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THERMAL MEASUREMENTS FOR FIRE FIGHTERS' PROTECTIVE CLOTHING[3]

REFERENCE: DeMars, K. A., Henderson, W. P., and Liu, M., **"Thermal Measurements for Fire Fighters' Protective Clothing,"** *Thermal Measurements: The Foundation of Fire Standards, ASTMSTP 1427,* L. A. Gritzo and N. J. Alvares, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2002.

ABSTRACT: Current test methods used for quantifying the thermal performance of fire fighters' protective clothing are not providing information needed to understand why fire fighters are being burned. Many of the thermal exposures where fire fighters receive serious bum injuries are much lower than those specified in current test methods. In addition, current test methods do not provide a means to measure performance changes associated with wet garment systems. New test apparatus have been developed for measuring thermal performance of protective clothing systems. A wide range of thermal exposures can be replicated. These test apparatus can measure the thermal performance of protective clothing systems that are dry or wet and also measure performance changes associated with garment compression. This is an overview of measurement issues critical to the development of standards for fire fighters' protective clothing and the safety of fire service personnel. Research efforts addressed in this document have been supported in part by the United States Fire Administration and the National Institute for Occupational Safety and Health.

KEYWORDS: burns, fire fighters, heat flux, predictive models, protective clothing, sensors, temperature measurements, test methods, thermal properties

Thousands of fire fighters are seriously burned each year and many lose their lives while exposed to fire fighting environments [13. Work is underway at the National Institute of Standards and Technology (NIST) to identify measurement needs for developing a better understanding of thermal performance for fire fighters' protective clothing and equipment. This research is not only providing insight related to thermal performance measurements, it is addressing important safety issues for the fire fighters that use this equipment. Thermal measurements in protective clothing systems are complex as a result

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of fabric movement, compression, changes in spacing and garment ease, and the dynamic movement of moisture in protective clothing while it is being used and heated from fire environments. It is documented that the current thermal measurement method used for fire fighter protective clothing product certification is overestimating performance related to the potential for human burn injury. The ability to accurately measure the thermal response of fire fighters' protective clothing to well controlled and quantified thermal environments is the primary function that provides critical information needed for understanding the actual field use performance of the clothing. Development of these measurement data and the analysis of these data should be an initial step in designing protective clothing systems. In addition, the accurate measurement of protective clothing material's thermal properties is essential for accurately predicting the thermal behavior of the protective clothing systems when exposed to a wide range of fire fighting thermal environments. The analysis of these measurement data and thermal performance predictions generated from thermal property measurements should be used to develop materials for training fire fighters in the proper use and limitations of their protective clothing systems. Currently, the understanding of how fire fighters' protective clothing systems really work in the field is only discovered through field use. Unfortunately, learning how protective clothing really works by use in the field sometimes leads to serious injury. This document provides an overview of current measurement technology that is assisting in the advancement of thermal performance for fire fighters' protective clothing.

FIRE FIGHTING THERMAL ENVIRONMENTS

The primary thermal exposures that a fire fighter must be concerned with are thermal radiation from flames, smoke, hot gas convection, and conduction from high temperature surfaces [2]. Each of these heat transfer modes has an impact on the thermal performance of fire fighters' protective clothing, and they all can independently cause burn injuries. However, in actual fire fighting situations these different components of heat transfer will likely be combined in varying fractions depending on the location and position of the fire fighter in relation to the fire's varying thermal environment. The fact that the component fractions of heat transfer vary during an exposure complicates the measurement process and increases the measurement uncertainty.

Another factor that varies during the process of measuring heat transfer through fire fighters' protective clothing systems is the amount of moisture in the system. Moisture is often a significant factor in the creation of fire fighter burn injuries. The moisture in fire fighters' protective clothing originates from human perspiration, hose spray, and weather. Moisture levels can be controlled to some degree when making thermal measurements in laboratory test environments. These laboratory environments initially provide a stable level of control over wetting and moisture conditions at the beginning of a thermal exposure. The protective clothing systems then respond to heating processes and begin to dry. Controlling moisture input to the protective clothing system after heating begins is difficult and accurately replicating wetting processes that take place in the field environment is difficult. However, basic information on wet thermal performance can be gained by studying the drying processes of wet protective clothing systems and applying this knowledge to physics based predictive models.

SENSORS AND MEASUREMENTS

To understand the thermal performance of fire fighters' protective clothing one must first measure the thermal environment around the fire fighter at any point in time while the person is doing their fire fighting job. Thermal radiation, total heat flux, and gas temperature measurements are used to quantify these environments. In addition, the impact of the surrounding environment on the fire fighter is measured by instrumenting the thermal protective clothing. This protective clothing instrumentation is located on the exterior surface of the clothing and inside the garment. Measurements inside the garment provide insight into not only how heat moves through the garment system but also help to understand how moisture moves through the protective clothing upon being heated. These interior measurements are typically made using thermocouples, thermistors, and small heat flux sensors. Use of each measurement device mentioned above varies with whether it is applied in the laboratory or the field.

LABORATORY vs. FIELD MEASUREMENTS

Laboratory tests alone do not provide all of the information needed for accessing the thermal performance of fire fighters' protective clothing. Certain measurements must be made while protective clothing systems are actually being used by fire fighters or worn by an instrumented manikin. Making thermal response measurements for protective clothing in field environments generally adds difficulty to the measurement process. Field measurements are often much more complicated to conduct than laboratory based measurements. Issues associated with these two means of measurement are:

Laboratory:

- Measurements are usually made under highly controlled conditions.
  Laboratory temperature, humidity, and air circulation
- Instrumentation is easily maintained and calibrated.
- Measurements are typically made in fixed test facilities using standardized test apparatus.
- Data logging is typically accomplished with the use of fixed data logging systems.

Field Measurements:

- Environmental conditions vary with the test location, time of day and year, and changing local weather conditions.
- It is more difficult to maintain and keep instruments calibrated.
- Providing cooling fluids for sustained heat flux measurements is much more difficult.
- Measurements are often made where humans or manikins experience dynamic movement. Instrument placement and attachment becomes critical.

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- Data logging systems are small and often carried by human or placed on manikin test subjects.
- Because field operated data loggers have limited capability fewer data channels are usually available.

From the above list, it is apparent that an accurate log of changing weather conditions is necessary while conducting field experiments. Issues associated with maintaining adequate fluids at appropriate temperatures for cooling heat flux gauges are important since test subjects may have to carry the fluids that produce the needed cooling. This additional weight may actually influence the performance of the individual taking part in the protective clothing test and may alter the results. Also since fewer data channels are usually available for recording measurements in the field, it is important to develop a logical set of measurements that may be correlated with other experiments, including those made in the laboratory.

TEMPERATURE MEASUREMENTS

To understand the thermal performance of fire fighters' protective clothing, thermal measurements must be made to quantify the thermal environment around the individual wearing the protective clothing. In addition, thermal measurements must be made on the surface of the protective clothing and inside of the protective clothing systems in order to quantify heat transfer through the clothing. In many cases, these measurements are used to predict if and when a fire fighter will receive a burn injury. The selection of temperature measurement devices is important for obtaining data that is appropriate for its final use. In addition, temperature measurements for protective clothing are strongly affected by the way the temperature measurement device is attached to and placed on or within the protective clothing system. Thermocouples have been the primary means of measuring temperature since modern forms of data logging came into existence.

Thermocouples are often selected for measuring temperature changes in fire testing. They are used to measure gas temperatures, surface temperatures, and the temperature of liquids and solids. The American Society for Testing and Materials (ASTM) Manual on the Use of Thermocouples in Temperature Measurement [3] suggests that a heat collecting pad attached to a thermocouple may be the best way to obtain an accurate surface temperature for materials that have a low thermal conductivity. Experiments with a range of thermocouple types, attachment methods and configurations, including heat collecting pads have been done [4][5]. These tests were conducted on the radiant panel apparatus described in the following section on test methods. One successful thermocouple attachment method, figure 1, is compared with temperature measurements made with a small heat collecting copper pad, figure **2.**

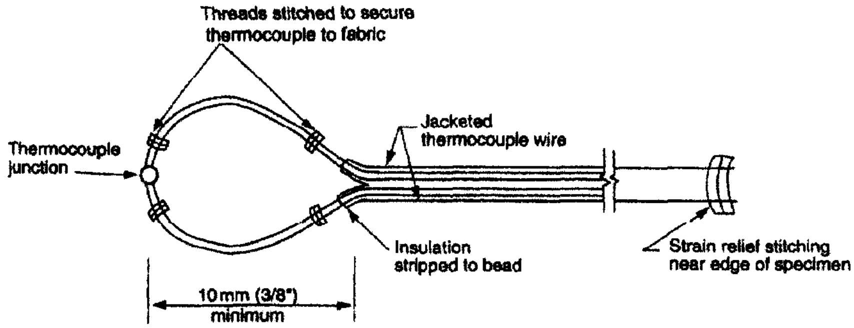

Figure 1 Thermocouple attachment to protective clothing fabrics [4].

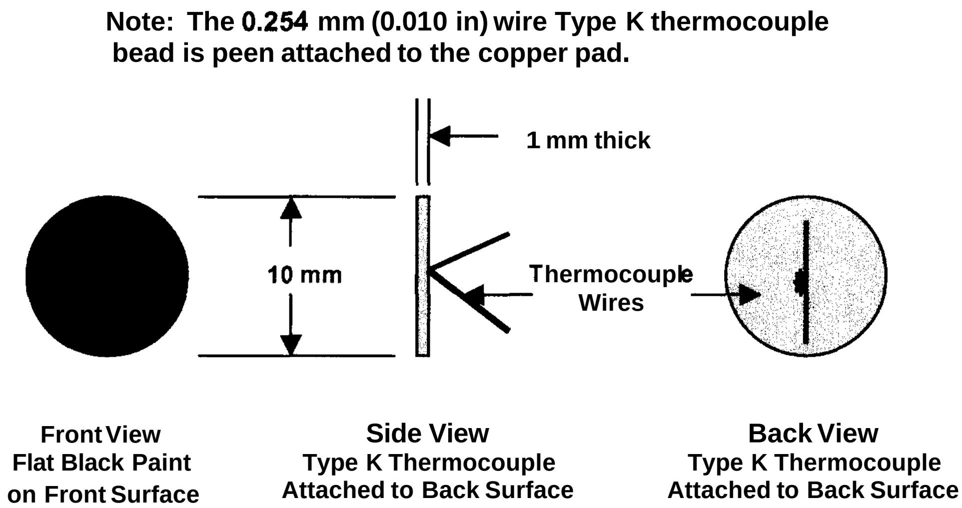

Figure **2** Heat collecting pad thermocouple.

Each of the thermocouple measurement systems shown above used 0.254 mm (0.010 in) diameter type K thermocouples. The thermocouple attachment method shown in figure 1 is described in detail in NISTIR 6400 [4]. Basically, the thermocouples were held in place against the fabric by making loop stitches across the bare thermocouple wires at the four places shown. Heat resistant thread was used. In addition, strain relief stitches were formed around the insulating jacket of the thermocouple wire. The heat collecting pad thermocouple was attached to the fabric by stitching across the back of the copper pad with heat resistant thread. The stitch pattern formed an X across the back side of the pad and held it flush with the fabric. Results of these measurements from a square wave exposure at 2.5 kW/m^2 are shown below in figure 3.

From these data it is clear that the temperature lag associated with the copper heat collecting pad is a significant disadvantage when attempting to measure rapidly changing temperatures that are affecting the performance of protective clothing and producing burn injuries. It should be noted that the copper pad is exhibiting slightly higher temperatures at the peak value and significantly higher temperatures when cooling. Another series of tests, reported in NISTIR 6750 [5], showed similar results. In this work a type K and a type J thermocouple are compared to a larger copper pad thermocouple system. The copper pad used a 0.254 mm (0.010 in) diameter wire type J thermocouple. The 39.9 mm (1.6 in) copper pad thermocouple system is described in reference [5]. The bare bead type K and type J thermocouples were also 0.254 mm (0.010 in) diameter wires. The copper pad thermocouple is shown in figure 4, and the test setup for the measurement experiments is shown in figure 5.

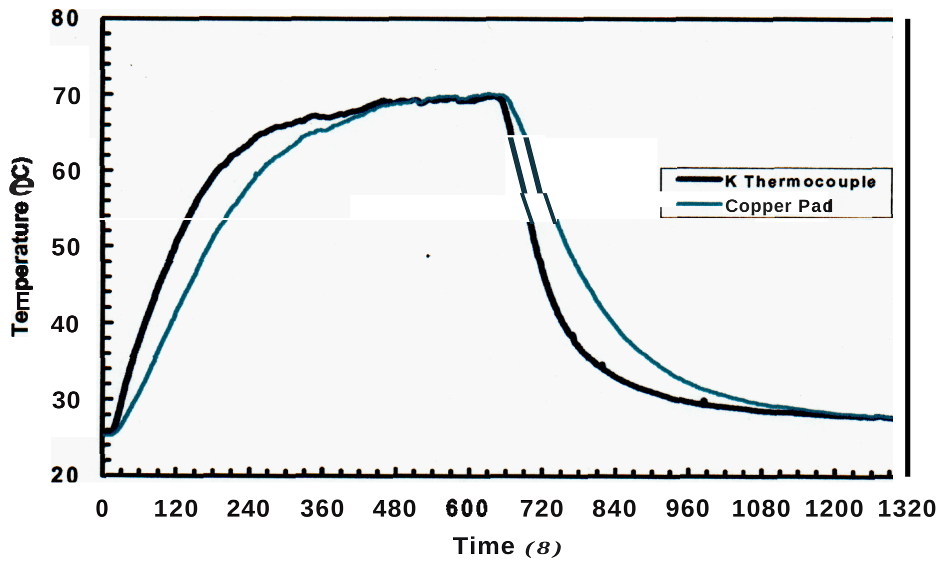

Figure 3 Comparison of bare thermocouple to a heat collecting pad thermocouple.

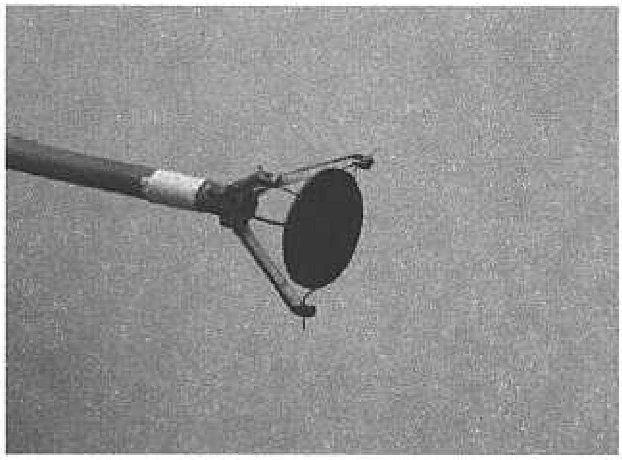

Figure 4 Large heat collecting copper pad thermocouple system [5].

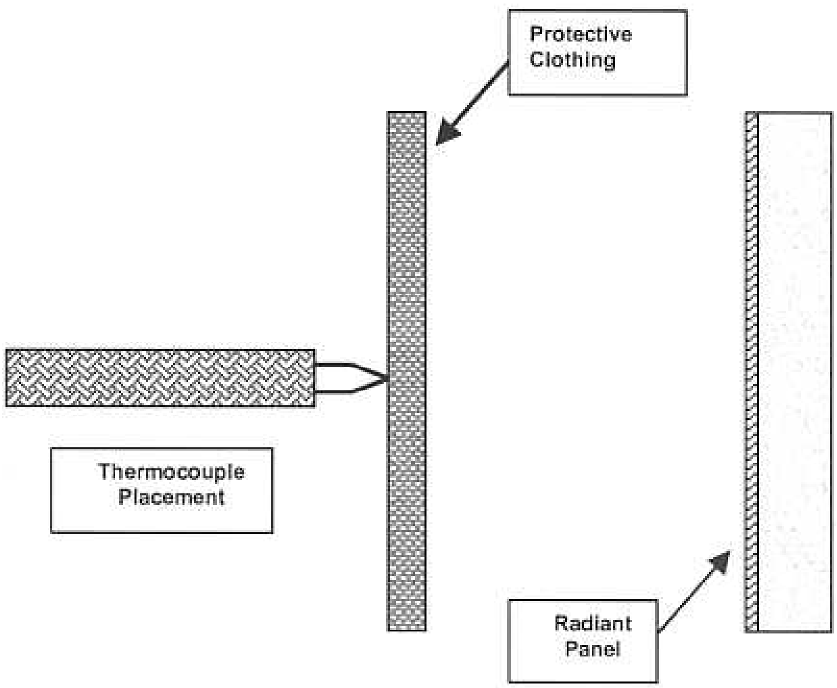

Figure 5 Arrangement for thermocouple and copper pad tests [5].

Data plots from these experiments exhibiting thermocouple temperature increase, not the actual test temperature rise as presented in figure 3, are given in figure 6. The total heat flux exposure for the tests shown in figure 6 was 5.0 kW/m^2. These plots show, as would be expected, that the more massive copper pad has a significantly longer thermal lag. In addition, it is shown that the type K thermocouple appears to provide a faster response time as compared to the type J thermocouple and the copper pad. However, the copper pad system does show a significantly higher temperature after about 200 s. These data suggest that the faster response measurements produced by the type K thermocouple may be more useful when studying rapid temperature changes that produce burn injuries. Although when looking at longer heating periods, the copper pad thermocouple system is likely to provide a more accurate peak temperature measurement.

One additional issue that has become apparent while measuring the thermal performance of fire fighters' protective clothing is that temperature measurements made on fabrics show significant variation. Much of this measurement variation has been found to be associated with fabric movement. Fabric movement easily changes the air space between garment layers, and this movement can result in temperature measurement variations of about ±8 °C (±14 °F) or more [4].

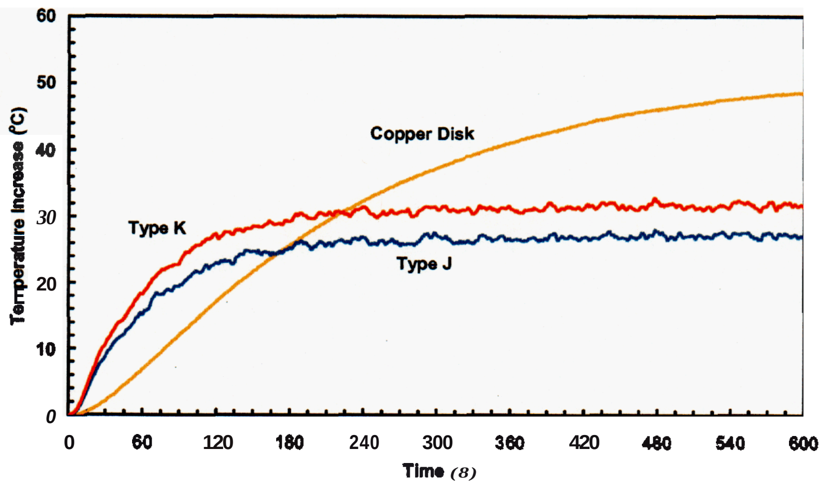

Figure 6 Comparison of bare thermocouples to a copper pad thermocouple system [5].

HEAT FLUX MEASUREMENTS

Heat flux measurements in the evaluation of thermal performance of fire fighters' protective clothing are needed for determining heat transfer rates through the garment systems and also for predicting the potential for burn injury. The measurements have traditionally been accomplished using copper slug calorimeters. These calorimeters have been useful in laboratory measurements for ASTM and National Fire Protection Association (NFPA) standards for thermal protective clothing. The primary use of these calorimeters has been with the TPP (Thermal Protective Performance) test. The original test method, ASTM D 4108, Standard Test Method for Thermal Protective Performance of Materials for Clothing by Open-Flame Method, led the way for development of additional test methods using the same measurement techniques. NFPA 1971 [6] modified D 4108 and applied it to fire fighters' protective clothing. The result of the test method development made a significant improvement in the thermal performance of fire service protective clothing. But more recently, a number of research efforts have shown that the copper calorimeter has design problems and that the results can be misleading [7][8].

According to findings from NISTIR 6750 [5], water cooled Schmidt-Boelter gauges may provide a solution to the accuracy and time limitations associated with proper use of the copper calorimeter measurements. At times, the copper calorimeter used with the NFPA 1971 TPP test has been referred to as a skin simulant sensor. However, the thermal properties of the copper calorimeters do not replicate human tissue properties.

SKIN SIMULANT SENSORS

Currently, there are several thermocouple based heat flux gauges that are referred to as skin simulant sensors. These are primarily sensors that are being used with instrumented manikin test systems. The sensors by themselves do not actually replicate human tissue thermal properties. These sensors are linked to complex computer programs that are designed to collect results from the sensors and then mathematically calculate predictions for bum injury. New sensor systems being developed by Keltner [8][9] and North Carolina State University (NCSU) [10] are attempting to improve the measurement capabilities €or protective clothing systems. The sensor by Keltner is being designed to closely replicate the thermal properties of human skin relative to its heating rate. The NCSU sensor is designed to improve measurement capabilities with instrumented manikin testing.

TEST METHODS

NFPA 1971 specifies one test method for measuring heat transfer through fire fighters' protective clothing [6]. This test method is recognized as the TPP test (Thermal Protective Performance test). It uses a bank of quartz radiant tubes and two Meeker burners as a heat source. According to the standard, these two modes of heating are balanced to provide a 50/50 radiant and convection heat source for the protective garment test specimens. A copper disk slug calorimeter is placed against the back surface of the test specimen and the outer shell material is directed toward the heat source. This method has been instrumental in providing a means for estimating thermal performance. However, there are several issues related to the test apparatus and method that have caused technically heated discussions. Some of the important issues are: 1) the quartz heaters do not provide a sufficient range of infrared radiant energy to replicate actual fire exposures; **2)** the copper slug calorimeter is constructed with multiple thermocouples attached to it, and its wiring connections create inaccurate data output; **3)** the copper calorimeter is being used to make test measurements in excess of **30** s where the instrument output is questionable because of nonlinear performance; 4) the test method does not provide enough data to determine the thermal response of each component of the protective system; 5) the test method is only designed to measure the thermal response of specimens exposed to a mid-range (84 kW/m^2) post-flashover fire environment; and 6) the burn prediction estimates generated by the test predict a longer time to burn injury than is actually the case in real fire fighting environments [9][10]. As a result of these issues, NIST has developed two new test apparatus that provide more detailed information on the thermal performance of fire fighters' protective clothing. These test apparatus are described in two NIST reports NISTIR 6400 [4] and NISTIR 6502 [11]. The first report, NISTIR 6400, describes a test apparatus that can be used to measure the thermal response of protective clothing systems while exposed to a wide range of thermal environments. Radiant heat for this test is generated from a gas fired radiant panel that produces an infrared spectrum extending across the full range produced by common structural and liquid pool fires. In addition, the specimens may be tested over a range of exposures from a low-level solar flux to a post-flashover fire. The post-flashover fire exposure may also include the addition of flames sweeping over the specimen's surface.

Figure 7 Protective clothing thermal response test apparatus [4].

The second test apparatus measures the thermal response of protective clothing systems to hot water or hot surfaces. This test apparatus allows the protective clothing specimens to be evaluated while undergoing dynamic compression. The apparatus compresses the protective clothing system against a flooring material submerged in a hot liquid or against a dry hot surface, and it is focused on measuring the thermal response of protective clothing systems to heat conduction. However, in the hot water bath tests, moisture absorption by protective clothing has been shown to significantly influence test results. Each of these test apparatus allows for specimens to be evaluated while wet or dry.

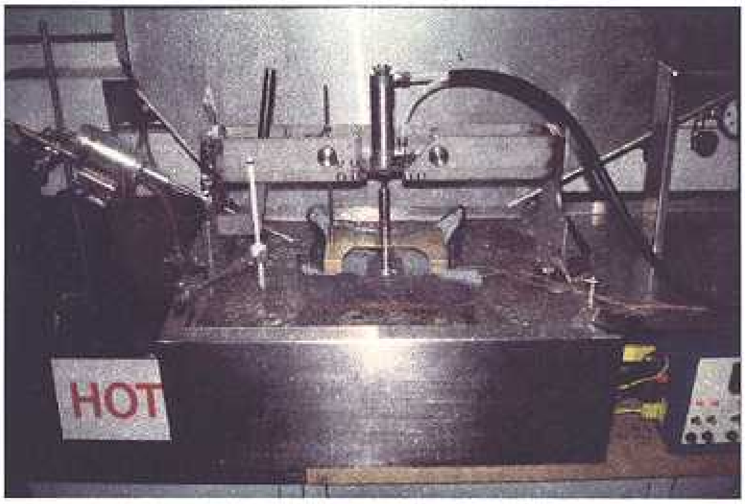

Figure 8 Wet protective clothing dynamic compression test apparatus [11].

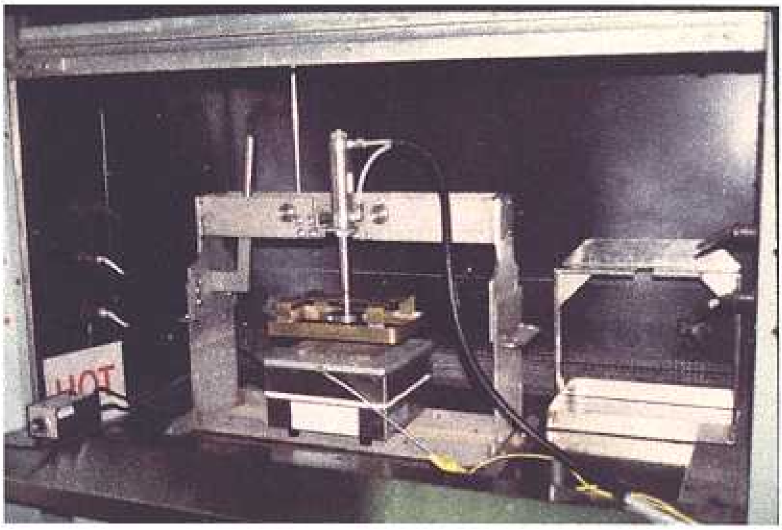

Figure 9 Dry protective clothing dynamic compression test apparatus [11].

Test data from the radiant panel test apparatus, figure 7, are shown in figures 3 and 6. A set of compressive test data exhibiting thermal response results for two different knee pad designs for fire fighters' protective clothing are shown in figure 10. These data were generated using the test apparatus assemblies shown in figures 8 and 9. Each of the tests, wet and dry, was conducted using the same compression sensor with a surface area of 3710 mm^2 (5.75 in^2) and the same compression force, 133 kPa (19.3 lbf/in^2). Surface temperatures for the tests were different. The wet test was conducted with a water temperature of 90 °C ± 2 °C (194 °F ± 4 °F). The dry test was conducted with a copper plate surface temperature of 260 °C ± 2 °C (500 °F ± 4 °F). The knee pad designs, 3 and 4, were basically identical except that they had different types of thermal padding. Each of the knee pad designs had an impermeable moisture barrier material incorporated in the system that prevented hot water and hot water vapors from penetrating the padding system and entering the inside of the garment. These data plots in figure 10 show that thermal response of protective clothing systems can vary significantly depending on the type of thermal exposure. Design 4 performs very well when tested in the hot water bath, but it exhibits a significantly higher rate of temperature rise than design 3 when compressed on the dry hot surface [11]. The thermal protective padding in design 4 was made from a material that would degrade when exposed to dry heat test conditions. These data demonstrate the importance of measuring the thermal performance of thermal protective clothing systems while exposed to a range of thermal environments, including wet and dry test conditions.

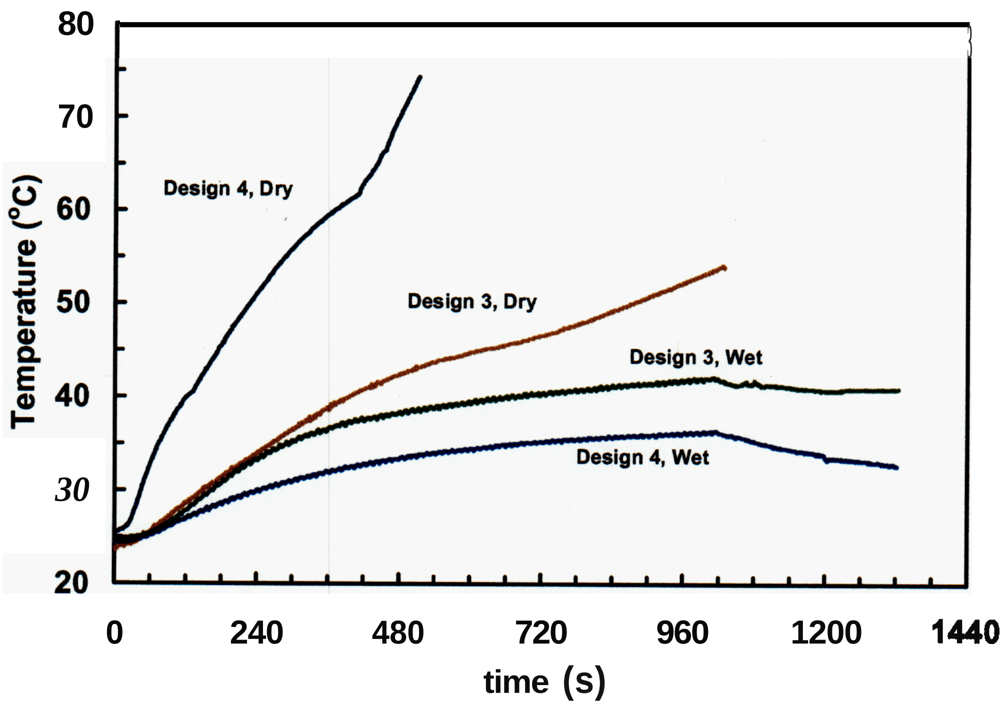

Figure 10 Comparison of wet and dry compressive thermal performance [11].

THERMO-PHYSICAL PROPERTIES MEASURMENTS

Another area where measurement technology is important to the study of fire fighters' protective clothing is the measurement of thermo-physical properties and the application of these measurement data to predicting thermal performance. A greater understanding of thermal performance is often gained by modeling the thermal response of materials to elevated temperature conditions or simulated fire exposures. Computer models are being developed to assist industry in the design of new protective clothing systems, assist as a tool for the fire service in selecting protective clothing, and will assist in training fire fighters concerning the thermal performance of their equipment. The models will also play a role in the investigation of fire fighter injury cases. One thermal protective clothing heat transfer model was recently developed by NIST and is described in NISTIR 6299 [12]. This one-dimensional model predicts changes in temperature gradient through thermal protective clothing as it heats from exposures to thermal radiation. The model currently predicts heat transfer for dry clothing systems and is being updated to include garment compression and moisture predictions. The following thermo-physical properties are currently being measured and used for predicting the thermal performance of fire fighters' protective clothing: density, thermal conductivity, specific heat or heat capacity, and the thermo-optical properties of transmissivity, reflectivity, and absorptivity. All of these properties are relatively easy to measure when the materials are dry and are at room temperature, and this is a reasonable starting point for developing the data sets. However, fire fighters don't typically work in this type of environment when they are fighting fires. Fire fighters are typically wet and their protective clothing is heated from thermal radiation and hot gas convection when fire fighting. Thermal property measurements become extremely difficult when materials are wet or degraded from thermal exposure, and confidence levels for measurements of wet or thermally degraded materials are low. As a result, NIST is in the process of developing measurement methods and analytical techniques that are expected to improve the measurement uncertainty and thermal performance predictions for wet materials. This work is currently underway and will be discussed in future reports.

UNCERTAINTY

Measurement uncertainty for each of the above test results is described in detail in the associated reference. The uncertainties listed here represent maximum measurement deviations that are expected from the measured data and are obtained from instrument literature or the referenced reports. See NISTIR 6400 [4] for a detailed description of uncertainty for the radiant panel test apparatus. The maximum estimated deviation for the measured values for the radiant panel test apparatus discussed above fell within a range of ±8 °C (±14 °F). Uncertainty for test results from the compression test apparatus described in NISTIR 6502 [11] was estimated to be less than ±5 °C (±9 °F) when the compressive force of 133 kPa (19.3 lbf/in^2) is applied. Temperature measurement variations are expected to be larger if compression force is varied by more than ± 14 kPa (± 2 lbf/in^2). Measurements presented in this document from NISTIR 6750 [5] for incident radiant flux had an uncertainty estimate of ± 3 % with an increased variation of ± 0.6 % with a ± 2 mm (± 0.1 in) change in sensor distance from the desired measurement location.

SUMMARY AND CONCLUSIONS

Advances in materials, design, and construction of fire fighters' protective clothing and the aggressive use of the protective clothing in fire fighting has led to the need for a better understanding of the gear's thermal performance. This need for a better understanding is primarily driven by the fact that thousands of fire fighters are continuing to be seriously burned. NIST with the support of the United States Fire Administration and the National Institute for Occupational Safety and Health has been studying the application of current measurement methods used to certify protective clothing systems. In addition, NIST is advancing measurement technology through the development of new test apparatus, measurement techniques, and methods for predicting thermal response of the gear to a wide range of thermal environments. Conclusions from this effort are: 1) fire fighters' protective clothing thermal performance must be evaluated while dry, when wet, in full loft and when fully compressed, **2)** it is apparent that thermocouple pad temperature measurement devices can create significant errors when attempting to measure heat transfer in protective clothing systems, and 3) a greater understanding of thermal performance may be gained by using materials thermal properties to model the behavior of protective clothing systems. These new measurement techniques and approaches to predicting thermal performance will provide opportunities for improving fire fighters' protective clothing. In addition, their application to the design of protective clothing and training in the fire service has the potential for reducing the number of serious burn injuries experienced by fire fighters.

ACKNOWLEDGEMENTS

Appreciation is extended to Mr. Robert T. McCarthy of the United States Fire Administration for assistance with this project. The United States Fire Administration, the National Institute of Occupational Safety and Health, and the National Institute of Standards and Technology provided funding for this work. Appreciation is extended to Mr. William Twilley of the Building and Fire Research Laboratory (NIST) for his assistance in the development of the experimental test apparatus and test data for this report.

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