2009 BFRL Project Description

Project Title: Characterization of Internal Flow of Fire Fighter Respirator

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BFRL Program: Advanced Fire Service Technologies

Objective: To improve respiratory protection of first responders by developing modeling tools, experiments, and instrumentation to characterize the environments internal to a firefighter's respiratory mask and predict the respiratory uptake of toxic gases and fine particulates from the surrounding environment in the presence of a leak.

Problem:

What is the problem? The level of protection offered by a first responder's respirator system during actual use is not well characterized. Protection factors are assigned under the "best" and "well controlled" conditions. There is evidence that at high work rates a Self-Contained Breathing Apparatus (SCBA) may be over-breathed, causing negative pressure conditions within the facepiece and the possibility of leakage. Computer simulations of the internal flow field and appropriate sensor metrics for a real-time warning system are lacking.

Firefighter Respiratory Protection is included as a Measurement Need in the USMS, NIST Special Publication 1048. It is also a high priority issue for the National Fire Service (National Fire Service Research Agenda Symposium, National Fallen Firefighters Foundation, 2005). Personnel monitoring capability that enables physiological monitoring of firefighters has been identified as a high priority need in the DHS Capstone IPT Representative High Priority Technology Area of Incident Management (2007). The Institute of Medicine of the National Academies has published several recent reports on respirators, including "Assessment of the NIOSH Head-and-Face Anthropometric Survey of U.S. Respirator Users" (2007). RAND studied respirator protection and usability tradeoffs for WTC cleanup workers after 9/11 (2002).

Why is it hard to solve? Protection factors are influenced by a wide range of parameters: fit, work rate, material care and maintenance, and others. Experimental data from actual use is difficult to obtain. Real-time measurements of the respiratory hazard must be conducted inside the respirator and before entry into the body. The complex shape of the space between face and respirator and the transient nature of the breathing process make this a difficult environment to measure. Sensor placement requires knowledge of dead spots in the flow field. The sensor must be small and appropriately located to quantify the protection level, and the measurement must be robust, indicating the level of respiratory hazard under all conditions of use.

How is it solved today, and by whom? The problem of measuring the respiratory uptake of toxic gases and fine particulates for a firefighter using a respirator in the field has not been

solved. There are many related efforts, however. NIOSH/NPPTL has ongoing programs to study the demand on respirators with exertion, the possibility and effects of leakage, and issues of respirator fit. A professor at the University of Maryland is studying the location and effects of dead space around the respirator. A group in the Netherlands is studying sampling probe measurements in military gas masks, with both experimental and computational components. In the Information Access Division of NIST/ITL, preliminary work has been performed on respirator fit using 3D facial data. There is interest in Taiwan in developing individual respirator fit. There is no evidence that respirator manufacturers have employed computer modeling of flow fields to assist in respirator design.

Why NIST? This project fits the BFRL mission and vision. It anticipates and meets the need to measure the level of protection provided by respirators for firefighters during actual use, thus promoting innovation and competitiveness of U.S. respirator manufacturers and improving safety. It provides knowledge in the form of computer model and experimental results that enable the selection and placement of sensors for real-time monitoring of respiratory protection. By providing the measurement science to improve safety for the fire service, this project is well aligned with the BFRL strategic priority of Measurement Science for Innovative Fire Protection. BFRL has the tools, the interest, the expertise, and the standing to carry out this project and deliver it to industries and standards committees that will put it to use. First responders are our stakeholders.

Approach:

What is the new technical idea? One new technical idea is to use computational fluid dynamics (CFD) to find the regions within the respirator that can be used to locate a sensor for real-time monitoring of firefighter respiratory safety. The computational space for the CFD code is the space between the respirator and the human face. Both of these are complex surfaces that can be obtained through 3D laser scanning and, in the case of the respirator, through CAD files if a willing manufacturer can be located. A separate computational tool translates each scanned image or CAD file into a 3D model that can be manipulated and combined, face to mask, to define the computational space. The CFD code has multiphysics capability that allows the determination of flow, particle motion, chemistry, heat, and fluid-structure interactions within the mask.

With respect to the experimental program the new technical idea is to integrate procedures and technology from separate standard test methods in a manner that tests firefighter respirators in failure modes while monitoring key parameters that predict protection levels. Fit factor measurements, a protection level parameter defined by the ratio of the ambient particulate concentration and the particulate concentration inside the mask, and respirator facepiece pressure measurements are used in an innovative way to predict fit factor from the pressure measurement. This concept has the potential to provide real-time protection information using miniaturized pressure sensors that can be integrated into firefighter respirators.

Why can we succeed now? The ongoing respiratory health problems of first responders that participated in the cleanup of the WTC disaster and the continuing threats of terrorism and natural disasters have focused attention on the issue of respiratory protection. Computational tools are now available that can create a computational space from laser scans and CAD files of

complex 3D objects (such as respirator masks and human faces). CFD and digital mapping are mature technologies. Instrumentation continues to grow in sophistication and shrink in size. Advances have been made in data storage and wireless communications. The technical staff at BFRL has the necessary expertise, experience, and contacts with the research and first responder community to successfully carry out this project.

What is the research plan? The experimental effort will concentrate on prescribing leaks (negative pressure conditions) in a firefighter SCBA to characterize the magnitude of the leak and the reduction of protection. Using a head form attached to a breathing simulator, the fit factor of an SCBA unit will be evaluated for a range of fit conditions and breathing rates. Facepiece pressure will also be monitored and simple models to predict protection levels from the pressure measurements will be evaluated. The results will depend on leak geometry and aerosol sampling position inside the mask. Selecting sampling positions that represent what the user actually inhales is an objective of the present experimental setup. The experimental effort will serve to guide the computational model development by providing a very repeatable set of conditions for comparison with simulation experiments.

The computational model is prepared by defining the 3D space between the headform and respirator mask that are used in experiments. A model of each separate component (headform and respirator) is prepared from 3D laser scans, then the two are combined computationally such that the respirator seal is in contact with the headform. The positions and sizes of the three leaks defined in the experiment are included in the model. Appropriate boundary conditions are set on the rigid surfaces of headform and respirator, the designated inlets and outlets, and the leaks. A CFD code determines the flow, pressure, particle motion, and chemical concentration at every location within the respirator, providing data that can be compared with the experimental results. Separate problems are run for each leak size and each breathing pattern that are studied experimentally.

Recent Results:

- Output - Butler, K.M., “A Computational Model of Dissipation of Oxygen from an Outward Leak of a Closed-Circuit Breathing Device,” NISTTN 1484, June 2007.
- Outcome -An experimental facility consisting of a breathing simulator, test head, firefighter SCBA, aerosol generator, and pressure sensor assembled to study pressure drop and protection factor from three leak sizes.
- Outcome -Flow and pressure fields over two breathing cycles were obtained for the 3D geometry representing the interior space bounded by a half mask respirator and a human head.

Standards and Codes: The firefighter respiratory equipment standard, NFPA 1981, is managed by the NFPA Technical Committee on Fire and Emergency Services Respiratory Protection Equipment (FAE-RPE). The PI will become involved in this committee.