Functional Design of Structural Firefighter Clothing Systems for Improved Comfort

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Functional clothing can be defined as clothing which is, "specifically engineered to deliver a pre-defined performance or functionality to the user, over and above its normal functions," (Gupta, 2011). Structural firefighter turnouts are an example of functional clothing which exists to protect the user during firefighting activities. For firefighters, clothing systems with multiple layers are necessary in order to provide several types of protection. The multi-layer clothing construction, however, hinders the ability of the wearer to release excess body heat. Therefore, an optimization between protection and comfort is needed to reduce incidents of heat strain, which lead to over 50% of all firefighter injuries and fatalities.

In order to solve this problem, functional design for protective clothing may be used as a guideline for managing the process. The functional design process instructs the designer step-by-step, from the initial design idea to evaluating the final prototype. The functional design process involves the following seven steps: 1)Design request made; 2)Design situation explored; 3)Problem structure perceived; 4)Specifications described; 5)Design criteria established; 6)Prototype developed; and 7)Design evaluation of prototype (Watkins, 1984). The functional design process served as an operational framework for identifying and developing prototypes that reduce the occurrence of heat stress currently experienced by firefighters.

For this particular research study, the challenge began in step three of the process, when the designer must determine which areas of functionality should be evaluated and what improvements can be implemented. The incorporation of numerous design modifications, however, was the most challenging step in developing structural firefighter prototypes with improved comfort performance. After initial modifications were individually explored on the garment level, an Interaction Matrix was used in step five of the functional design process.

An interaction matrix identifies specifications that are in direct conflict by denoting them with a "0", specifications that require accommodation in order to be in the same design as a "1", and specifications that create no conflict as a "2" (Watkins, 1984). The design modifications evaluated in this study included clothing ventilation, systems modularity, strategic layer reductions, and air gap volume analysis. These modifications were assessed for their ability to coincide in the same design. In Figure 1, the interaction matrix tool illustrates concepts which are in direct conflict with one another, such as adding ventilation into a multi-layer modular suit, which would require detachment of layers that is not possible if vents are sewn through all three clothing layers.

Figure 1. Interaction Matrix for Structural Firefighter Prototype Designs

	1	*2*	*3*	*4*	*5*	*6*	*7*
1. Active Zipper Ventilation	-	2	1	2	2	**0**	2
2. Active Vertical Ventilation		-	**0**	2	2	**0**	2
3. Passive Open Ventilation			-	2	**0**	**0**	1
4. Reduction of Thermal Liner				-	2	2	1
5. Single Layer Modular Suit					-	2	1
6. Multi Layer Modular Suit						-	2
7. Stretch Component Panels							-

Once design criteria was established, a digital logic decision making tool was used to assist in developing full garment prototypes which were then evaluated for manikin level THL according to ASTM F 1291 and 2370. Further, physiological responses were predicted using RadTherm® human modeling software. Prototypes developed included a single layer modular suit (USAR), a vented suit, a turnout with stretch panels, and a revolutionary prototype (Figure 2) combining venting and stretch panels. Prototypes were compared to a control turnout typical of what is commonly purchased on the market today.

Results demonstrated increases in predicted manikin THL for the USAR, Venting, and Revolutionary prototypes. The USAR prototype had significantly greater THL performance due to the removal of layers within the clothing system. The addition of zipper vents along the vertical side seams of the coat and pants contributed to the improvement in heat loss in both the Venting and Revolutionary prototypes. The Stretch prototype, however, did not show a heat loss benefit as it was an ergonomic design focused on improving range of motion. This suit design may reduce the amount of metabolic heat produced by the body when performing physical tasks such as pulling, crawling, kneeling, and climbing.

Predicted physiological responses mirrored the manikin THL results. USAR, Venting, and Revolutionary prototypes demonstrated the greatest improvements in comfort, compared to the Control. The Stretch prototype had predicted physiological responses worse than that of the Control, indicating poorer physiological comfort. Further testing is necessary on the human wear level to measure physiological responses of firefighters including heart rate. This study suggests that design modifications such as venting and modularity are successful for improving comfort and reducing the heat stress experienced by the firefighter.

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