-4 minutes until it is fully deflated. Remove any foreign material from surface of tent prior to storage.
7. Fold the tent and water-cooled mattress pad and place them in the storage unit. Place all additional components in the storage unit after removing any foreign material.

Maintenance Notes

1. Clean the coils evaporator and condensing coils of the air-conditioning unit every 6 months.
2. If dirty, the water-cooled mattress pad may be washed by hand or in a front load washing machine. After washing, the mattress pad may be hung dry or tumble-dried on low heat in a dryer.
3. Change batteries in the air conditioning and water-cooled mattress pad remotes as needed.
4. Store system in clean, dry environment.

Glossary

Transient Analysis on Heat Illness Victim

M – rate of metabolic heat production, Btu/hr*ft^2

W – rate of mechanical work accomplished, Btu /hr*ft^2

q_{res} – total rate of heat loss through respiration, Btu /hr*ft^2

K – effective conductance between core and skin, Btu /hr*ft^2*°F

SkBF – mass flow rate of blood, lbm/hr*ft^2

C_{pbl} – specific heat of blood, Btu /lbm*°F

T_{cr} – temperature of core compartment, °F

T_{sk} – temperature of skin compartment, °F

m_{cr} – mass flow rate of core compartment, lbm/hr

m_{sk} – mass flow rate of skin compartment, lbm/hr

C_{cr} – specific heat of core, Btu /lbm*°F

q_{dry} – sensible heat loss from the skin, Btu /hr*ft^2

q_{evap} – latent heat loss from the skin, Btu /hr*ft^2

q_{cond} – heat loss through additional conductive component, Btu /hr*ft^2

q_{conv} – heat loss through water bath, Btu /hr*ft^2

$dt_{cr}/d\theta$ – change in core temperature with respect to time, °F/hr

$dt_{sk}/ d\theta$ – change in skin temperature with respect to time, °F/hr

Building Load

$q_{transient}$ – time dependent load on the structure, Btu/hr

m_{air} – mass of air in space, lbm

$C_{p, air}$- specific heat of air, Btu /lbm*°F

$T_{outside}$ – outside air temperature, ^{o}F

T_{inside} – inside air temperature, ^{o}F

$\Delta\theta$ – time required to cool structure to operating temperature, hr

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