Relationship between Structural Firefighter Protective Clothing Ease and Heat Loss

Reannan Riedy, Meredith McQuerry, Ph.D., & Sherry Schofield, Ph.D., Florida State University

Keywords: Firefighter, thermal comfort, protective clothing, heat stress, manikin

Background: Since the National Fire Protection Association (NFPA) began collecting injury and fatality data almost 50 years ago, heat strain and overexertion have been the number one cause of acute firefighter fatality (Fahy et al., 2019). The structural turnout ensemble provides protection against steam, heat and flame, and physical injury through the incorporation of multiple layers; however, the additional fabric thickness and air layers reduces the body's ability to dissipate heat efficiently (Havenith, 1999). The majority of firefighting activities do not involve flame exposure but still require the donning of turnout gear (Den Hartog, 2010; *NFPA 1971*, 2018), further increasing the likelihood of experiencing heat stress related to the turnout ensemble.

This project is part of a larger scope study, in which the overarching purpose was to research and develop innovative novel pattern designs and garment modifications for heat stress reduction in structural firefighter turnout suits. When considering design and fit, the ease and drape of the garment impacts the volume of air layers, directly affecting the amount of heat transferred through the clothing system by convection and evaporation (Bouskill et al., 2002; Havenith, 1999). Previous research has sought to understand the interaction between air gap volume and total heat loss (THL) by exploring impacts in heat flux settings (Fu et al., 2013), modifications to garment layer fit, stretch materials (McQuerry, DenHartog, et al., 2017), and impacts on ventilation and thermal insulation (Bouskill et al., 2002; McQuerry et al., 2016; McQuerry, Den Hartog, et al., 2017), amongst other topics. However, there remains a gap in the research on ease allowances in turnout suit design and their relationship with heat loss. Therefore, the purpose of this research was to determine the impact of ease allowances on air gaps in turnout suits and their subsequent impact on heat loss when worn on a three-dimensional form (sweating thermal manikin).

Method: Four sets of an industry-recognized turnout suit were o ANDI Thermal Manikin. Chest ease allowances evaluated were 6", 8", 10", and 12". Alterations were made in the chest, starting from the armscye and down through the waist, maintaining proper fit over the hips. The full systems ensemble included the turnout coat, turnout pants, 100% cotton station wear T-shirt, cotton underwear, athletic shorts, suspenders, gloves, socks, boots, and helmet (Fig. 1). A breathing apparatus (SCBA) was not included. A 35-zone ANDI dynamic thermal manikin housed in an environmental chamber was utilized to collect thermal insulation (R_t) and convective heat loss (Q_{dry})

measurements according to ASTM F1291, and evaporative resistance (R_{et}) and evaporative heat loss (Qwet) measurements according to ASTM2370. Each ensemble was tested under both static (standing) and dynamic (walking) conditions to determine the impact of forced convection for a total of 48 repetitions. Data was then used to calculate the average predicted manikin THL (Qpredicted; W/m^2) of eachensemble in both static and dynamic conditions which was analyzed between groups using one- way ANOVAs and two-sample post hoc t-tests.

In addition, a Size Stream SS20 3D body scanner was utilized to determine the volume of the air gap and distance between the base layer and each turnout suit. Three scans of each ensemble were conducted, calculating the average surface area (in^2) and volume (in^3) for the base layer and each individual suit. The air gap surface area and volume for each suit when worn over base layers was calculated by subtracting the volume, or surface area, of the base layer from the volume, or surface area, of each suit. Average air gap distance (mm) was then calculated.

Table 1. Convective heat loss, evaporative heat loss, and predicted THL results by suit.

Convective Heat Loss, Evaporative Heat Loss, and Predicted THL Results								
Suit	Condition	Avg. Qdry	Avg. Qwet	Predicted THL (W/m2)	Condition	Avg. Qdry	Avg. Qwet	Predicted THL (W/m2)
6"	Static /Standing	30.8	45.0	75.8	Dynamic /Walking	42.7	81.1	123.8
8"		29.9	43.5	73.4		40.3	85.6	125.8
10"		31.1	42.9	74.0		39.3	84.8	124.1
12"		28.4	44.5	73.0		40.9	75.3	116.2

Results: Predicted manikin THL varied by suit and between static and dynamic movements (Fig. 2). There were no statistically significant ($p<0.05$) differences between the predicted THL measurements for all suits when under static conditions. However, significant differences were found between the 10" and 12" suits ($p < 0.05$) in dynamic conditions and there was a slight trend towards statistical significance ($p < 0.1$) between the 6" and 12" ease suits and between the 12" suit compared to the 8" and 6" suits ($p = 0.06$ and $p = 0.1$, respectively).

The predicted THL for the suit with 6" chest east supports previous research that indicated that a reduction in air gap volume may improve heat loss under static conditions (McQuerry, DenHartog, et al., 2017), but also remained consistent with previous findings in which there was no statistical significance when comparing to the THL of larger suits. Similarly, it was found that reductions in ease below 8" prevented the proper closure in the neck area of the turnout coat. Results also exemplified the detriment of increasing internal air gap beyond 10" as the 12" suit showed significantly reduced manikin THL, even in the walking condition with forced convection which is a more favorable environment for heat loss.

Conclusions: It is well-documented in the literature that air gaps between the body and multiple clothing layers impact the body's ability to lose metabolic heat efficiently. A reduction in internal ease measurements does trend towards statistically significant increases in THL, to a point, with fit limitations being reached before benefits can be significantly and meaningfully realized. An increase in standard internal chest ease measurements significantly decreases heat loss, even when forced convection from movement is considered. The results of this study indicate a valid recommendation for turnout gear manufacturers to maintain or reduce their internal chest ease measurement to between 8-10" of ease in order to improve firefighter heat loss and safety. This is, of course, given that proper thermal protection and other standard safety testing is conducted to ensure no reduction in protection occurs by reducing excess insulation.One limitation of this study was the specific focus on chest ease with slight adjustments made in the chest and torso areas of the turnout coat only. Additional research should continue to assess novel design features for turnout suit heat loss improvements and include further prototyping of suit modifications based off of the findings from this study.

References:

Bouskill, L. M., Havenith, G., Kuklane, K., Parsons, K. C., & Withey, W. R. (2002). Relationship between clothing ventilation and thermal insulation. *AIHA Journal : A Journal for the Science of Occupational and Environmental Health and Safety*, *63*(3), 262–268. https://doi.org/10.1080/15428110208984712

Den Hartog, E. A. (2010). Challenges in Future Personal Protective Equipment – An Overview of Developments in User Needs. *Research Journal of Textile and Apparel*, *14*(4), 22–37. https://doi.org/10.1108/RJTA-14-04-2010-B003/FULL/XML

Fahy, R., Petrolli, J., & Molis, J. (2019). NFPA: Firefighter Fatalities in the US-2019. *NFPA Research Report*, *1*(26).

Fu, M., Weng, W., & Yuan, H. (2013). Effects of multiple air gaps on the thermal performance of firefighter protective clothing under low-level heat exposure. *84*(9), 968–978. https://doi.org/10.1177/0040517513512403

Havenith, G. (1999). Heat Balance When Wearing Protective Clothing. *Annals of Occupational Hygiene*, *43*, 289–296. https://academic.oup.com/annweh/article/43/5/289/160067

McQuerry, M., Den Hartog, E., & Barker, R. (2017). Effect of Self-Contained Breathing Apparatus (SCBA) on Heat Loss in Structural Firefighter Turnout Suits. 1–5. https://doi.org/10.14504/AJR.4.5.1

McQuerry, M., DenHartog, E., & Barker, R. (2016). Evaluating turnout composite layering strategies for reducing thermal burden in structural firefighter protective clothing systems. *Textile Research Journal*, *87*(10), 1217–1225. https://doi.org/10.1177/0040517516651101

McQuerry, M., DenHartog, E., & Barker, R. (2017). Analysis of air gap volume in structural firefighter turnout suit constructions in relation to heat loss. *Textile Research Journal*, *88*(21), 2475–2484. https://doi.org/10.1177/0040517517723024

NFPA 1971: Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting. (2018). National Fire Protection Association. https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=197