2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
MODELING & SIMULATION, TESTING AND VALIDATION (MSTV) MINI-SYMPOSIUM
AUGUST 17-19 DEARBORN, MICHIGAN

ANALYSIS OF SOLDIER EFFECTIVENESS IN A MINE RESISTANT AMBUSH PROTECTED GROUND VEHICLE

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ABSTRACT

This paper presents modeling methodology and results for a study of Soldier effectiveness in a hot environment. The effectiveness of Soldiers is diminished under conditions of high heat stress. Excessive heat stress will degrade mental and physical performance capabilities and eventually cause heat casualties. The core temperature of a human body provides the "best" single physiological measure to estimate physical work capabilities during hot weather operations. Prediction of Soldier effectiveness in extreme environments can be accomplished through the use of segmental human thermoregulation models. Differences in physiological characteristics among Soldiers can affect thermoregulatory response and must be accounted for when predicting effectiveness. Additionally, prediction accuracy can be improved by combining human thermoregulatory models with a complete characterization of the thermal environment. Human thermal models representing Soldiers with significant physiological differences among them were placed into a full-vehicle thermal HVAC predictive model of a Mine Resistant Ambush Protected (MRAP) vehicle. The simulation was performed to support US Army PM-MRAP in its effort to improve Soldier effectiveness under conditions typically encountered on MRAP vehicles fielded in Iraq.

INTRODUCTION

Excessive heat stress can degrade the mental and physical performance capabilities of Soldiers to the point that it can eventually result in heat casualties. Given that heat stress is defined as "environmental and host conditions that tend to increase body temperature" [1], the core temperature of a human body provides the "best" single physiological measure to estimate physical work capabilities during hot weather operations.

Fortunately, Soldier effectiveness in extreme environments can be accurately predicted through the use of segmental thermoregulation models [2, 3]. These sophisticated thermal models of the human body are able to react to transient and asymmetric boundary conditions by simulating changes in blood flow, metabolic heating and sweat evaporation at the skin surface. Differences in physiological characteristics among Soldiers can also be accounted for since these may affect thermoregulatory response and subsequently provide a more accurate prediction of effectiveness.

Heat stress can result from a combination of environmental and mission risk factors. Environmental risk factors consist of air and surrounding temperatures, air speed, humidity, and solar irradiation. Mission risk factors consist of activity level, clothing, and length of heat exposure. In light of this, prediction accuracy can be improved by combining complete characterizations of human thermoregulatory models with those of the surroundings (e.g. vehicle, building). Such coupled simulations allow the temperatures and heat rates of both the thermoregulatory models and the surroundings to be solved for simultaneously.

METHODOLOGY

A utility was developed to automate the process for building a physiological description of a non-standard (i.e., not 50th percentile) body build. Only the target body size (expressed as a percentile of the population) and the physiological description of a 'standard man' are required as inputs. The physiological description consists largely of a list of segments, tissues and the properties associated with them, such as segment lengths and tissue radii, thermal properties (e.g basal metabolic and blood perfusion rates, conductivity, density, specific heat, etc.), sensitivity coefficients and active thermoregulation distribution coefficients.

The utility automatically adjusts the passive system parameters of the baseline physiology [2] in proportion to known deviations from overall weight, height, and individual segment lengths of the 50th percentile male by assuming a Gaussian distribution ranging from the 1st percentile to 99th percentile and centered at the mean (50th percentile) [4]. Once a physiological description can be established, it can be applied directly to a shell-element representation of the human geometry for use by a thermal solver. Since the geometry will be automatically scaled to match the physiology upon the start of the thermal solution, it is not necessary that the geometry size and dimensions match the physiological description.

Building Physiologies

From the desired body build specification and the physiological description of the standard man, the whole-body height and weight can be obtained from established anthropometric data [4]. The body fat mass (kg) for the individual can be calculated based on the following correlation valid for males of normal build [5]:

$$BF_{male} = 0.685W - 5.86H^{3} + 0.42 \qquad (1)$$

The fat layer in each body segment can then be adjusted by applying a single fat adjustment factor to each fat layer in the model -- obtained by dividing the target whole body fat mass by the baseline physiology's fat mass.

Since the underlying physiological description defines tissue content for each segment by an outer tissue radius, rather than by mass, the fat layer radii were adjusted as necessary while updating the segment-level skin radii to maintain required skin thickness. Applying a similar technique to obtain the corresponding whole body weight for the desired percentile, the masses of all of the tissue layers residing under the fat layer in each segment were adjusted, until the target whole-body mass was reached.

Validation of the overall technique was performed by comparing the actual whole body surface area of the resulting physiology, defined by the outer radii and lengths of each segment, with the Dubois surface area, A_D, obtained from the target percentile's height and weight.

$$A_D = 0.202W^{0.425}H^{0.725} \qquad (2)$$

Since the focus of this project was military in nature, the upper 5% and lower 5% of percentiles were excluded from this study in accordance with the military's intent to accommodate no more than 90% of the general population. At the lower extreme, the 5th percentile male's surface area (A_{actual} =1.49m^2, A_D=1.59 m^2) was within 7% of its predicted value while at the upper end, the 95th percentile male's surface area (A_{actual} =2.20m^2, A_D =2.27 m^2) deviated from its target value by only 4%.

Model Setup

Seven unique human thermal models representing Soldiers with a variety of body builds ranging from the 5th percentile to the 95th percentile were placed into a full-vehicle thermal HVAC predictive model of a Mine Resistant Ambush Protected (MRAP) vehicle. The geometry of each Soldier was customized to have a different body size and pose. Figure 1 shows the Soldier geometry with body size labels for each. All seven Soldiers were dressed in a t-shirt, briefs, desert BDU shirt and pants, and socks and shoes.

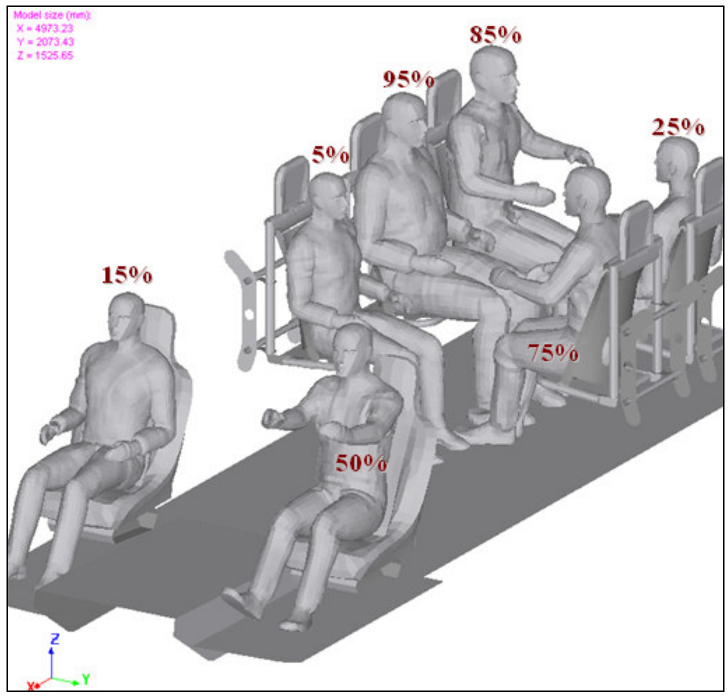

Figure 1: Soldier geometry labeled with body size

Table 1 presents the high-level body size descriptions of the Soldiers, as well as their corresponding boundary conditions. Each Soldier was modeled with an activity level of 1.2 met, which correlates to a seated but slightly active physical state. The air velocities near each Soldier were approximated from previously obtained CFD results of the vehicle interior, while the local air temperatures were calculated automatically during the solution using a sub-volume air flow and heat transfer modeling technique [6].

Table 1: Soldier body size and boundary conditions

Body Size (percentile)	Height (m)	Weight (kg)	Met Rate	Air Velocity (m/s)
5	1.54	51.7	1.2	0.2
15	1.62	59.8	1.2	0.6
25	1.64	64.7	1.2	0.4
50	1.7	73.5	1.2	0.6
75	1.76	82.4	1.2	0.4
85	1.81	87.3	1.2	0.2
95	1.84	95.3	1.2	0.2

The Soldiers were placed in an MRAP model that had been initialized with a heat soak condition. The heat soak (vehicle off) was simulated from 5:00am to 6:00pm in a hot desert environment. Figure 2 shows the ambient air temperature and solar irradiance values. A transient cool down period was modeled from 6:00pm to 10:00pm. The engine was modeled at idle and a prototype air conditioning system was modeled to provide the maximum possible cooling under idle conditions (18kW of heat). Figure 3 shows average air and surface temperatures inside the vehicle during the transient cool down period.

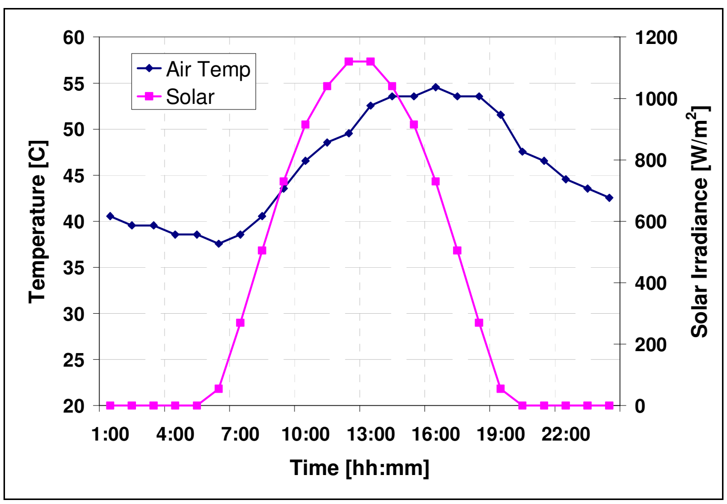

Figure 2: Ambient air temperature and solar load

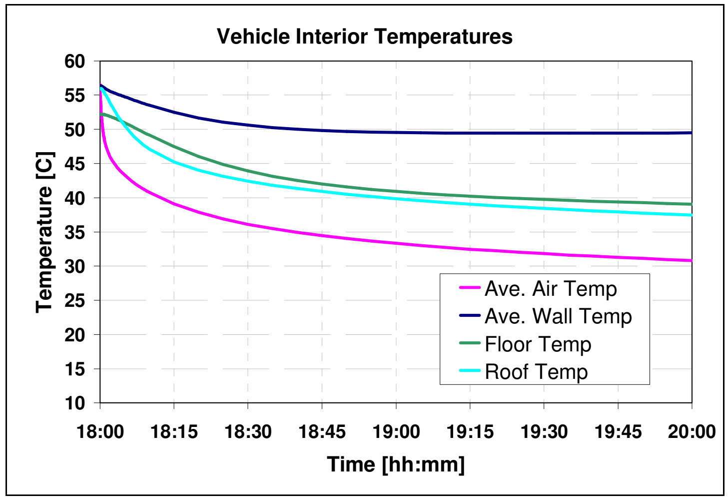

Figure 3: Vehicle interior average temperatures

RESULTS

The objective of the simulation was to obtain physiological results for each individual Soldier in the MRAP to determine whether or not effectiveness could be maintained for the duration of the vehicle's transient cool down period. Figure 4 provides a visualization of the Soldiers' skin and clothing temperatures and illustrates the detail in which the temperature profiles were predicted. This snapshot represents the thermal state of the Soldiers six minutes after entering the hot vehicle.

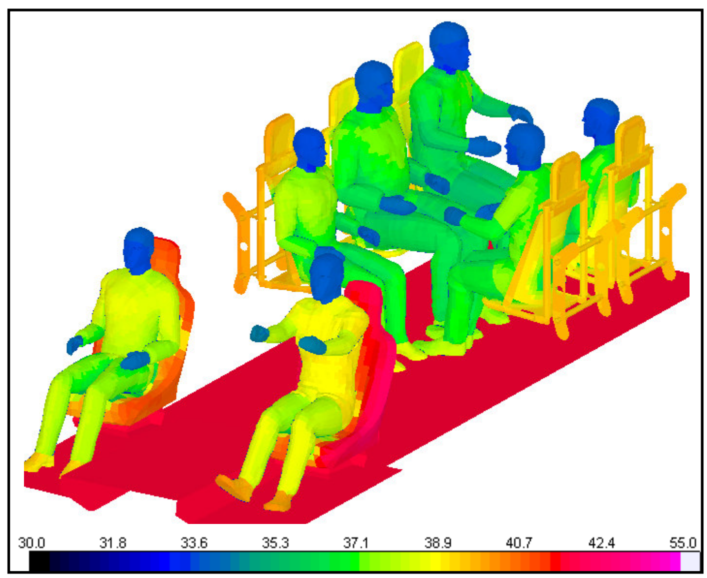

Figure 4: Surface temperatures after 6 minutes of transient cool down.

Figure 5 shows the core temperature (rectal temperature) for all seven Soldiers. Soldier effectiveness can be maintained for the duration of an exercise as long as core temperature does not deviate more than 1 degree in uncontrolled environments and 1.5 degrees in controlled environments. The graph shows that the largest core temperature rise was incurred by the 95th percentile Soldier. The maximum deviation in core temperature was 0.52˚C.

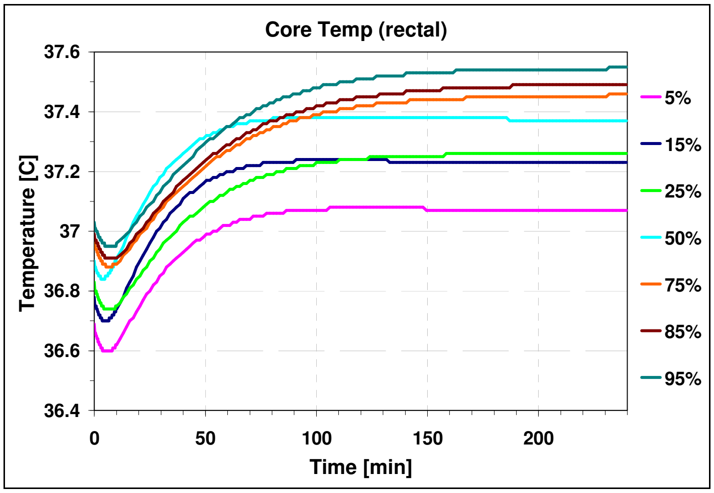

Figure 5: Transient core temperature for 7 Soldiers

Figure 6 and Figure 7 show the mean skin temperature and overall sweat rate. These plots show that the highest mean skin temperature and sweat rate were experienced by the driver and commander, the 50th and 15th percentile Soldiers, respectively. This was due to the front of the vehicle having the highest air and surface temperatures at the start of the cool down simulation.

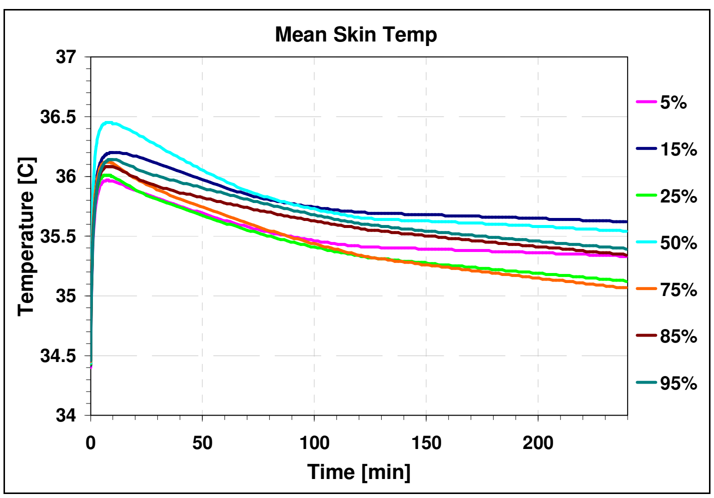

Figure 6: Mean skin temperature plot

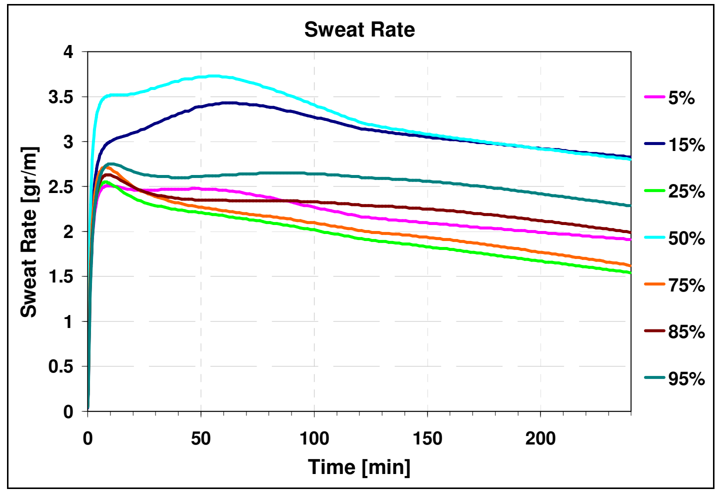

Figure 7: Transient sweat rate (grams/minute)

Figure 8 and Figure 9 provide plots of overall thermal sensation and comfort based on the Berkeley Comfort Model scales. Both scales range from -4 to +4 (very cold to very hot and very uncomfortable to very comfortable, respectively). All of the Soldiers experience a thermal sensation spike when they first enter the hot vehicle. Their sensation then slowly decreases towards neutral as the vehicle cools down. Figure 9 illustrates that the Soldiers experience discomfort due to the hot environment present early in the cool down; however, their comfort improves as the air and surface temperatures drop inside of the vehicle. Also, as evidenced in the plots of core and skin temperature, the driver (50th percentile Soldier) is the hottest and least comfortable person at the beginning of the simulation.

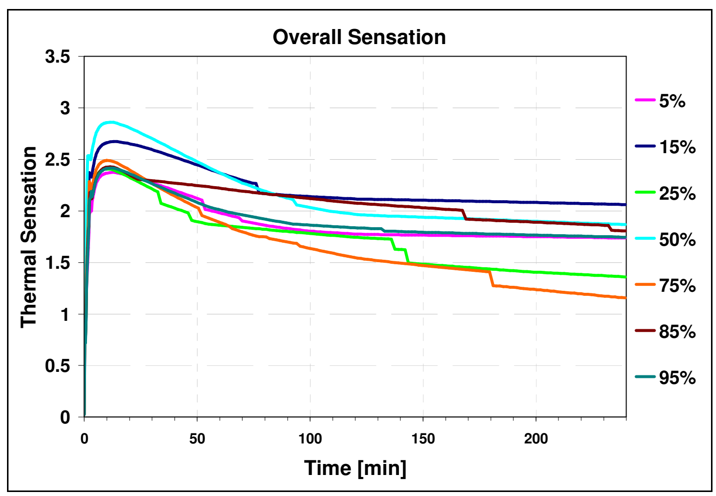

Figure 8: Overall thermal sensation

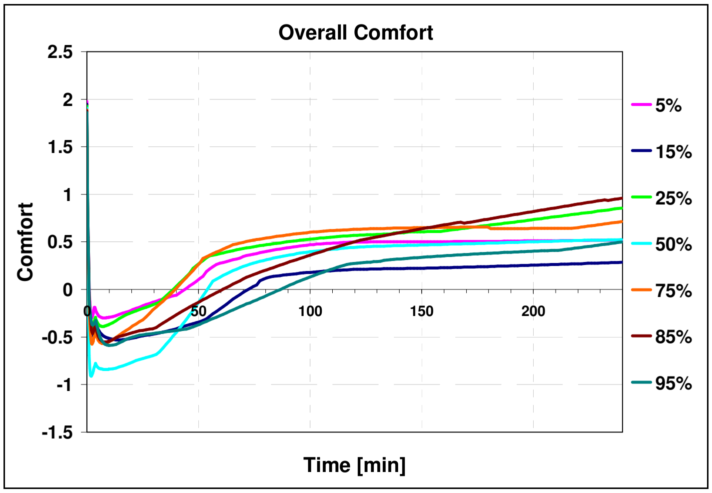

Figure 9: Overall thermal comfort

CONCLUSION

The effectiveness of Soldiers with varying physiological builds was examined by simulating their thermoregulatory response when placed in an MRAP vehicle experiencing a transient cool down after an initial hot soak. Although the thermal sensation and comfort results indicate that actual Soldiers would feel hot and uncomfortable for a significant amount of time after first entering the vehicle environment being modeled, the core temperature results show that Soldier effectiveness would not be adversely affected. Furthermore, since a wide range of physiological builds were accounted for in this simulation, it can be expected that the environment within the vehicle compartment will be safe for all passengers regardless of physiological build under the simulated conditions.

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