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Aqueous Extinguisher Discharge and the Effects on Core Body Temperature and Skin Burn/Frostbite

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14. ABSTRACT
The US Army has relied on hydrofluorocarbon (HFC) extinguishing agents for many of its fire suppression applications. However, production of HFCs is being phased down due to their high global warming potentials. One alternative low-GWP agent being investigated for crew protection is water mixed with a freeze point depressant. This report summarizes an evaluation of the use of water in a fire protection system. Specifically, we present modeling and simulation results of an aqueous agent when discharged into a confined space onto a vehicle crew member under varying environmental conditions. Crew survivability was assessed for both extreme cold and hot cases within the military vehicle operating temperature range. Body core temperature and immediate skin effects were evaluated in this study. Results indicate that body core temperature thermal injury thresholds were exceeded in the hot case (125°F ambient temperature and 150°F agent temperature), whereas they were not exceeded in the most extreme cold case evaluated (-23°F ambient and -40°F agent temperature). Analysis of immediate skin effects indicated that greater than 2nd degree burns will occur with a 125°F ambient and a 125°F agent temperature. Similarly, frostbite is predicted with a -25°F ambient and a -25°F agent temperature.

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TEST REPORT

Aqueous Extinguisher Discharge and the Effects on Core Body Temperature and Skin Burn/Frostbite

1.0 Executive Summary

Since the cessation of production of high ozone depleting substances such as halon 1301 (bromotrifluoromethane, CF_3Br), the US Army has relied on hydrofluorocarbon (HFC) extinguishing agents for many of its fire suppression applications. However, production of HFCs is being phased down due to their high global warming potentials (GWP). Therefore, the Army initiated a research program to evaluate potential environmentally friendly, low-GWP chemicals as candidate fire extinguishing agents for use in automatic fire extinguishing systems (AFES) that protect the crews of Army vehicles against fire and explosions caused by combat threats. The current effort is a continuation of research conducted for ground and aviation weapon systems [1,2,3,4]. One of the few remaining potential low-GWP agents identified for crew protection is water mixed with a freeze point depressant. This report summarizes an evaluation of the use of water in a fire protection system in a collaborative effort between the US Army DEVCOM GVSC and ThermoAnalytics, Inc. Specifically, we present modeling and simulation results and an assessment of the effects of an aqueous agent when discharged into a confined space onto a vehicle crew member under varying environmental conditions. This study was conducted using a water spray, whereas a fielded solution would require a freeze point depressant be added to the water to be viable in the required operating temperature ranges. The addition of a freeze point depressant will increase the heat capacity and thermal conductivity of the agent which would make thermal injury more likely. Thus, the results presented in this report are considered to be best case for a water spray system. The effects of a fine mist may be more benign, but this study does not consider that case. Crew survivability was assessed for both extreme cold (e.g., frostbite) and extreme hot (e.g., skin burns) cases within the military vehicle operating temperature range. Body core temperature and skin effects were evaluated in this study over a duration of five minutes following extinguisher discharge to remain consistent with other relevant survivability criteria. Results indicate that body core temperature thermal injury thresholds were exceeded in the hot case (125°F ambient temperature and 150°F aqueous agent temperature), whereas core body temperature thresholds were not exceeded in the most extreme cold case evaluated (-23°F ambient and -40°F aqueous agent temperature). Analysis of immediate skin effects indicated that greater than 2nd degree burns will occur with a 125°F ambient and a 125°F aqueous agent temperature. Similarly, frostbite is predicted with a -25°F ambient and a -25°F aqueous agent temperature. In summary, these results indicate that, within required vehicle environmental operating conditions, thermal injury and incapacitation are possible if an aqueous agent is discharged onto the crew. Thermal injury under the same conditions is not expected with legacy, gaseous agents due to their different thermo-physical properties.

2.0 Introduction

The Army relies on halon 1301 (bromotrifluoromethane), HFC-227ea (heptafluoropropane), HFC-125 (pentafluoroethane), dry chemical (sodium or potassium bicarbonate based powders), carbon dioxide, and water mixed with a freeze-point depressant additive (potassium acetate) to provide fire protection for its ground vehicle and aviation weapon systems. However, halon 1301 and HFC227-BC (HFC-227ea mixed with 5% to 10% sodium bicarbonate dry chemical by weight) are the only agents approved for use in automatic fire extinguishing systems (AFES) that protect the crew compartments of ground vehicles. The other materials listed are used to protect unoccupied compartments or in portable extinguishers. Due to international agreement, production of halon 1301 was eliminated in 1994 because of its high ozone depletion potential via the Montreal Protocol on Substances that Deplete the Ozone Layer [5]. Since then, the Army has transitioned to HFCs or other alternatives, such as sodium bicarbonate dry chemical, for all new vehicles. On 15 October 2016, Parties to the Montreal Protocol adopted the "Kigali Amendment" [6]. While this amendment does not restrict the use of HFCs, it calls for the gradual reduction of their consumption (production + imports – exports – destruction). The phasedown schedule for the US started with a 10-percent reduction in 2019 and culminates in an 85-percent reduction in consumption by 2036 (Appendix A). As a result, alternative low-GWP chemicals for fire suppression systems will likely be needed.

In response, the Army resurrected the Low-GWP Alternative Fire Suppressants program. The focus of this effort is to evaluate the feasibility of commercially available and emerging chemicals to replace high-GWP fire suppression agents in its weapon systems [1-4]. To be considered a viable alternative to HFC227-BC, the Army's replacement for halon 1301 in vehicle crew AFES, the candidate must meet unique military requirements including the "Selected Crew Casualty Requirements" (Appendix B) and allow personnel to stay within the protected space without incapacitation for at least 5 minutes after a fire suppression event.

Aqueous agents and water mist systems are common in commercial, fixed applications protecting machinery spaces. However, a combination of gaseous and dry chemical agents is the choice for military ground vehicle crew protection systems as described above. Operational concerns include cleanup, i.e., the post-discharge residue from an agent comprised of a water and additive (e.g., potassium acetate) mixture. Less well understood are the safety issues associated with applying an aqueous agent directly onto personnel. The potential risks are compounded if the affected occupants are unable to quickly egress, such as is the case of vehicle crewmen operating in a combat environment. As part of an assessment of the viability of an aqueous agent in an AFES protecting the crew of a military vehicle, this study evaluated the thermal effects of a discharge spray onto the exposed skin of a typical ground vehicle crewman. Specifically, our aim is to develop casualty criteria, with incapacitation limits, due to exposure to extreme cold and hot aqueous agents, e.g., effects of heat stress or hypothermia.

Herein we report modeling and simulation results that address the effects of an aqueous discharge on a recipient's core body and exposed skin temperatures that may lead to heat stress, hypothermia, skin burns, or frostbite. This study was conducted using water, whereas a fielded solution would require a freeze point depressant to be viable in the required operating and storage temperature ranges. The addition of a freeze point depressant will increase the heat capacity and conductivity of the agent which would make thermal injury more likely. Thus, the results presented in this report are considered to be best case. The effects of a fine mist may be more benign, but this study does not consider that case. The conditions used in these tests were consistent with the limits of military ground vehicle ambient operating temperature extremes of 51.7°C (125°F) and -31.7°C (-25°F) and storage temperatures of 71.1°C (160°F) and -51.1°C (-60°F). Due to the higher thermal capacity of an aqueous solution compared to air, a series of simulations was run with varying aqueous fluid and ambient air temperatures. The resulting data were used to assess the thresholds of thermal injuries.

This evaluation was a collaborative effort conducted by the DEVCOM Ground Vehicle Systems Center (GVSC) and ThermoAnalytics, Inc.

3.0 Modeling and Simulation Methodology

The study was split into two phases to evaluate the effect of the soldier's ability to complete the mission. Phase 1 focused on crew members' core body temperatures. More specifically, a series of human thermal modeling simulations was conducted to determine the impact of exposure to extreme fluid temperatures and ambient/radiant conditions on a 50th percentile male's core body temperature, i.e., heat stress or hypothermia. The focus of Phase 2 was on skin damage of the soldier. Capabilities of the simulation process were extended to determine criteria such as the duration of exposure to the AFES spray needed to induce second degree burns. Published burn prediction criteria were examined to determine the most applicable 2nd degree burn criterion for the Army medical authority to consider. Outputs from this extended human thermal simulation analysis were skin temperatures, which were utilized to generate a threshold of thermal dose causing second degree burns as a function of water temperature at time of discharge. The skin temperatures were also employed to forecast the risk of frostbite over the duration of the exposure.

TAITherm thermal modeling software (ThermoAnalytics, Inc.) was used to simulate the soldier in a crew cabin environment over a range of agent temperatures and environmental conditions. The TAITherm Human Thermal Model (HTM) was also used to predict the dynamic thermal response of the simulated soldier while accounting for clothing, human tissue thermal properties, and active thermoregulation.

This thermoregulation model simulates the process by which the body attempts to maintain a constant core temperature by shivering, sweating, and altering skin blood flow. This model calculates surface and deep tissue temperatures within the human body as described by a surface mesh. More specifically, it computes temperatures at each quadrilateral or triangular element from the surface of the clothing to the core of the body segment. Heat storage, three-dimensional conduction (between neighboring elements), and the heat transferred due to changes in blood flow, metabolism, and sweating at the skin surface are all accounted for within the model.

The human thermal model in TAITherm is based on a complex physiological model in which the body is divided into 20 segments (face, head, neck, chest, right and left shoulders, etc.). Segmented thermoregulation models are the most accurate way to predict the core temperature of a human body when subjected to transient, asymmetric environments. Tissue thickness and thermal properties (skin, fat, muscle, bone, lungs, brain, etc.) are assigned to each of the twenty segments. The model characterizes the transport of heat and moisture through tissue and clothing layers. Clothing is defined by its thermal resistance, evaporative resistance, and clothing area augmentation factor. The HTM predicts skin and underlying tissue temperatures, as well as blood and body core temperatures, based on environmental conditions, clothing, and activity level. The simulations of the AFES spray assumed a droplet size distribution that ranged from 10 microns up to 0.5 mm.

3.1 Phase 1 – Core Body Temperature

The objective of the Phase 1 simulations was to determine the combination of aqueous fire extinguishing agent temperature and environmental conditions likely to produce heat stress or hypothermia. The extinguisher modeled used a 3.5-liter (213 in^3) cylinder containing 2.5 kg (5.5 lbs.) of water and charged to 62 bar (900 psig) with nitrogen at 21°C (70°F). As illustrated in Figure 1, the simulated environment created for phase 1 consisted of a generic Army vehicle crew cabin with a 50th percentile male soldier model placed inside in a seated position.

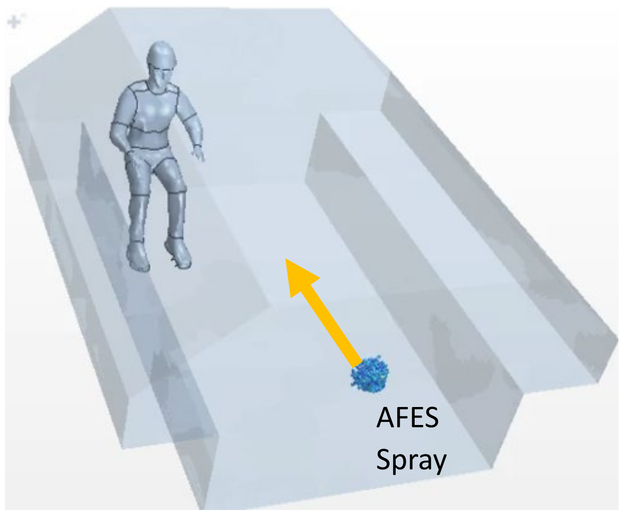

Figure 1: Phase 1 Simulated Crew and Environment

Clothing on the soldier model varied based on the scenario simulated. A summer ensemble was selected for hot weather scenarios, while a winter ensemble was selected for cold weather. Clothing properties were taken from a standard Army combat uniform definition [7] and a cold weather work/rest study used in previous contract efforts [8]. The "area factor" shows the increase in area used for the simulation, based on the corresponding location on the soldier, to account for the additional size of the article of clothing.

A water vapor analysis was used to simulate 100% relative humidity for all scenarios. TAI investigated using three different water compartment density specifications to inform on the relative humidity values used inside the crew cabin for the 5-minute vehicle simulations. The investigation found no appreciable difference in cabin relative humidity between the variants. That is, varying the water compartment vapor density had no effect on the input used (relative humidity) to describe the wet environment inside the cabin, even at the hottest simulated air temperature of 158°F.

A heat transfer coefficient (HTC) sensitivity study was then conducted to gauge the convective effect of HTCs used between the AFES solution and the soldier. Values between 50 and 250 W/m^2-K were selected to benchmark the physiological response of the soldier. A final HTC value of 80 W/m^2-K was identified based on engineering judgement and previous knowledge of convective liquid behavior from a past contract effort [9] to select that value.

The core body temperature threshold for heat stress during work-rest cycles was obtained from military training guidelines [10]. Core body temperature rises between 1.0°C and 1.5°C can be sustained with few persons incurring exhaustion from heat strain. A core body temperature increase of 1.5°C is indicative of heat stress while increases of 3.0°C signal the onset of heat stroke. In the study reported herein, a core body temperature increase of 1.5°C is considered the threshold for heat-induced injury.

The core body temperature threshold for cold stress was obtained from military training guidelines [11]. A decrease in simulated core body temperature of 2.0°C is indicative of the onset of hypothermia. A core temperature drop of 5.0°C or more is expected to result in a severe decline in mental functions [12]. In the study reported herein, a core body temperature decrease of 2.0°C is considered the threshold for cold-induced injury.

A summary of the threshold limits for both the hot and cold cases are shown in Figure 2. Green indicates normal operation, yellow indicates the onset of thermal injury, and red indicates that incapacitation is expected.

Figure 2: Phase 1 Core Body Temperature Thresholds.

The simulated scenario was developed to model the change in core temperatures of a 50th percentile male soldier experiencing a range of agent temperatures, ambient temperatures, and radiant conditions. The thermal model used in the simulation incorporates the clothing material properties, AFES fluid temperatures, and ambient air temperatures in the compartment. The simulated soldier is subjected to an ambient condition until thermal equilibrium is achieved, followed by the AFES discharge, and 5 minutes of cabin exposure.

3.2 Phase 2 – Frost Bite and Skin Burn Risk

The objective of the Phase 2 simulations was to determine the combination of discharged aqueous agent temperature and ambient environmental conditions that would reach the thresholds for second degree burns or frostbite.

As shown in Figure 3, the simulated environment in Phase 2 was the same generic Army vehicle crew cabin as used in Phase 1. A single 50th percentile male soldier model was placed inside the crew cabin in a seated position, but in the front of the vehicle as opposed to the rear. The position of the soldier was moved to simulate the worst-case scenario for skin damage, that is, as close to the fluid discharge as is safe from mechanical injury.

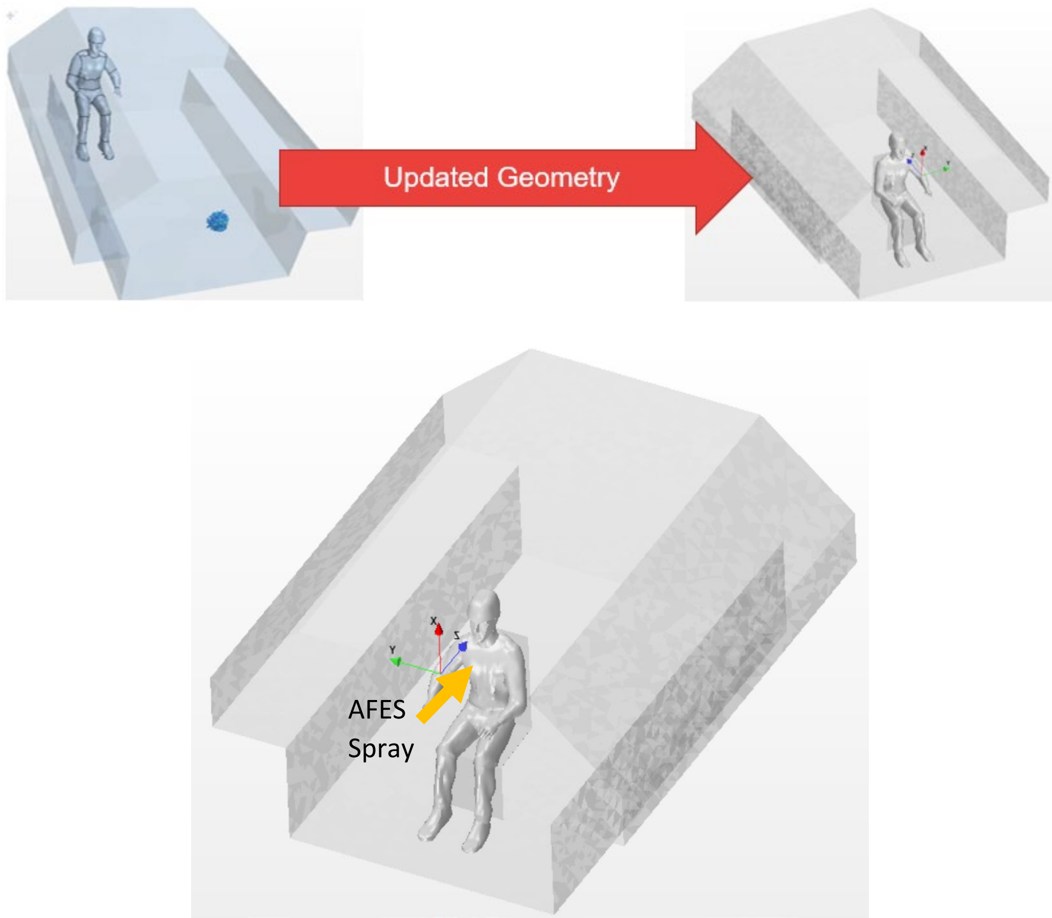

Figure 3: Phase 2 Simulated Crew and Environment

The simulated clothing did not change. The simulated scenarios again used 100% relative humidity. Spatial distribution of the heat transfer coefficients between the discharge spray and vehicle with soldier were the same as those used in Phase 1. In this Phase 2 effort CFD records (HTCs and fluid temperatures mapped to every element in the soldier model) were incorporated into the model for the first ~250ms of the simulation prior to the 5-minute simulation using the original HTC setup for Phase 1. Figure 4 shows the mass flow rate of the extinguisher discharge versus time [13]. The sampling points were chosen to capture a nominal AFES discharge, in this case between 40 ms and 225 ms (duration of agent spray onto occupant) as indicated in Figure 4.

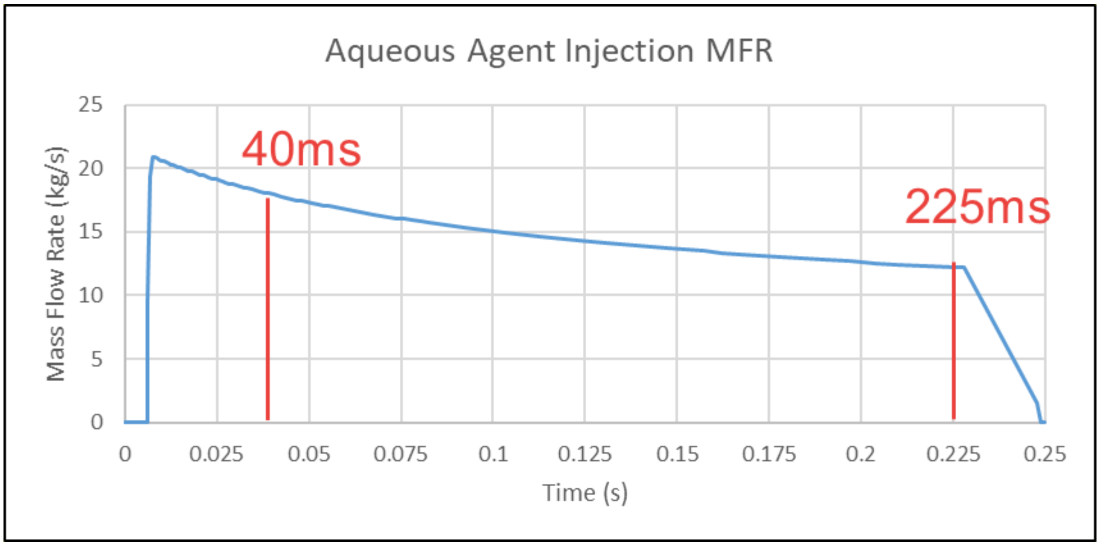

Figure 4: AFES Agent Discharge Mass Flow Rate versus Time

Additional model inputs that affect skin temperature included the effect of the soldier's sweating, shivering, vasodilation, and vasoconstriction. The soldier's activity level was assumed to be a 1.0 metabolic equivalent, which is a resting heart rate equivalent expected while sitting quietly. The metabolic heat rate (or activity level) is an important determinant in the amount of heat generated by a human. Activity level is commonly specified as a heat rate per body surface area with "metabolic equivalent of task" (MET), where one MET (58.1 W/m^2) corresponds to the activity of a human sitting quietly. The TAITherm HTM takes activity level as an input, but the actual metabolic heat rate produced in a human can increase if the human's core temperature rises above the set point of 98.6 degrees F (37 degrees C).

The predicted skin damage temperature thresholds for burn injury were determined based on work by Henriques and Moritz [14]. Destruction of the tissue layer in human skin may start when the tissue temperature of the basal layer rises above 44°C (111°F). The Henriques burn damage integral formula is shown in Equation 1, where P is the (Arrhenius equation) frequency factor (s^{-1}), a given, ΔE is the activation energy for skin (J/mol), R is the universal gas constant (J/kmol-K), T is the absolute temperature of the basal layer or at any depth of the dermis, and t is the total time for which T is above 44°C (317.15 K) in Equation 1. If simulated skin temperatures were less than 44°C, then it was assumed there was no burn risk and there was no contribution to the integral. When the value of the integral is between 0.5 and 1.0, first degree burns are possible. Second degree burns occur when the value of the integral is greater than 1.0. In this study, an integral value greater than 1.0 is considered the threshold for burns.

$$\Omega = \int_0^t \left(P^{-\frac{\Delta E}{RT}}\right) dt$$

Equation 1

The skin *surface* temperature threshold for frostbite (which happens beneath the surface), -4.8°C (23°F) corresponds to a five percent probability of frostbite occurring [15]. It is recognized that the U.S. Army Research Institute for Environmental Medicine's (USARIEM) Cold Weather Ensemble Decision Aid (CoWEDA) [16] takes a much more conservative approach, considering soldiers at risk of frostbite when skin temperature falls below +5°C (41°F). However, as implemented, the more stringent -4.8°C threshold may not indicate how cold an environment must be to cause frostbite. Specifically, related research [17] has found that accounting for cold-induced vasodilation (CIVD) improves the accuracy of the wind chill equivalent temperature (WCET) method of determining the frostbite threshold. CIVD causes the face and other glabrous (i.e., hairless) areas of skin to warm, delaying the onset of frostbite. CIVD is not incorporated into the human thermal simulation presented in this text; doing so is suggested as a future task.

Figure 5 illustrates the hot and cold thermal injury thresholds used herein.

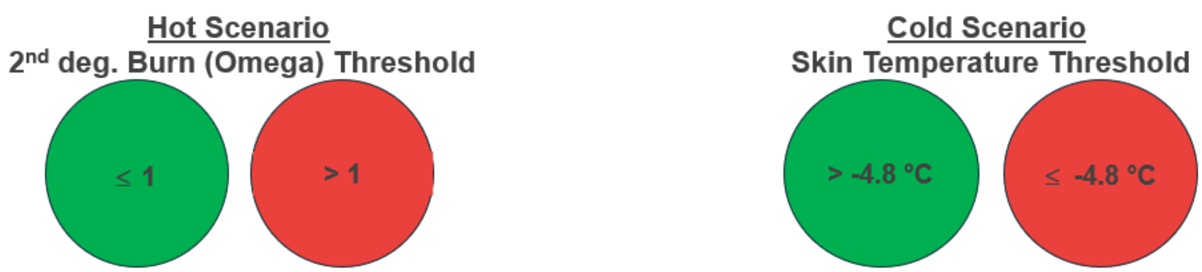

Figure 5: Phase 2 Hot and Cold Skin Damage Temperature Thresholds

The same process as used in Phase 1 was employed to simulate the risk of thermal injury, using the same MET rate (1.0) for both. The process included shivering and sweating. Skin and core temperatures were recorded. The Phase 2 simulation timeline is illustrated in Figure 6.

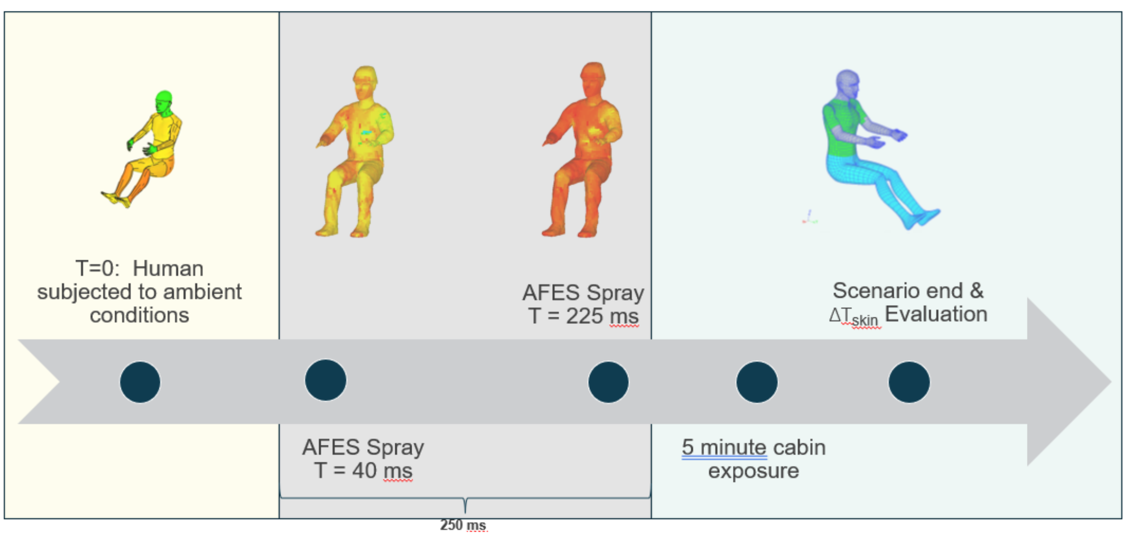

Figure 6: Phase 2 Simulated Scenario Timeline

4.0 Results

4.1 Phase 1 Results – Core Temperature Analysis

Results of the Phase 1 hot-case simulations indicate that a five-minute exposure can result in thermal injuries or even be fatal, as shown in Table 1. A core temperature change of 1.5°C (2.7°F) was exceeded in a 51.6°C (125°F) ambient environment, and 65.6°C (150°F) AFES fluid, which indicates thermal injury is likely (indicated by red in Table 1).

Table 1: Phase 1 Hot Case Results

Ambient Temperature (°F)	AFES Temperature (°F)	Total Change in Core Temperature (°C)	Time of failure (minutes)
125	158	2.16	4.00
125	155	2.03	4.25
125	150	1.79	4.5
120	145	1.37	NA
120	140	1.17	NA
120	135	0.99	NA
115	130	0.71	NA
110	125	0.50	NA
105	120	0.32	NA
100	115	0.2	NA
95	110	0.12	NA
90	105	0.08	NA
85	100	0.07	NA

Results of the Phase 1 cold-case simulations indicate that a five-minute exposure will not cause hypothermia regardless of ambient temperature or AFES fluid temperature, as shown in Table 2. A slight rise in core temperature is seen over the duration due to the shivering response. Skin temperatures drop as exposure gets colder, but the effect is mitigated by the thermal insulation provided by the garments.

Table 2: Phase 1 Cold Case Results

Ambient Temperature (°F)	AFES Temperature (°F)	Total Change in Core Temperature (°C)	Time of failure (minutes)
-25	-40	+0.07	NA
-20	-34.2	+0.07	NA
-15	-28.4	+0.07	NA
-10	-22.6	+0.07	NA
-5	-16.8	+0.07	NA
0	-11.5	+0.07	NA
5	-5.2	+0.07	NA
10	0.6	+0.07	NA
15	6.4	+0.07	NA
20	12.2	+0.07	NA

4.2 Phase 2 Results - Skin Damage Analysis

Results for the Phase 2 hot-case simulations indicate that a five-minute exposure can cause thermal injury and thus reduced soldier capacity as shown in Table 3 (indicated by red). An omega value representing the threshold for 2nd degree burns ($\Omega > 1.0$) was exceeded in a 51.7°C (125°F) ambient environment with 51.7 °C (125°F) AFES fluid spray, as well as a 46.1°C (115°F) ambient environment with 54.4°C (130°F) fluid spray. In the extreme hot cases, the mean skin temperature increased significantly to potentially dangerous, burn-inducing temperatures.

Table 3: Phase 2 Hot Case Results

Ambient Temperature (°F)	AFES Fluid Temperature (°F)	Maximum Skin Temperature (°C)	Burn Potential (< 5 min)	Reaches 2nd Degree Burn at time
125	125	49.39	Yes	46.8 seconds
115	130	50.57	Yes	20 seconds
105	120	45.97	No	N/A

Results for the phase 2 cold-case simulation indicate that a five-minute exposure can cause thermal injury and thus reduce soldier capacity as shown in table 4 (indicated by red). Skin temperature values decreased below the frostbite threshold of -4.8°C in a -31.7°C (-25°F) ambient environment with -31.7°C (-25°F) AFES fluid spray, as well as in a -20.6°C (-5°F) ambient environment with -27.1°C (-16.8°F) fluid spray.

Table 4: Phase 2 Cold Case Results

Ambient Temperature (°F)	AFES Fluid Temperature (°F)	Minimum Skin Temperature (°C)	Frostbite Potential (< 5 min)	Frostbite risk at time
-25	-25	-12.40	Yes	110.8 seconds
-5	-16.8	-5.55	Yes	266.2 seconds
0	-11.5	-3.57	No	N/A
10	0.6	0.41	No	N/A

5.0 Conclusions and Recommendations

Water-based agents are among the few known low-GWP substances that may be suitable for use in automatic crew fire protection systems. This study indicates that the discharge of a water-based agent from an extinguisher in the crew compartment of a tactical or combat vehicle can cause thermal injuries when the ambient temperature is near the hot or cold extremes of the required operating range. The risk of thermal injury under the same conditions is not expected with gaseous or dry chemical agents due to their thermo-physical properties.

This study was conducted using a spray of pure water, whereas a fielded solution would require a freeze-point depressant to be viable in the required operating ranges. Addition of the depressant will increase the heat capacity and thermal conductivity of the agent which would make thermal injury more likely. It is recommended that future analysis address the addition of freeze-point depressants (and perhaps other additives). Thus, the results presented in this report are expected to be best case for a system that sprays an aqueous solution sprayed directly on the vehicle crew. Additional technology development to regulate the AFES fluid temperature in these extreme conditions, or modification of vehicle-level operating temperature requirements would be required to make aqueous agents feasible for use in automatic crew fire protection systems. These changes are most likely not practical.

Finally, the study assumed a standard water spray; it did not consider the safety of fine water mists applied in occupied compartments. Therefore, it is recommended that efforts and continued investigation be made to understand the risk of thermal injury expected with a fire protection system that, at operating temperature extremes, discharges a fine mist of water with freeze-point depressants (and perhaps other additives).

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Appendix A. Kigali Amendment HFC Phasedown Schedule

On 15 Oct 2016, Parties to the Montreal Protocol adopted the "Kigali Amendment" that adds HFCs to the Montreal Protocol and gradually reduces their consumption (production + imports - exports - destruction) as shown below:

	Article 5 Group 1	Article 5 Group 2	Article 2
Baseline	2020-2022	2024-2026	2011-2013
Formula	Average HFC consumption	Average HFC consumption	Average HFC consumption
HCFC	65% of baseline	65% of baseline	15% of baseline*
Freeze	2024	2028	Not applicable
1st step	2029 – 10% Reduction	2032 – 10% Reduction	2019 – 10% Reduction
2nd step	2035 – 30%	2037 – 20%	2024 – 40%
3rd step	2040 – 50%	2042 – 30%	2029 – 70%
4th step	None	None	2034 – 80%
Plateau	2045 – 80%	2047 – 85%	2036 – 85%

* For Belarus, Russian Federation, Kazakhstan, Tajikistan, Uzbekistan 25% HCFC component of baseline and different initial two steps (1) 5% reduction in 2020 and (2) 35% reduction in 2025

Group 1: Article 5 parties not part of Group 2
Group 2: GCC, India, Iran, Iraq, Pakistan

Appendix B. Selected Crew Casualty Requirements

Parameter	Requirement
Fire Suppression	Extinguish all flames without reflash
Skin Burns[a]	Less than second degree burns (<2400°F-s over 10 sec or heat flux < 3.9 cal/cm^2)
Toxic Gases[a]	Acid Gases (HF + HBr + 2·COF_2) < 746 ppm-min (5 min dose) Other toxic gases (e.g., CO_2, CO, NOX, HCN) are also measured
Oxygen[b]	Levels at breathing locations of at least 16%
Overpressure[b,c]	Lung damage <11.6 psi; Ear damage ≤ 4 psi
Discharge Impulse Noise[d]	No hearing protection limit: <140 dBP Single hearing protection limit: <165 dBP
Discharge Forces[e]	Not to exceed 8 g averaged over 30 milliseconds
Agent[f]	Concentration within occupational safety limits
Fragmentation[g,h]	Ejected non-agent particles <300 micrometers Non-Shatterable Cylinders (NONSHAT)

a) Ripple, Gary and Mundie, Thomas, "Medical Evaluation of Nonfragment Injury Effects in Armored Vehicle Live Fire Tests," Walter Reed Army Institute of Research, September 1989.

b) Swanson, Dennis, "Fire Survivability Parameters for Combat Vehicle Crewmen," Department of the Army, Office of the Surgeon General, 20 February 1987.

c) Rice, W. A., "Noise Specification for Automatic Fire Extinguishing Systems (AFES)," Dept. of the Army Memorandum, 14 Nov 2013.

d) "Hearing Conservation Program," US Army Pamphlet 40-501, January 2015; similar criteria are found in "Design Criteria Noise Limits," MIL-STD-1474, 1997.

e) Extrapolated from the 57 N-m limit given in reference (a).

f) Lowest Observed Adverse Effects Level per "NFPA 2001 Standard on Clean Agent Fire Extinguishing Systems," (HFC-227ea) and "NFPA 12A Standard on Halon 1301 Fire Extinguishing Systems," National Fire Protection Association (NFPA).

g) Section 3.4.1.3 in "VALVE AND CYLINDER ASSEMBLIES, HALON 13O1," MIL-DTL-62547.

Section 3.3.9 in "CYLINDERS, STEEL, COMPRESSED GAS, NON-SHATTERABLE, SEAMLESS, 1800 PSI AND 2100 PSI," MIL-DTL-790