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Assessing the Impact of Advanced Cooling Technology in Firefighting Gear during Live Burn Scenario

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Conflicts of interest (COI)

None Declared.

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CRediT author statement

Zhaochong Yu: Software, Formal analysis, Visualization, Writing- original draft. Lorenna Altman: Data curation, Project administration, IRB approval. Qichen Fang: Resources. Ryan Bellacov: Writing - review & editing. Rosie Davis: Formal analysis. Kermit Davis: Writing - review & editing. Ashley Kubley: Conceptualization, Supervision, Funding acquisition. Myoung

Ok Kim: Conceptualization. Mark Schulz: Resources. Vesselin Shanov: Resources. Williams Jetter: Supervision. W. Jon Williams: Supervision. M Minhaj: Data curation. Zahid Hasan: Data curation. Marepalli Rao: Methodology, Writing – original draft, Writing - review & editing. Amit Bhattacharya: Supervision, Conceptualization, Resources, Funding acquisition, Writing – original draft, Writing - review & editing.

Data availability:

Data available on request from the authors.

AI detailed statements:

No AI was utilized at any stages of the hypothesis, data collection, data evaluation, manuscript preparation etc.

Ethical Approval

The Institutional Review Board (#2022-0682) of the University of Cincinnati approved the study.

Clinical Significance

We are introducing a new product, which might help firefighters in controlling body temperature when fighting fires. The product is tested in a live burn facility and compared with a standard firefighter coat. Testing is so designed to help the engineers to learn from the data for improving the product.

Abstract

Objective: A firefighter wears a standard safety coat, its model unchanged for many years, when tackling a fire. We designed a new cooling system coat with carbon nano tube-based fabric and pouches inside the coat for coolants and fans. The coats, one standard and the other still evolving, are compared on several metrics including core body temperature and thermal comfort.

Methods: An experimental protocol was designed involving a live burn facility under the paradigm of non-inferiority study with firefighters trying both coats. The metrics are measured at several phases of the protocol. Multivariate t-test is used to compare the performance of the coats.

Results: The new coat is not inferior to the standard coat.

Conclusion: The new coat in its final form, which is yet to be tested fully, is a plausible replacement for the standard coat.

Keywords: Perceptions, Borg Scale, Respiratory Distress, Heart rate, Heart rate variability, Dry ice as a coolant, Hyperthermia.

Learning Outcomes

- The design of the safety coat firefighters use in combating fires has not changed for many, many years. We designed a novel coat with carbon nano tube-based fabric and pouches inside the coat, accommodating coolants and fans, and a new fabric.
- We designed a protocol, operational in a live burn facility, for comparing the performance of the standard coat and the new evolving coat, on several metrics.
- This is the first paper expounding the proof-of-concept in the introduction of a novel coat in a live burn facility.

1. Introduction

More than a million people work in the United States as career (34%), volunteer (53%), or paid-per-call (12%) firefighters[1]. Firefighters regularly perform physiologically and physically demanding tasks in high-heat and toxic environments[2-6]. Heat accumulates in firefighters as their heat gain from the environment and physical movement (increased metabolism) is greater than their heat loss. Firefighters are also exposed to heat stress from the metabolic heat they are generating while performing a task[7-9]. Heat stress leads to increased heart rate (HR) and oxygen intake; a physiological phenomenon called heat strain[10]. The heavy protective equipment firefighters must wear to prevent injury from external hazards simultaneously contributes to increased heat strain[11]. The central nervous system's functionality is compromised as the core-body temperature (CBT) rises, potentially leading to postural instability, which can cause injuries such as slips, trips, and falls[2,6].

The increased HR and breathing rate firefighters experience due to heat stress while performing their duties increase their risk of ischemia and sudden cardiac arrest. Ischemia, among other cardiac episodes, contributes to 45% of on-duty deaths experienced among firefighters[8]. These cardiac events most commonly occur while fighting a fire, responding to, or returning from an emergency call, and during high-intensity training. Heat strain can also lead to heat-related disorders such as heat exhaustion or heat- stroke, which can cause permanent disability or death[10]. These cardiac events have also been found to occur after fighting a fire, as blood clotting risk increases in response to physical exertion and extreme heat[12].

Firefighters must wear protective gear to reduce heat-related hazards due to fire, radiation, and convection. The gear includes a protective coat and pants, a helmet, gloves, boots, and a self-contained breathing apparatus (SCBA), with a total weight of approximately 26 kilograms[13,14]. These factors, in addition to the psychophysiological demands that firefighters experience in high-heat environments, further contribute to increased CBT[11]. Increases in CBT can generally be regulated by a process called thermoregulation, which is the ability to maintain an internal temperature in a safe range of 36 to 38 °C[11]. Changes in brain temperature and CBT have been shown to correlate with one another[15]. Heat is thought to build up in the brain when dissipation mechanisms, such as sweating, are insufficient in removing heat in the body[16]. The bulky gear worn by firefighters further prevents heat dissipation, and this can lead to permanent damage to brain cells[15].

The overall strain on both the physical and psychophysiological well-being of firefighters causes autonomic nervous system stress, impacting the heart's rhythm. This can be measured by a parameter known as heart rate variability (HRV), which quantitatively assesses the change in HR that an individual is experiencing over time[17]. Heart rate variation is controlled by the autonomic nervous system communicating with the heart through the sympathetic branch of the autonomic nervous system[17]. Heart rate variability becomes irregular under stressful conditions due to hyperactivity of the sympathetic nervous system[17]. Heart rate variability is the most used indicator of autonomic nervous system stress. The cardiovascular response to different job-related stressors can also be measured by monitoring HRV[18]. The regulation of HRV after physical exertion is a strong predictor of mortality; abnormal recovery denotes a higher risk of death[19]. A high HRV is generally associated with strong fitness levels[20]. A low HRV is associated with lower cognitive and physical performance, cardiovascular disease, psychological stress, depression, and anxiety[17]. Congestive heart failure has also been linked to decreases in HRV[21]. Recent studies suggest that exposure to large temperature variabilities also reduces HRV, further presenting a risk to firefighters[22].

The current design of the standard firefighter (SF) coat has remained the same for several years. The new cooling system (CS) coat uses carbon nanotube (CNT)-based fabric and includes two pouches each with a fan and a switch, which can be turned on or off manually (Figure 1). The coat and the pants weigh about 4.5 kg. The pouches can accommodate different types of coolants. When the switch is turned on, air flows through the coolants and circulates inside the coat. The new coat is experimental. When a firefighter with the new coat emerges from the live burn facility, the engineers, on hand, check whether the fan is working, and if the coolant is still functional. If they are not, they take notes on how best to rectify its deficiency. In any case, our objective is to compare the standard coat and the coat with a new CNT fabric, irrespective of the functionality of the fans and dissipation of coolants too soon, on several metrics. In other words, we want to compare the performance of the SF coat and a coat with a new fabric, ignoring its novel features. The project comes under the paradigm of non-inferiority study. The goal is to find evidence that the new coat is not inferior to the standard coat.

In summary, the main objective of the current study was to contrast the SF and the current version of the CS coat on several metrics including physiological measurements (CBT, HR, HRV, and Heat Storage—HS) and perceptions (e.g. Thermal Comfort, Borg Scale, and Respiratory Distress). A preliminary hypothesis is that the CS coat is as good as the SF coat (non-inferiority study) on all metrics. If the hypothesis is supported, the designers will work on improving the CS coat for future testing.

The idea of a coat with coolants is not new. Chou and associates[23] examined the effectiveness of ice packs inside the coats on rectal, skin, and body temperature. An experiment was conducted inside a laboratory with a relatively high temperature of 30 °C and 50% relative humidity. They also experimented with phase change material (PCM) at different temperatures for the coats. It was observed that PCM at 20 °C is more effective than other cooling devices. Their experiment does not reflect the real conditions of firefighting. Our experiment for comparing the coats was set in a live burn facility in which a fire was started deliberately, and firefighters pursue activities reflecting real life situations.

2. Methods

2.1 Experimental Protocol

A protocol was set up for the firefighters to follow at the live burn facility. After donning a coat (SF or CS), baseline measurements were taken. Then the firefighter entered the live burn facility and carried out firefighting tasks for about ten minutes (Scenario 1). It was followed by a rest period for about 30 minutes (Rest period 1 is outside the live burn facility) and this pattern was repeated two more times (Scenario 2 in the live burn facility for about ten minutes followed by a rest period (Rest period 2) outside the live burn facility for about 30 minutes and followed by Scenario 3 inside the facility for about ten minutes). We recorded times spent by the firefighters inside the live burn facility in Table S.1 of the supplement (http://links.lww.com/JOM/B860).

The baseline spanned twenty minutes after wearing a coat. It was used to collect data on several metrics such as HR, HRV, and CBT at one-second intervals for each firefighter on each coat. Data collection was outlined in Figure 2.a. Data on perceptions (Borg Scale, Thermal Comfort Scale, and Respiratory Distress Scale) of how a firefighter felt after wearing a coat were obtained on each firefighter at the end of each scenario and during the baseline time. The data collection procedure was outlined in Figure 2. b.

2.2 Data Collection

2.2.1 Participants

Data were obtained from ten firefighters using the SF coat. Each firefighter was instructed to stay inside the live burn facility at least ten minutes in each scenario. However, only six firefighters followed the protocol. We are using data on these six firefighters (mean ± SD: age 35.6 ± 8.9 years; weight 111.5 ± 10.7 kg; height 180.4 ± 11.5 cm).

Data were obtained from ten firefighters using the CS coat. All these firefighters followed the protocol (mean ± SD: age 36.3 ± 8.4 years; weight 116.1 ± 9.7 kg; height 184.2 ± 9.8 cm).

The inclusion criteria were that only full-time firefighters from Ohio, with experience of at least 3 years. They had to be between the ages of 21 to 50 years. Females were excluded from the study due to the restricted cut and fit of the gear. The Institutional Review Board (#2022-0682) approved the study, and each participant gave written informed consent before the experiment started.

2.2.2 Core Body Temperature, Heart Rate, Heart Rate Variability, and Heat Storage

The live-burn exercise protocol served to mimic the conditions of routine firefighting, during which physiological parameters of HR, HRV, and CBT of the firefighters were monitored during the entire protocol period using a bioharness system (ZEPHYR™ Performance Systems). A bioharness was placed across the subject's bare chest upon their arrival at the live burn facility. At the end of the testing, the bioharness was removed. In addition, the following measures were calculated: a) Heat Storage (HS) (watts per hour) = (average CBT (◦C) at scenarios – average CBT (◦C) at the baseline) * body weight (kg) * specific heat capacity of body tissue (0.97 watts per hour/kg ◦C) [3,10]; b) percent of total time spent over the threshold for hyperthermia (38° C) at the baseline, Scenarios 1, 2, and 3, and Rest periods 1 and 2. (Table S.6 and Figure S.1, http://links.lww.com/JOM/B860) We also identified the progress of HR from the baseline to the rest periods 1 and 2. (Figure 3. b.)

2.2.3 Perceptions

Subjects reported perceived physical exertion scales BORG, Thermal Comfort (TC), and Respiratory Distress Scales (RD) during the baseline before starting the live-burn exercise, and then after each scenario[24-26]. The BORG scale ranged from 6—being very, very light to 20—being very, very hard. The Thermal Comfort Scale ranged from 0—unbearably cold, to 4—comfortable, and to 8—unbearably hot. The Respiratory Distress scale ranged from 1—my breathing is ok right now to 7—I can't breathe (Figure 4. a).

2.3 Data Analysis

2.3.1 Physiological responses

The average physiological parameters for each scenario, rest period, and baseline were calculated. We used a multivariate two sample t-test (Hotelling's T-squared test) procedure on the data comparing the coats at all the epochs, consisting of baseline, scenarios and rest periods. This procedure is equivalent to multivariate analysis of variance (MANOVA). In view of small sample sizes, we used bootstrap multivariate two sample t-test to test the equality of population mean vectors at the epochs.

2.3.2 Perceptions

For each firefighter, under each coat and each perceptive scale, we collected data at the baseline and after each scenario. We used a multivariate two sample t-test (Hotelling's T-squared test) procedure on the data comparing the means of perceptions at the epochs by coats. In view of small sample sizes, we used bootstrap multivariate two sample t-test to test the equality of population mean vector at the epochs by coats.

3. Results

3.1 Fulfillment of the Protocol

Each firefighter with each coat was asked to spend at least ten minutes in each scenario. Only six firefighters with SF coats completed the stipulated protocol. All ten firefighters completed the protocol with the CS coat. The observed difference between the coats on completion (six out of ten on the SF coat versus ten out of ten on the CS coat) was found to have p-value 0.09. For the rest of the analysis, we used the data from firefighters, who completed the protocol.

3.2 Physiological Measurements

The primary purpose of the study is to examine how well a firefighter is protected from hyperthermia (Figure 3. a) while firefighting inside a live burn facility. During Rest Period 1, the firefighters crossed the hyperthermia temperature on both coats. However, the temperature never went beyond 38.4 °C on average and the coats indeed differed significantly (p=0.033) when CBT was examined at all epochs of the protocol. The significance was also corroborated by the bootstrap method (0.029).

As expected, HR increased in response to firefighting inside the live burn facility over successive scenario of the protocol. Again, as expected, HR decreased during the rest periods from the scenarios (Figure 3. b). However, HR never reached the baseline average suggesting increased fatigue coupled with dehydration[27]. There were no significant differences in the observed averages of HR over the epochs of the protocol between the coats (p=0.33). The bootstrap p-value was 0.36.

There were no significant differences in the observed averages of HRV (p = 0.82) and HS (p = 0.19) at all epochs of the protocol between CS and SF coats. The bootstrap p-values were 0.85 and 0.20, respectively.

The numerical results are reported in the supplement (Tables S.2-6, http://links.lww.com/JOM/B860) and the graphs (Figure 3) in the main paper.

3.3 Perceptions

3.3.1 Perceived Exertion (Borg scale)

The firefighters felt equally comfortable with both coats at the baseline. When performing tasks inside the live burn facility, the coats became more oppressive but never reached the unbearable stage. The average Borg Scale over the stages of the protocol was not significantly different across the coats ($p = 0.56$).

3.3.2 Thermal Comfort

However, the thermal comfort averages over several stages of the protocol were significantly different across the coats ($p<0.001$), with the CS coat being preferred over the SF coat. When inside the live burn facility, perception hovered between 'comfortable' and 'unbearably hot.'

3.3.3 Respiratory Distress

At the baseline, the average respiratory distress scale was exactly the same between the coats. At the remaining stages of the protocol, some differences were observed in the averages. However, the differences in the averages between the coats were not significantly different ($p = 0.44$).

The summary statistics along with p-values are reported in the supplement (Tables S.7-9, http://links.lww.com/JOM/B860) and the graphs (Figure 4) in the main paper.

4. Discussion

When our team designed the CS coat, it was not clear whether it would be functional at the same level as the SF coat. The CS coat was made up of a different fabric on the interior portion, which included a carbon nanotube material. In addition, two pouches were sewn inside the coat where coolants could be placed. Further, a fan with a switch was installed to pump air through the coolants and throughout the inside of the coat. With this initial design, it was not clear whether ice packs or dry ice should be utilized, whether fans would work when executing protocol tasks inside the live burn facility, and at what speed the fan should run. Some of the factors that needed to be considered were the impact of completing fire activities that require strenuous exertions, lifting, moving, dragging, bending, stretching, etc. All of these could impact the functionality of the fans and cooling system. If the fan fails, the CS coat is no different from the SF coat functionally. If the fans fail, mostly it was the case, through the tasks inside the live burn facility, the coolants were duds, utterly useless. Successful running of fans was critical for the CS coat to make a mark. It was a steep challenge to make fans function through thick and thin. The engineering team in our project needed all the information the firefighters can give wearing CS coats. To document functionality of the fans in the first phase of development, a researcher checked the status of the coolants and functionality of the fans when the firefighter emerged from the live burn facility. There were many cases of pre-mature ice melting and fan(s) dead in the first few minutes of the protocol. Learning from the failures of fans and coolants, engineers continued to improve the CS coat design.

The researchers hypothesized that the CS coat was not inferior to the SF coat on all metrics of interest. To test this hypothesis, we had planned to utilize data from ten firefighters on each coat but due to several unforeseen circumstances beyond our control, four did not complete the protocol with the SF coat. Some surprises emerged from our analyses. On CBT, the SF coat emerged better than the CS coat in the sense that its line graph of average CBT over the phases of the protocol is below that of the one associated with the CS coat (Figure 3.a). The difference was significant. On Thermal Comfort, it was the other way around. The CS coat was better (Figure 4.c). Otherwise, there is no significant difference between the average metrics (Table S.10, http://links.lww.com/JOM/B860). Overall, the null hypothesis of non-inferiority was not rejected but may have resulted from a couple of study design factors including 1) low number of participants, 2) different periods of data collection (e.g., SF in winter, CS in spring), and 3) one size fits all CS coat. The recruited firefighters came with their own SF coats. However, we supplied the CS coats, which we took an inordinately long time to supply with. Further, there was a relatively low number of firefighters that provided us with the data. The experimental conditions at the live burn facility are supposed to mimic reality, but the conditions may have been harsher than reality.

As for the timing of data collection from the live burn facility for SF and CS coats, there were two different seasons involved (e.g., SF coat in winter with temperature ranging 15 to 19 °C, CS in late spring from 19 to 27 °C). The scheduling of when the coats were to be evaluated was mainly dependent on the development schedule of the CS coat, as the prototype process was not completed until early spring. However, the conditions inside the live burn facility and workload for the firefighters are identical no matter what the temperature outside is. Prior to the entry to the live burn facility, a fire was started on the first floor in a specific live burn room. In Scenario 1, the firefighters were instructed to carry out the same maneuvers: carry a hose into the burn room on the first floor for fire control; climb the stairs to the second floor with the hose. In Scenario 2, search the first floor and then come out; take the hose to the burn room for fire control. In Scenario 3, bring the hose to the second-floor search; bring the hose back down the stairs to the fire room for fire control. In each scenario, the firefighters were instructed not to spend more than fifteen minutes. We expected the metrics to reflect coats worn but not on what the temperatures were outside.

Firefighter protective gear increases the metabolic rate of firefighters due to movement resistance and increased body mass. Moreover, the protective gear, whether it is the SF coat or CS coat, weighs about a quarter of the firefighters' average weight. As a result, firefighters experienced increased oxygen consumption, skin temperature, CBT, HR, and perception scales[14]. Firefighters are unable to rely on natural thermoregulation to cool the body due to their encompassing protective gear and extreme environmental conditions (e.g., extreme heat). Thus, cooling interventions to protect them from the negative effects of heat stress are necessary to reduce physiological strain and adverse health effects[28]. Some of previous interventions include ice vests, dry ice air-cooled vests, and liquid-circulated garments[28]. Other potential interventions are passive recovery, extractor, and misting fans, hand and forearm water immersion, or vests made of phase-changing material[14]. To ensure wide use and effective protection, it is important that the cooling intervention be practical and comfortable for the firefighters. Some of these interventions worked effectively but testing was done in an artificial environment inside a lab. In an in-depth literature review, Douzi and associates[29] concluded that cooling garments, ice vests, and air ventilation are the most effective cooling techniques. Cooling vests work by dissipating heat away from the body[14]. The CS coat had a built-in cooling fan and coolant modules designed to optimize dissipation of heat. Preliminary data revealed some benefits, but the CS prototype coat development was ongoing with respect to heat dissipation and functionality. In the laboratory study that is a companion to the live burn study (manuscript in preparation), our research team found the CS coat had significantly lower CBT as compared to the SF coat during standardized training tasks in low heat conditions with no difference in postural balance parameters and heart rate metrics[30].

Bennet and associates[31] compared four-pack cool vests versus six pack cool vests in reducing heat strain, but the experiment was conducted in a lab. Smolander and associates[32] examined the effects of wearing an ice vest on some physiological measurements, but the experiment was conducted in a lab. Selkirk and associates[33] compared active and passive cooling during work in a warm environment while wearing firefighting protective clothing, but the experiment was conducted in a controlled environment. Carter[34], Giesbrecht[35] and their associates examined the effectiveness of immersing hands and forearms in water under heat stress while working with heavy gear in a hot and humid environment. Two major differences between these studies and our study are: a) our fire coat used CNT based fabric, and b) a live burn facility, mimicking reality.

While the current results did not specifically show improvements in the targeted metrics for the CS coat, the research team has already identified key design characteristics and changes that can improve the performance of the next generation prototype. We are hopeful that continuous prototype improvement will result in a better coat that remains protective of the firefighter as well as provides an improved thermal environment, better preparing the firefighter to withstand the intense temperatures of a live burn event.

The cost of the improved CS coat that resulted from this study is unknown. The production company is yet to make the improved version which can be marketed. Our group believes that once manufacturing gets into full swing, the coat will be widely used, the cost will go down beating the price of an SF coat.

5. Limitations

While the firefighters who participated were similar in stature, the actual fit of the CS coat likely varied from firefighter to firefighter thus impacting the efficiency and effectiveness of the cooling system, ultimately impacting the outcome metrics.

Other considerations are that the study population was limited to Caucasian males, with an average age in their thirties. Furthermore, the live burn scenarios were only simulations of fire activities rather than actual fires. While the live burn facility allowed the fire to be controlled and the environmental conditions to be controlled, actual physiological responses may be different in real life conditions where firefighters have additional life-threatening stresses.

6. Conclusion

Overall, only two metrics were found to be significantly different between the SF and CS coats. More specifically, statistically significant differences were found with respect to the metrics CBT and Thermal Comfort between the coats. Seven metrics were under focus for comparing the coats. Seven hypotheses were tested using the data on the same subjects. A multiple testing adjustment was warranted. Bonferroni correction was implemented on the observed p-values. Each observed p-value was multiplied by seven. Adjusted p-values were reported in Table S.10 (http://links.lww.com/JOM/B860).

Seeking significance was not our goal. Establishing parity between the coats was the main goal. Improving the CS coat using the data generated from the evolving CS coat was another goal. We can say that our goals were met. The current study falls under the ‘proof-of-concept,’ where this was the first prototype of a new system designed to cool a firefighter prior to entering a live fire and throughout the fire suppression activities. Based on these results, the research team has already started to redesign the CS coat to improve its efficiency and effectiveness of heat dissipation as well as maintaining overall functionality.

Added while revising the manuscript: The project entered the second year of experimentation. The evolving CS coat gave rise to a LC (LION’s cooling system) coat, in which fans were robustly running through all activities at the live burn facility.

References

1. National Fire Department Registry Summary. (2023). In U.S.F. Administration, ed.

2. Morris, C., and Chander, H. (2018). The Impact of Firefighter Physical Fitness on Job Performance: A Review of the Factors That Influence Fire Suppression Safety and Success. Safety *4*, 2-11. 10.3390/safety4040060.

3. Van Gelder, C.M., Pranger, L.A., Wiesmann, W.P., Stachenfeld, N., and Bogucki, S. (2008). An experimental model of heat storage in working firefighters. Prehosp. Emerg. Care *12*, 225-235. 10.1080/10903120801907430.

4. LeBlanc; PR, and Fahy, R. (2003). Full Report: Firefighter Fatalities in the United States–2002. . National Fire Protection Association, Quincy, MA, 2003.

5. Soteriades, E.S., Targino, M.C., Talias, M.A., Hauser, R., Kawachi, I., Christiani, D.C., and Kales, S.N. (2011). Obesity and risk of LVH and ECG abnormalities in US firefighters. J Occup. Environ. Med *53*, 867-871. 10.1097/JOM.0b013e318221c6fe.

6. Singh, U., Mani, A., James, K., Rao, M.B., and A, B. (2019). Effects of Heat Exposure from Live-Burn Fire Training on Postural Stability of Firefighters. Ergonomics Int J *3*. 10.23880/eoji-16000213.

7. Aljaroudi, A., Bhattacharya, A., Kadis, D., Strauch, A., Quinn, T., and Williams, W. (2017). The Effect of Industrial Hyperthermia on Firefighters' Cognitive Function in Warm Humid Environment. Presented at the 64th annual meeting of the American College of Sports Medicine; 2017 May 30 - June 3; Denver, CO.

8. Aljaroudi, A., Bhattacharya, A., Yorio, P., Strauch, A., Quinn, D., and Williams, W. (2021). Probability of hyperthermia in a hot environment while wearing a liquid cooling

garment underneath firefighters' protective clothing,. Journal of Occupational and Environmental Hygiene, 1-9. 10.1080/15459624.2021.1898622.

9. Aljaroudi, A., Kadis, D., Bhattacharya, A., Strauch, A., Quinn, T., and Williams, W. (2020). Effect of continuous cooling on inhibition and attention while wearing firefighter's PPE in a hot environment Journal of occupational and environmental hygiene *17*, 243-252. 10.1080/15459624.2020.1726933.

10. Mani, A., Musolin, K., James, K., Kincer, G., Alexander, B., Succop, P., Lovett, W., Jetter, W., and Bhattacharya, A. (2013). Risk factors associated with live fire training: buildup of heat stress and fatigue, recovery and role of micro-breaks. Occupational Ergonomics *11*, 109-121. 10.3233/OER-130212.

11. Aljaroudi, A., Bhattacharya, A., Strauch, A., Quinn, T., and Williams, W. (2022). Effect of cooling on static postural balance while wearing firefighter's protective clothing in a hot environment. INTERNATIONAL JOURNAL OF OCCUPATIONAL SAFETY AND ERGONOMICS, 1-7. 10.1080/10803548.2022.2138142.

12. Newman, T. (2017). Why Do Firefighters Have an Increased Risk of Heart Attacks? .

13. Nybo, L. (2012). Brain Temperature and Exercise Performance: Brain Temperature and Exercise Performance. Experimental Physiology *7*, 333–339. 10.1113/expphysiol.2011.062273. .

14. Barr, D., Gregson, W., and Reilly, T. (2010). The Thermal Ergonomics of Firefighting Reviewed. *Applied Ergonomics 41*, 161–172. 10.1016/j.apergo.2009.07.001.

15. Kiyatkin, E.A. (2010). Brain Temperature Homeostasis: Physiological Fluctuations and Pathological Shifts. . Frontiers in Bioscience, *15*. 10.2741/3608.

16. Thompson, C., Ferrie, L., Pearson, S.J., Highlands, B., and Matthews, M.J. (2024). In the heat of the moment: the effects of extreme temperatures on the cognitive functioning of firefighters. Ergonomics, 1-15. 10.1080/00140139.2024.2326584.

17. Shinn, J., Lee, J., Yang, S., Lee, M., and Chung, I. (2016). Factors related to heart rate variability among firefighters. Annals of Occupational and Environmental Medicine *28*, 1-9. 10.1186/s40557-016-0111-6.

18. Meina, M., Ratajczak, E., Sadowska, M., Rykaczewski, K., Dreszer, J., Bałaj, B., Biedugnis, S., Węgrzyński, W., and Krasuski, A. (2020). Heart Rate Variability and Accelerometry as Classification Tools for Monitoring Perceived Stress Levels—A Pilot Study on Firefighters. Sensors *20*. 10.3390/s20102834.

19. Cole, C.R., Foody, J.M., Blackstone, E.H., and Lauer, M.S. (2000). Heart Rate Recovery after Submaximal Exercise Testing as a Predictor of Mortality in a Cardiovascularly Healthy Cohort. . Annals of Internal Medicine *132*. 10.7326/0003-4819-132-7-200004040-00007.

20. Labs, D.I. (2023). Average HRV by Age, Gender | Normal HRV Range for Men & Women.” WHOOP.

21. Navya Alugubelli, Hussam Abuissa, and Roka., A. (2022). Wearable Devices for Remote Monitoring of Heart Rate and Heart Rate Variability—What We Know and What Is Coming. Sensors *22*. 10.3390/s22228903.

22. Tang, M., He, Y., Zhang, X., Li, H., Huang, C., Wang, C., Gao, Y., Li, Y., Kan, H., Hu, J., and Chen, R. (2021). The Acute Effects of Temperature Variability on Heart Rate Variability: A Repeated-Measure Study. Environmental Research *194*. 10.1016/j.envres.2020.110655.

23. Chou, C., Tochihara, Y., and Kim, T. (2008). Physiological and subjective responses to cooling devices on firefighting protective clothing. European journal of applied physiology *104*, 369-374. 10.1007/s00421-007-0665-7.

24. Morgan, W., and Raven, P. (1985). Prediction of distress for individuals wearing industrial respirators. . American Industrial Hygiene Association Journal *46*, 363-368. 10.1080/15298668591394987.

25. Borg, G. (1982). Psychophysical Bases of Perceived Exertion Medicine & Science in Sports & Exercise, *14*, 377-381.

26. O'Sullivan, S. (1984). Perceived Exertion A Review. . Physical Therapy; 1984 *64*, 343-346. 10.1093/ptj/64.3.343.

27. Group, E.K.C.E. (1986). Ergonomic work design for people at work. In (Van Nostrand Reinhold Company), pp. 225-241.

28. Aljaroudi, A., Bhattacharya, A., Strauch, A., Quinn, T., and Williams, W. (2017). Utilization of Active Cooling on Postural Balance while Wearing Firefighter's Ensemble in Warm Humid Environment. Presented at the World Congress of International Society of Posture and Gait Research; 2017 June 25- 29; Ft. Lauderdale, FL.

29. Douzi, W., Dugue, B., Vinches, L., Al Sayed, C., Halle, S., Bosquet, L., and Dupuy, O. (2019). Cooling during exercise enhances performances, but the cooled body areas matter: A systematic review with meta-analyses. Scandinavian Journal of Medicine & Science in Sports *29*, 1660-1676. 10.1111/sms.13521.

30. Bellacov, R., Davis, R., Davis, K., Altman, L., Kubley, A., Kim, M., Schulz, M., Rao, M., Bhattacharya, A., Yu, Z., and Priya, M. (2024). Enhancing Firefighter Performance

and Safety: Evaluating the Impact of a Cooling Vest on Core Body Temperature and Physical Performance. Submitted.

31. Bennett, B.L., Hagan, R.D., Huey, K., Minson, C., and Cain, D. (1995). Comparison of two cool vests on heat-strain reduction while wearing a firefighting ensemble. European journal of applied physiology and occupational physiology *70*, 322-328. 10.1007/BF00865029.

32. Smolander, J., Kuklane, K., Gavhed, D., Nilsson, H., and Holmér, I. (2004). Effectiveness of a light-weight ice-vest for body cooling while wearing fire fighter's protective clothing in the heat. International journal of occupational safety and ergonomics *10*, 111-117. 10.1080/10803548.2004.11076599.

33. Selkirk, G.A., McLellan, T.M., and Wong, J. (2004). Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. Journal of occupational and environmental hygiene *1*, 521-531. 10.1080/15459620490475216.

34. Carter, J., Rayson, M., Wilkinson, D., Richmond, V., and Blacker, S. (2007). Strategies to combat heat strain during and after firefighting. Journal of Thermal Biology *32*, 109-116. 10.1016/j.jtherbio.2006.12.001.

35. Giesbrecht, G.G., Jamieson, C., and Cahill, F. (2007). Cooling hyperthermic firefighters by immersing forearms and hands in 10 C and 20 C water. Aviation, space, and environmental medicine *78*, 561-567.

Figure Legend

Figure 1. The Cooling System coat, which used carbon nanotube-based fabric with two pouches and a fan to cool the firefighter. The arrows identify the location of the pouches which can take dry ice.

Figure 2. Protocol of the order of sessions in the Live Burn Facility. a) sessions at which measurements on core body temperature (CBT), heart rate (HR), and heart rate variability (HRV) were collected. b) sessions at the end of which data on Thermal Comfort, Respiratory Distress, and Borg Scale was collected.

Figure 3. Physiological measurements for Standard coat (SF) and Cooling System coat (CS) as a function of the session (scenario and rest): a) Average Core Body Temperature (CBT); b) Average Heart Rate (HR); c) Average Heart Rate Variability (HRV); and d) Heat Storage by Scenario Versus Baseline.

Figure 4. Subjective Perceptions for Standard coat (SF) and Cooling System coat (CS) as a function of session (scenario and rest): a) Description of all scales; b) Borg Scale (6 to 20); c) Thermal Comfort (0 to 8); and d) Respiratory Distress (1 to 7).

Appendix A. Supplement

Additional data analyses are reported in the supplement.

Figure 1

Figure 2

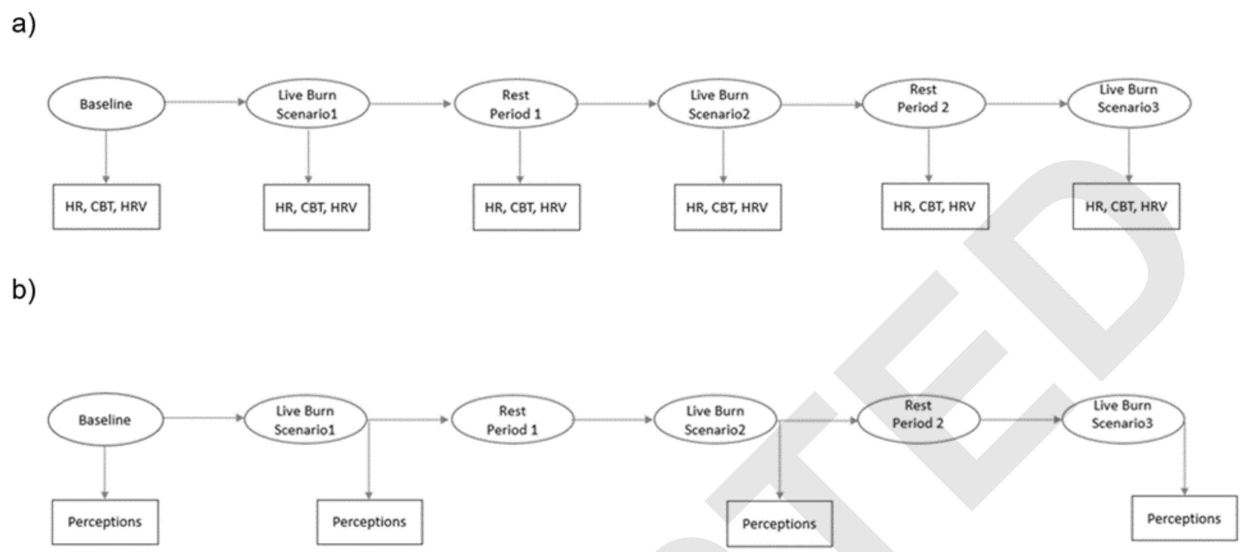

a)
Baseline
Live Burn Scenario1
Rest Period 1
Live Burn Scenario2
Rest Period 2
Live Burn Scenario3
HR, CBT, HRV
HR, CBT, HRV
HR, CBT, HRV
HR, CBT, HRV
HR, CBT, HRV
HR, CBT, HRV
b)
Baseline
Live Burn Scenario1
Rest Period 1
Live Burn Scenario2
Rest Period 2
Live Burn Scenario3
Perceptions
Perceptions
Perceptions
Perceptions

Figure 3

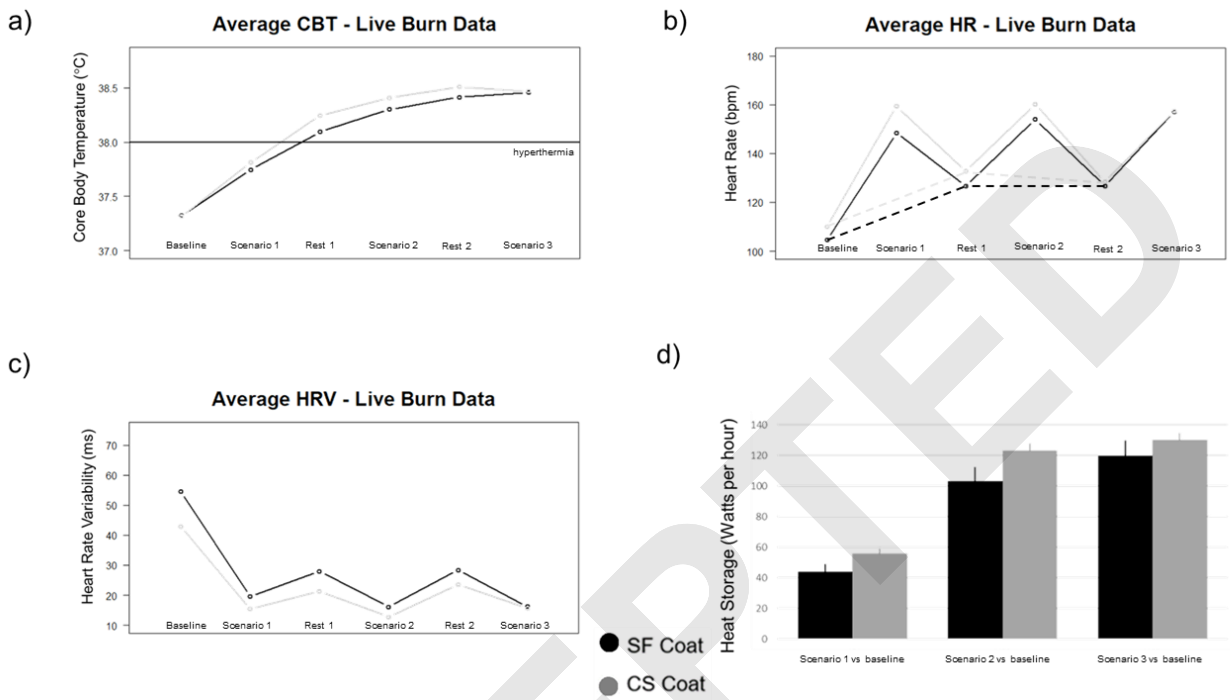
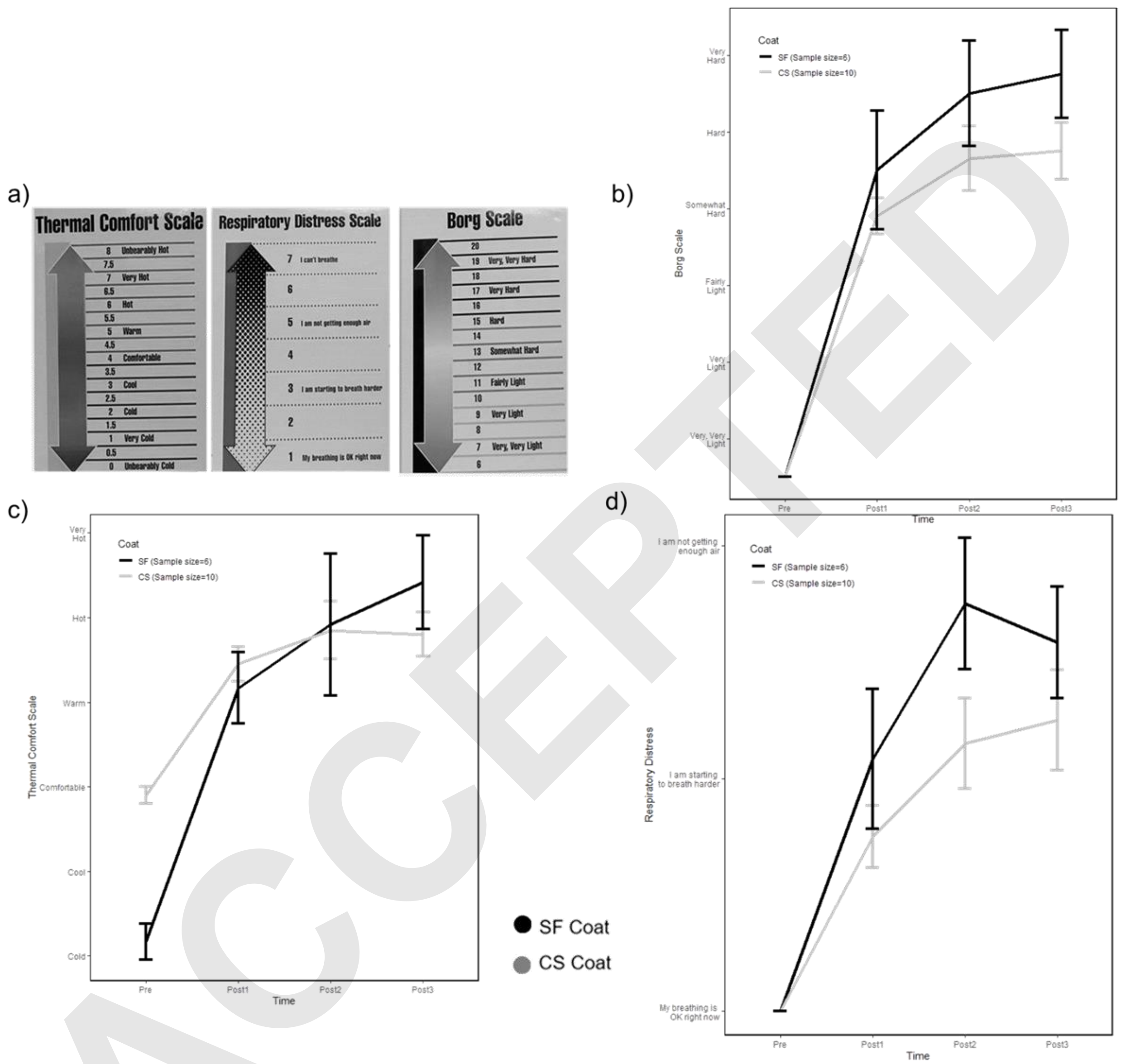
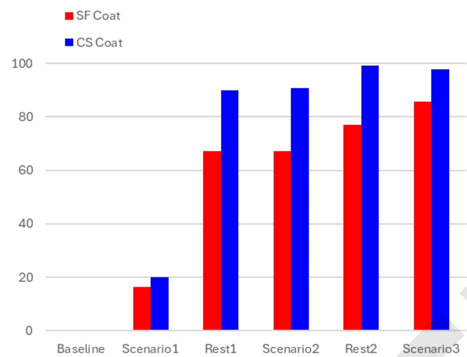

a)
Average CBT - Live Burn Data
Core Body Temperature (°C)
38.5
38.0
37.5
37.0
hyperthermia
Baseline
Scenario 1
Rest 1
Scenario 2
Rest 2
Scenario 3
b)
Average HR - Live Burn Data
Heart Rate (bpm)
180
160
140
120
100
Baseline
Scenario 1
Rest 1
Scenario 2
Rest 2
Scenario 3
c)
Average HRV - Live Burn Data
Heart Rate Variability (ms)
70
60
50
40
30
20
10
Baseline
Scenario 1
Rest 1
Scenario 2
Rest 2
Scenario 3
d)
Heat Storage (Watts per hour)
140
120
100
80
60
40
20
0
Scenario 1 vs baseline
Scenario 2 vs baseline
Scenario 3 vs baseline
SF Coat
CS Coat

Figure 4


a)
Thermal Comfort Scale
8 Unbearably Hot
7.5
7 Very Hot
6.5
6 Hot
5.5
5 Warm
4.5
4 Comfortable
3.5
3 Cool
2.5
2 Cold
1.5
1 Very Cold
0.5
0 Unbearably Cold
Respiratory Distress Scale
7 I can't breathe
6
5 I am not getting enough air
4
3 I am starting to breath harder
2
1 My breathing is OK right now
Borg Scale
20
19 Very, Very Hard
18
17 Very Hard
16
15 Hard
14
13 Somewhat Hard
12
11 Fairly Light
10
9 Very Light
8
7 Very, Very Light
6
b)
Coat
SF (Sample size=6)
CS (Sample size=10)
Very Hard
Hard
Somewhat Hard
Fairly Light
Very Light
Very, Very Light
Borg Scale
Pre
Post1
Post2
Post3
Time
c)
Coat
SF (Sample size=6)
CS (Sample size=10)
Very Hot
Hot
Warm
Comfortable
Cool
Cold
Thermal Comfort Scale
Pre
Post1
Post2
Post3
Time
SF Coat
CS Coat
d)
Coat
SF (Sample size=6)
CS (Sample size=10)
I am not getting enough air
I am starting to breath harder
My breathing is OK right now
Respiratory Distress
Pre
Post1
Post2
Post3
Time

Supplement:

Figure S1. **Percentage of time above hyperthermia temperature by coats – live burn data**



The average Borg Scales by each scenario under each coat is given in Table S7 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 4.b of the main paper.

We recorded time spent under each activity in Table S1.

Table S1. **Time spent (in minutes) in the Live Burn Facility**

SF					
FF ID	Scenario1	Rest1	Scenario2	Rest2	Scenario3
1	15	29	26	33	25
2	15	18	15	21	15
3	15	29	26	33	25
4	11	30	12	39	12
5	15	18	15	21	15
6	17	20	16	19	17
7	3	20	9	15	9
8	6	19	1	19	3
9	6	19	1	19	3
10	3	20	9	15	9
CS					
FF ID	Scenario1	Rest1	Scenario2	Rest2	Scenario3
1	15	17	15	20	15
2	11	30	12	39	12
3	14	22	15	24	16
4	10	19	12	28	12
5	17	20	16	20	15
6	10	19	12	28	12
7	17	32	16	33	15
8	15	17	15	20	15
9	17	32	16	33	15
10	14	22	15	24	16

The average CBT by each session under each coat is given in Table S2 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 3.a of the main paper.

Table S2. **Mean CBT by coats – live burn data - multivariate t-test**

CBT	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value	Bootstrap p-value
SF(n=6)	37.74	38.09	38.30	38.41	38.45	37.74	0.0328	0.029
CS(n=10)	37.81	38.25	38.41	38.51	38.46	37.81		

The average HR by each session under each coat is given in Table S3 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 3.b of the main paper.

Table S3. **Mean HR by coats – live burn data - multivariate t-test**

HR	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value	Bootstrap p-value
SF(n=6)	105.45	148.52	126.73	154.09	126.65	157.15	0.3323	0.361
CS(n=10)	112.73	159.08	132.90	159.98	128.49	157.05		

The average HRV by each session under each coat is given in Table S4 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 3.c of the main paper.

Table S4. **Mean HRV by coats – live burn data - multivariate t-test**

HRV	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value	Bootstrap p-value
SF(n=6)	53.14	19.55	28.02	16.09	28.35	16.28	0.8215	0.845
CS(n=10)	39.41	15.67	21.17	12.91	23.48	15.62		

The average HS by each scenario under each coat is given in Table S5 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 3.d of the main paper.

Table S5. **Heat Storage by coats – live burn data – two sample multivariate t-test**

Coat	Scenario1	Scenario2	Scenario3	p-value	Bootstrap p-value
SF(n=6)	43.90	103.28	119.56	0.1923	0.199
CS(n=10)	55.90	123.06	129.98		

The average percentage of time above hyperthermia temperature by each scenario under each coat is given in Table S6 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure S1 in the supplement.

Table S6. **Percentage of time above hyperthermia temperature by coats – live burn data – two sample multivariate t-test**

Coat	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value
SF(n=6)	0.00%	16.26%	67.24%	67.17%	77.03%	85.60%	0.5662
CS(n=10)	0.00%	19.88%	89.84%	90.78%	99.23%	97.69%	

Table S7: **Averages of Borg Scales by coat – multivariate t-test for two samples.**

Coat	Baseline	Scenario1	Scenario2	Scenario3	p-value	Bootstrap p-value
SF (n=6)	6	14	16	16.5	0.5563	0.553
CS (n=10)	6	12.8	14.3	14.5		

The average Thermal Comfort by each scenario under each coat is given in Table S8 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 4.c of the main paper.

Table S8: **Averages of thermal comfort scales by coat – multivariate t-test for two samples.**

Coat	Baseline	Scenario1	Scenario2	Scenario3	p-value	Bootstrap p-value
SF (n=6)	2.17	5.17	5.92	6.42	<0.0001	<0.0001
CS (n=10)	3.9	5.45	5.85	5.8		

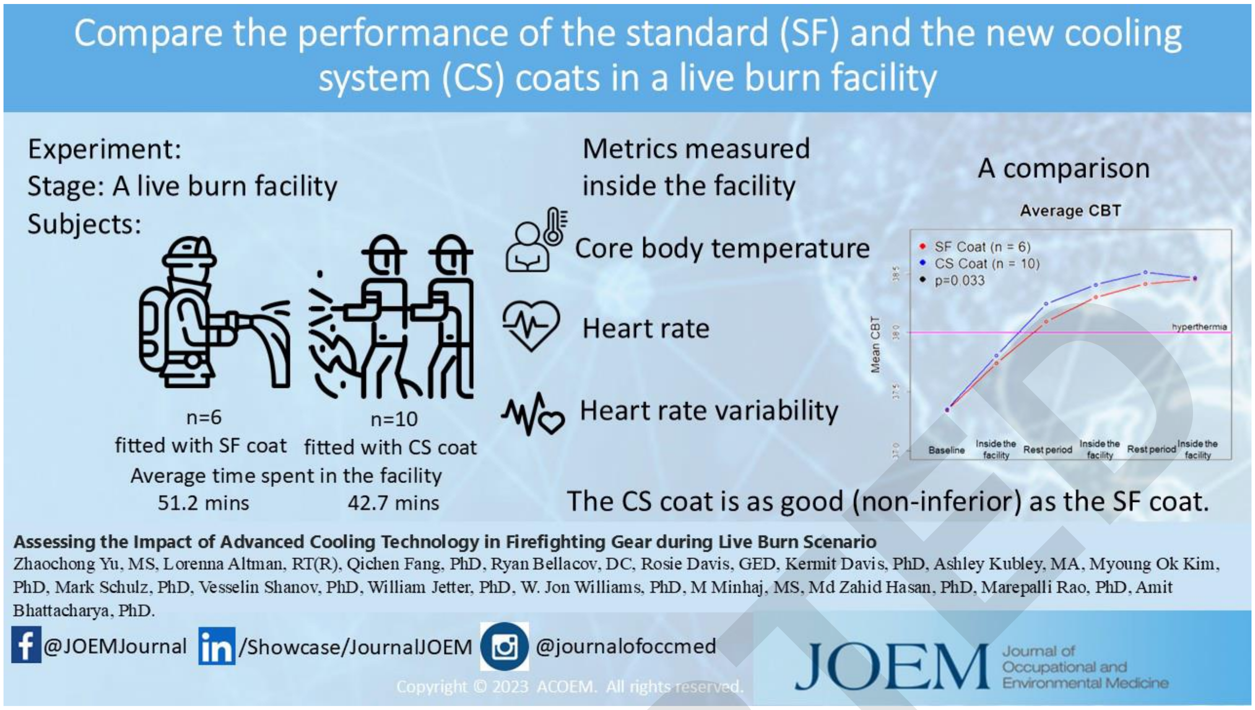
The average Respiratory Distress by each scenario under each coat is given in Table S9 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 4.d of the main paper.

Table S9: **Averages of respiratory distress by coat – multivariate t-test for two samples.**

Coat	Baseline	Scenario1	Scenario2	Scenario3	p-value	Bootstrap p-value
SF (n=6)	1	3.17	4.5	4.17	0.4422	0.46
CS (n=10)	1	2.5	3.3	3.5		

Table S10. **Summary of statistical analyses comparing the performance of coats.**

Research Interest		Test	p-value	Comment on Coats	Adjusted p-value
Physiology	CBT	multivariate t-test	0.0328	SF coat is better.	0.2296
	HR	multivariate t-test	0.3323	No difference.	1.0
	HRV	multivariate t-test	0.8215	No difference.	1.0
	HS	multivariate t-test	0.1923	No difference.	1.0
Perceptions	Borg Scale	multivariate t-test	0.5563	No difference.	1.0
	Thermal Comfort Scale	multivariate t-test	<0.0001	CS coat is better.	<0.0001
	Respiratory Distress Scale	multivariate t-test	0.4422	No difference.	1.0


Compare the performance of the standard (SF) and the new cooling system (CS) coats in a live burn facility
Experiment:
Stage: A live burn facility
Subjects:
n=6
fitted with SF coat
n=10
fitted with CS coat
Average time spent in the facility
51.2 mins
42.7 mins
Metrics measured inside the facility
Core body temperature
Heart rate
Heart rate variability
A comparison
Average CBT
SF Coat (n = 6)
CS Coat (n = 10)
p=0.033
hyperthermia
Mean CBT
Baseline
Inside the facility
Rest period
Inside the facility
Rest period
Inside the facility
The CS coat is as good (non-inferior) as the SF coat.
Assessing the Impact of Advanced Cooling Technology in Firefighting Gear during Live Burn Scenario
Zhaochong Yu, MS, Lorenna Altman, RT(R), Qichen Fang, PhD, Ryan Bellacov, DC, Rosie Davis, GED, Kermit Davis, PhD, Ashley Kubley, MA, Myoung Ok Kim, PhD, Mark Schulz, PhD, Vesselin Shanov, PhD, William Jetter, PhD, W. Jon Williams, PhD, M Minhaj, MS, Md Zahid Hasan, PhD, Marepalli Rao, PhD, Amit Bhattacharya, PhD.
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