NISTIR 6993

Thermal Performance of Fire Fighters' Protective Clothing.
3. Simulating a TPP Test for Single-Layered Fabrics

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1 Abstract

Fabrics that are used in firefighter turnout gear are specifically designed to offer protection from various extreme conditions that may arise during fire exposures. To optimize the design of these garments and understand the conditions for which protection is offered requires knowing how the transient response of the fabrics is affected by the many possible factors that arise. A model was recently developed that describes the heat and mass (moisture) transfer across protective fabrics subjected to incident thermal conditions and illustrated the importance of including moisture transport effects even under low incident flux conditions. This model is now used to study the transient response of protective fabrics to high intensity, short duration heat flux exposures. Numerical simulations of a Thermal Protective Performance test were conducted for two fabrics used as outer shell materials for turnout garments. Predicted results were found to favorably agree with experimental measurements, with Thermal Protective Performance ratings from the model within 6% of measured ratings. The ability of the model to describe the temperature across the entire thickness of the fabric rather than simply present a sensor response during an exposure provides additional information that can be further utilized to predict the thermal degradation of the materials.

2 Introduction

A review of the statistics for the years 1990 through 2000 shows a general downward trend in the number of firefighter injuries [1] and fatalities [2] due to burn injuries (note that these statistics include both thermal and chemical burns). While this trend points to increased safety from burns to the fire service, in the year 2000 there were still 6 deaths and 4500 injuries to personnel where the nature of the injury or fatality was attributed to burns. Firefighting is inherently dangerous but there is still much work that can be done to prevent burn injuries and fatalities.

Firefighter protective clothing garments are the shield for the firefighter from insults that could prove otherwise harmful or fatal. Two items related to protective garments may be suggested to further decrease the number of burn incidents. The first item is added education for the fire fighter regarding the level of protection offered by his / her protective garments under fire conditions. The second item is technological advancements in the materials utilized and the design of these garments, advancements that optimize material properties so as to provide the greatest level of protection. Both items require an enhanced understanding of the response of protective fabrics to thermal and environmental conditions experienced during fire exposures.

As part of ongoing work aimed at improving fire service technologies and reducing fire loss, a simplified model was recently developed [3] that describes the transient response of textile materials subjected to incident radiative and convective heat fluxes. The model incorporates not only the effects of heat transported across multiple fabric layers but also accounts for the presence and transport of moisture across these layers as well. The treatment of moisture allows for adsorption / desorption within the fibers as well as water vapor diffusion through the porous material. Initial results obtained using this model focused upon the response of fabrics (both wet and dry) that were subjected to low levels of incident heat flux. The results showed good agreement with measured responses and demonstrated the importance of including the presence and transport of moisture when analyzing the thermal behavior of protective fabrics.

Firefighter exposures are not limited to simply low incident flux conditions and, therefore, we wish to expand the range of conditions for which the model will reliably predict the response of protective fabrics. We consider here heat flux exposures of high intensity but short duration and choose to emulate a Thermal Protective Performance (TPP) test for single-layered fabrics [4]. TPP tests are used as an attempt to quantify the insulating characteristics of fabrics under conditions that may be observed during a fire. These test are typically of short duration, less than 30 seconds, and expose the fabric to high incident convective and

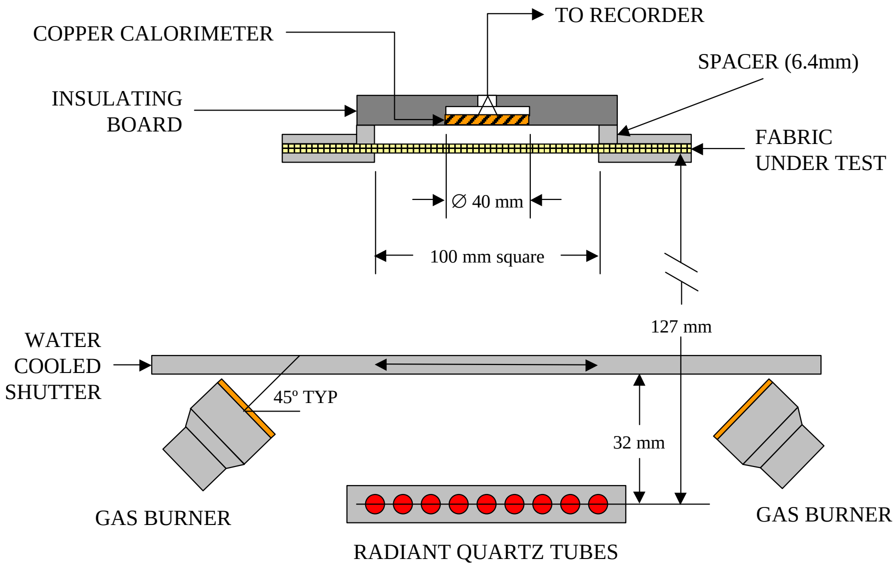

Figure 1: Schematic of the test apparatus for determining the TPP rating of the single-layered fabric. A series of radiant quartz tubes and two gas burners supply convective and radiant heat to the fabric under test. The heat transferred across the fabric is measured with a copper calorimeter positioned 0.0635 m (0.25 inch) above the fabric.

radiative fluxes.

Two protective fabrics are considered in the following work: Nomex IIIA, a blend of 93% Nomex, 5% Kevlar and 2% P140 fibers; as well as a 60% Kevlar and 40% Polybenzimidaxazole (PBI) blend[1]. The material weight for both fabrics was 0.254 kg/m^2 (7.5 oz/yd^2) and both materials are used as outer shell fabrics for turnout garments. A series of experimental TPP tests were conducted on each fabric as were numerical simulations utilizing the simplified model. The simulated transient response of the heat sensor used in the TPP test, a slug copper calorimeter, is compared with the measured response obtained from the experiments. From these response curves, the predicted TPP rating also is compared with the rating obtained from the experiments.

3 The TPP Test

The configuration for the single-layered TPP test utilized in this report follows ISO Standard 17492 [4] and is presented schematicly in figure 1. A series of radiant quartz tubes and a set of two burners supply incident heat flux to the test fabric. The orientation of the apparatus is such that the heat sources lie beneath the test fabric with the heat impinging on a single exposed surface. If the fabric has a preferred orientation, then it is set in the appratus such that the exterior surface is the side directly exposed to the incident flux. Heat is transferred across the fabric to the sensor assembly positioned 0.064 m (0.25 inch) above the fabric. The sensor assembly is composed of a copper slug calorimeter, an insulating board and a series of iron / constantan thermocouples. The calorimeter face is coated with a flat black paint so as to absorb radiant flux.

Although configuration shown in figure 1 is not standard in the United States, the setup and procedure is similar to, and does include, elements of both the NFPA standard TPP test [5] and the (withdrawn) ASTM standard TPP test [6]. Similar to the NFPA standard TPP test, the heat source specified includes a

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[1] Certain commercial materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose

combination of two burners and a set of radiant quartz tubes, providing both convective and radiative modes of heat transfer. With the inclusions of the burners and the radiant quartz tubes, and with proper balancing (described in the calibration procedure below), the incident heat flux is presumed to have equal contributions (50%/50%) from the two heat transfer mechanisms. As in the withdrawn ASTM standard, an 0.064 m (0.25 inch) spacer is placed between the fabric under test and the sensor assembly, providing an insulating air gap for single-layered fabrics.

In the presented configuration, calibration of the test apparatus is performed by first setting the radiant energy from the radiant quartz tubes to be (40 ± 10) kW/m^2, and then measuring the combined flux from the radiant quartz tubes and the burners with a total calorimeter / radiometer combination. Adjustments are made to both sources so as to insure the total heat flux of (80 ± 2) kW/m^2 and the contribution of 40 kW/m^2 due to incident radiation. Once the heat sources have been properly set, the total calorimeter / radiometer combination is removed and the calorimeter inserted at a location corresponding to what would be the exposed face of the test fabric. The calorimeter is then directly exposed to the heat sources. Incident heat flux is evaluated from temperature measurements of the calorimeter. For a 10 second sampling period of calibration, the average temperature rise should be (148 ± 3.7)°C.

Following the calibration procedure, the fabric under test and the spacer blocks are placed within the apparatus. The water cooled shutter is then opened to expose the fabric to the incident heat flux. Temperature measurements are obtained from the thermocouples within the calorimeter. The TPP rating is established by plotting on a single set of axes the time versus temperature response of the calorimeter along with a curve that represents the onset of a second-degree burn for applied heat flux versus time [7]. The intersection of the two curves yields the time, t_b for which the fabric and air gap would have provided protection from the applied exposure. This time is then used in the relation,

$$\text{TPP rating} = F \times t_b, \tag{1}$$

where F is the applied heat flux, the specific value of which is obtained from the calibration procedure, and t_b is the time to second-degree burn, obtained from the plot. The units of the TPP rating are thus either kJ/m^2 in the SI system or, as is common in the United States, cal/cm^2 (the minimum NFPA Standard TPP rating of 35 cal/cm^2 for protective garments would correspond to an SI rating of 1460 kJ/m^2 and a 17.5 second exposure until the onset of a second-degree burn).

4 Simulating the TPP Test

The computer code utilized to simulate the thermal and mass transport across textile materials is called the **P**rotective **C**lothing **P**erformance **S**imulator (PCPS) [3, 8]. PCPS is specifically designed to solve a simplified system of model equations and calculate the response of one-dimensional textile fabrics subjected to conditions that may be observed during fire exposures. The numerical model incorporates separate layers of a composite fabric so as to evaluate the response of both the individual materials and the entire ensemble. Heat is supplied to the fabric by applying a combination of two boundary conditions. The first is a specified external radiant flux and the second is an ambient gas temperature. The presence of moisture within the fabric, the ambient environment and any air gaps are included in the model. Transport of water vapor across the system is through diffusion and is computed during a simulation. The model also allows adsorption and desorption of moisture within the pore spaces.

Material properties for the individual fabrics are drawn from a database coded into the software with values taken from the measurements of Lawson and Walton [9]. As the material properties were only measured over finite temperature ranges up to 100°C, they are taken to be constant above this limit. The material properties do not account for any thermal degradation that may occur at sufficiently high temperatures.

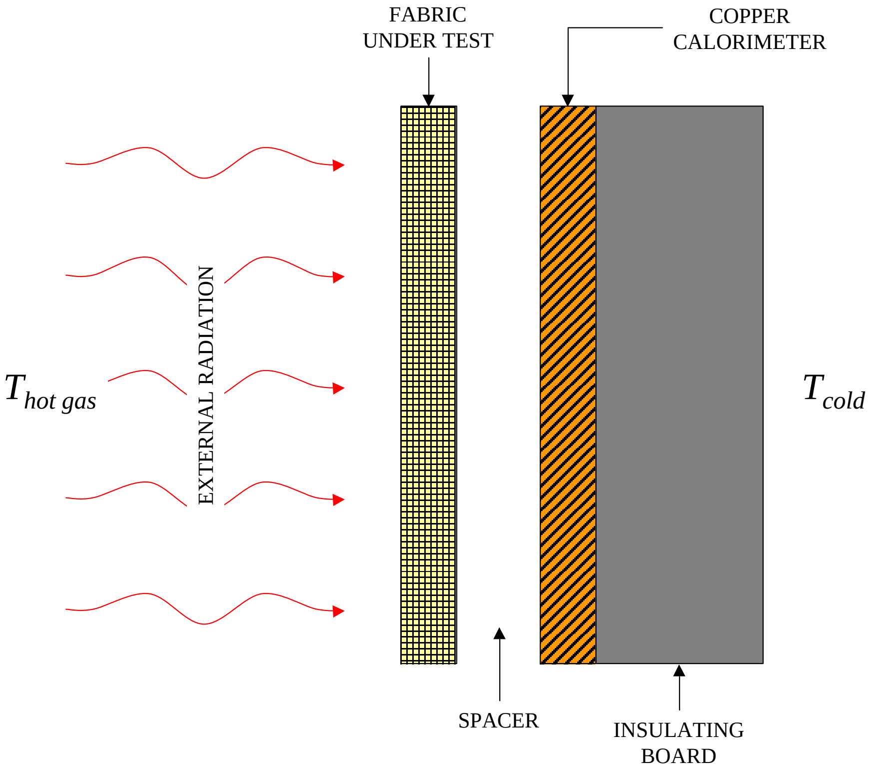


Figure 2: The model of the ISO Standard 17492 TPP test apparatus used for predicting the TPP rating of a single layer fabric.

While developed for porous materials, the governing equations for PCPS were formulated utilizing a continuum approximation. Therefore, in addition to considering heat and mass transfer through woven fabrics, PCPS also will simulate the transfer of heat through nonporous materials as well. The sensor assembly of the TPP test is simulated as a layer of copper and a layer of insulating board. The entire TPP test apparatus is presented as a series of individual layers of a multi-component "fabric."

A schematic representation of the configuration utilized for simulating the TPP test is presented in figure 2. Heat is supplied to the left boundary of the fabric under test from a hot gas ambient and an externally applied radiant flux. Between the fabric and the copper calorimeter is an air gap 0.064 m in width. Beyond the copper, without an air gap, is a layer of insulating material which is exposed to the cold ambient.

4.1 Calibration of the Model

As previously stated, the net heat flux (convective and radiant fluxes) supplied to the fabric under test is set during the calibration procedure by measuring the temperature rise in the calorimeter over a 10 second sampling. The need for the time averaging is due to the fact that the instantaneous flux is constantly changing during the test. As the material warms, the temperature difference between the fabric surface and gas decreases, diminishing the convective heat flux to the fabric. Similarly, the net incident radiation decreases due to the re-radiation of the fabric surface as it warms. Thus, although we may initially supply 80 kW/m^2 of heat energy to the fabric, at the end of the 10 second exposure the value may vary significantly. To determine the combination of externally supplied radiant energy and the hot ambient temperature necessary to achieve the 148°C rise in temperature, it is necessary to perform a calibration procedure similar to that employed

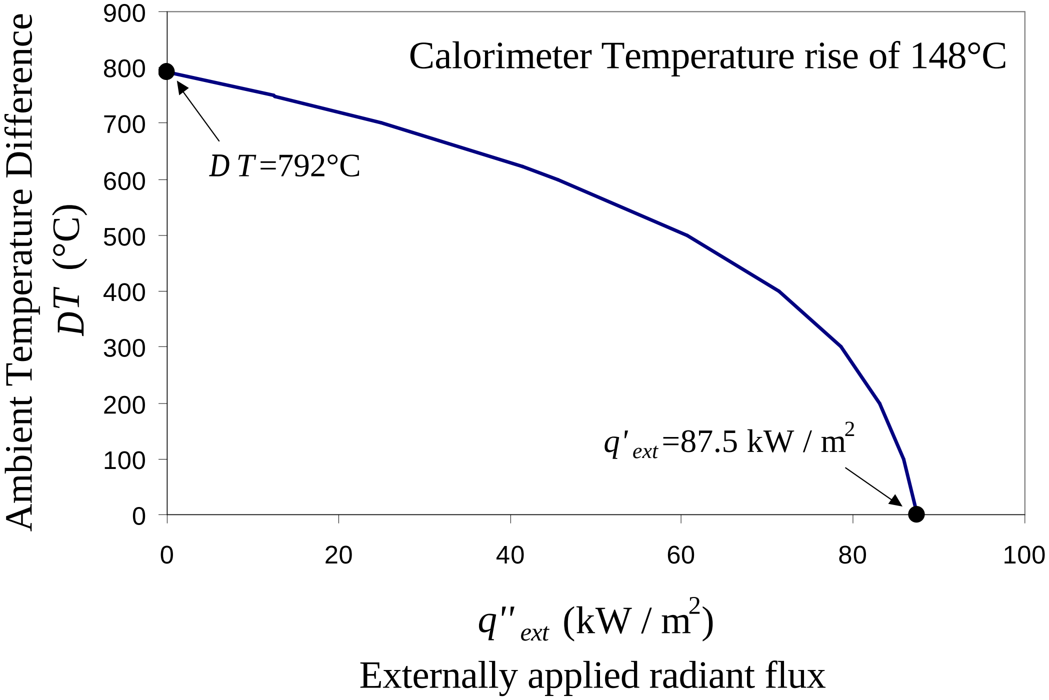


Figure 3: Required ambient temperature difference versus external radiant flux that produces a temperature rise of 148°C for a 10 second exposure to bare copper calorimeter during calibration of TPP test.

during the experiment.

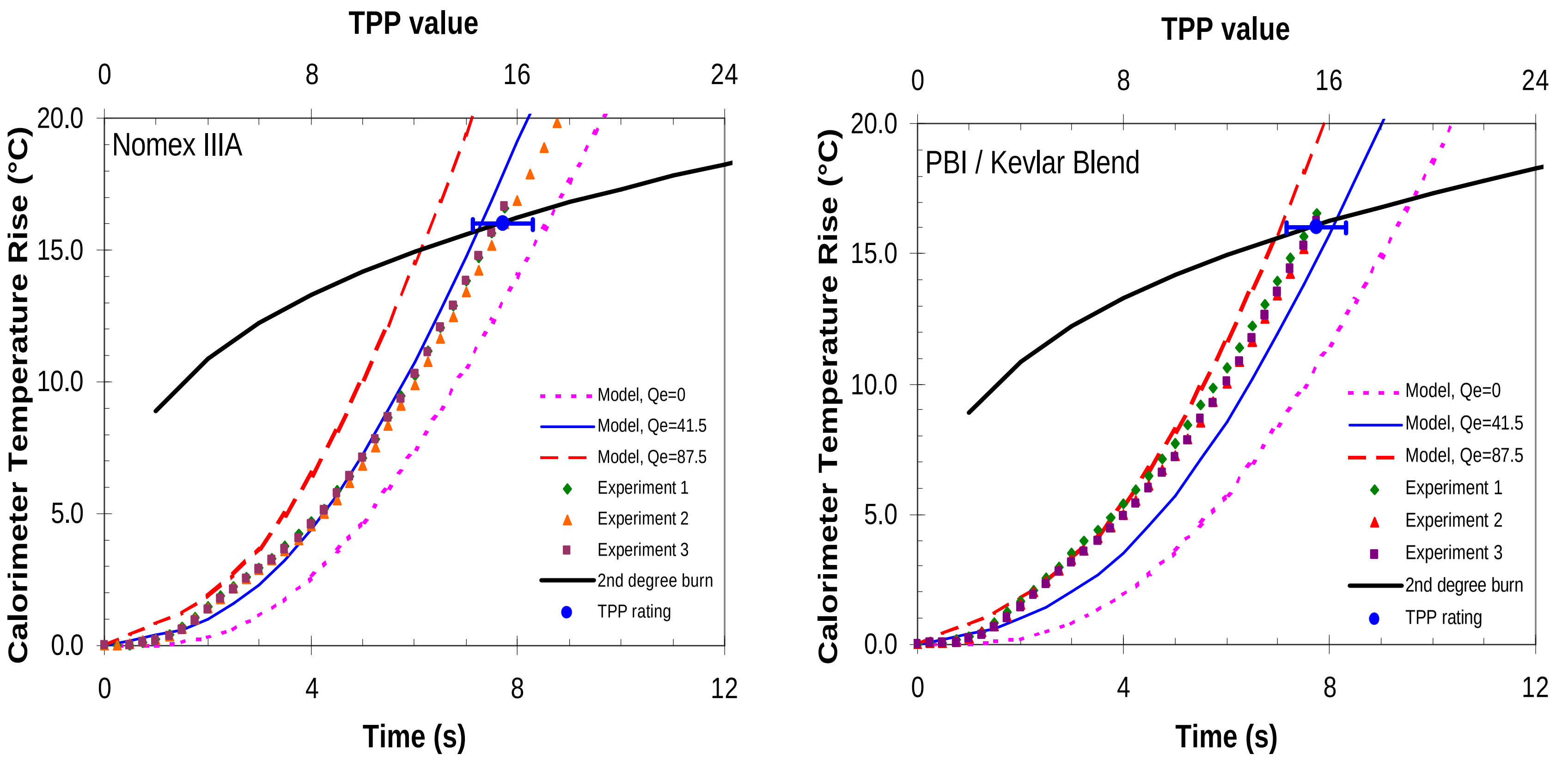
To mimic calibration, a series of simulations were performed in which the fabric and air gap were removed from the model, as in the physical test, and the copper was exposed directly to the heat sources. Simulations were run for 10 seconds with the average temperature of the copper obtained at the end of the simulation. The incident radiant flux and the hot gas temperatures were adjusted until the desired 148°C rise was obtained.

Results of the calibration procedure are shown in figure 3. For the required 148°C temperature rise, the difference between the ambient environment temperature and the initial temperature of the material is plotted as a function of the external radiant flux. For zero externally supplied flux, and thus entirely convective heating, the temperature difference between the ambient and the initial temperature of assembly must be 792°C The inital temperature difference then decreases as the level of externally applied radiant flux increases. For an ambient temperature equal to the initial temperature of the fabric, and thus heating strictly from the applied radiation, a flux value of 87.5 kW/m^2 is required. As expected the applied flux must be greater than the specified average of 80 kW/m^2 of the ISO standard to account for the convective and radiative losses that occur as the material warms.

4.2 Results and Discussion

Experimental measurements for the TPP results presented were conducted in the thermal lab of DuPont's Spruance Plant facility. Raw data was then transferred to and analyzed at NIST. Numerical simulations of the TPP tests were also conducted at NIST.

The results of the study are presented in figure 4. Figure 4a is for the Nomex IIIA simulations and experiments while figure 4b is for the PBI / Kevlar blend. These plots present the temperature of the copper calorimeter as a function of time. For each material three experimental tests were performed with the



(a) (b)

Figure 4: Calorimeter temperature response for (a) Nomex IIIA and (b) PBI / Kevlar blend. Solid lines denote model simulations and discrete points experimental measurements. The TPP criteria curve for onset of second-degree burn is also presented.

measured results presented as the discrete points. The TPP rating obtained from the experiments is presented as the larger solid dot overlaying the second-degree burn criteria. Results of the numerical simulations are presented as the solid and dashed lines for three unique incident flux conditions. The nominal 50% convective, 50% radiative incident flux is presented as the solid line. The short dashed line corresponds to zero externally applied radiative flux and represents strictly convective heating. The long dashed line corresponds to an externally applied radiative flux equal to 87.5 kW/m^2.

The experimental results for each of the fabrics show that the temperature of the calorimeter rises monotonically for the duration of the test. There is, however, for each of the fabrics a slight inflection that occurs shortly, approximately 2 seconds - 3.5 seconds, into the test. An overall TPP rating for each of the fabrics was calculated by averaging the results of three independent tests. For Nomex IIIA, the experimental TPP rating was measured as (640±50) kJ/m^2 ((15.4±1.2) cal/cm^2) and for the PBI / Kevlar blend the TPP rating was measured as (650±50) kJ/m^2 (15.5±1.2) cal/cm^2). The uncertainty in the experimental TPP rating is presented as the error bars of figure 4. This uncertainty was calculated using the statistical variation of the three independent measurements (Type A) as well as the allowable limits of the test configuration (Type B). The type B uncertainty was evaluated by considering rectangular probability distributions for the the tolerance limits presented [4]. Using a coverage factor of two, for each of the materials the expanded uncertainty was evaluated as plus or minus 7.5%.

The model results for Nomex IIIA show that for the idealized 50% radiative and 50% convective case the temperature is underpredicted for a range of approximately 2 seconds to 3.5 seconds, and then overpredicted as time increases and the calorimeter temperature approaches the second-degree burn criteria. Unlike the experimental results, there is not an inflection in the curve. At no time during the length of the test does the temperature predicted by the model vary by more than 1°C from the experimental measurements. For the high radiative flux simulation, the curve rises at a much steeper rate and intersects the second-degree burn curve more than one second before the 50/50 case. For the zero radiative flux simulation, and thus pure convection, the curve rises at a shallower rate and intersects the second-degree burn curve more than one second later than the 50/50 case.

Similar results are observed for the PBI / Kevlar blend. Again, early in the simulation, the model underpredicts the temperature for the 50/50 case. Unlike the previous results, however, this trend continues for the entire length of the experiment although the results are converging near the end of the test. The model does not do quite as accurate a job of predicting the temperature for the PBI / Kevlar blend test as compared to the Nomex IIIA test; however, the predicted temperature is always within 2°C of measured values. Similar to the Nomex IIIA results, the higher level of radiation results in a steeper rise in the calorimeter temperature and for no radiative flux, a shallower rise.

As observed from the results, higher amounts of radiative flux result in a faster rise in the calorimeter temperature. This expected result is due to the penetrating nature of the incident radiation. Unlike convection, which is treated as a surface phenomena, radiation can penetrate into and across the entire width of the fabric. Thus the temperature of the outer surface of the fabric, the surface exposed to the incident heat flux, is greater for the strictly convective case, but the heat transferred across the fabric and to the calorimeter is greater for the case of pure radiation. This result is clearly dependent upon the optical properties of the material under test. For highly reflective surfaces, such as aluminized outer shells in proximity garments, this behavior would not be expected. The results demonstrate the importance of identifying the nature of the incident heat flux when ascertaining the amount of protection afforded by protective fabrics.

A comparison of the TPP ratings achieved from the experimental measurements and model predictions is presented in table 1. Although the Nomex IIIA value is slightly underpredicted and the PBI / Kevlar blend slightly overpredicted in both cases the predictions lie within 6% of the measured values. Further, the predicted values lie within the calculated uncertainty for the measured results. As described above, the predicted TPP ratings for both materials under pure radiative heating is significantly less than for the idealized 50/50 case, while for strictly convective heating the TPP rating is significantly greater.

Condition	Nomex IIIA		PBI / Kevlar	
	kJ/m^2	cal/cm^2	kJ/m^2	cal/cm^2
Measured	640±50	15.4±1.2	650±50	15.5±1.2
50% Convective / 50% Radiative	607	14.5	682	16.3
Radiative limit	510	12.2	582	13.9
Convective limit	732	17.5	803	19.2

Table 1: Measured and predicted TPP ratings for Nomex IIIA and PBI / Kevlar blend.

Mentioned previously, an interesting feature of the experimental data is the presence of a slight inflection for both of the materials. For Nomex IIIA, this occurs at approximately (2 - 2.5) seconds, whereas for the PBI/Kevlar blend it occurs at approximately (2.5 - 3) seconds. Neither inflection is very sharp, but each corresponds to a change in the rate of temperature rise in the calorimeter. The model did not reproduce these results; however, it may provide a explanation for the observed inflections.

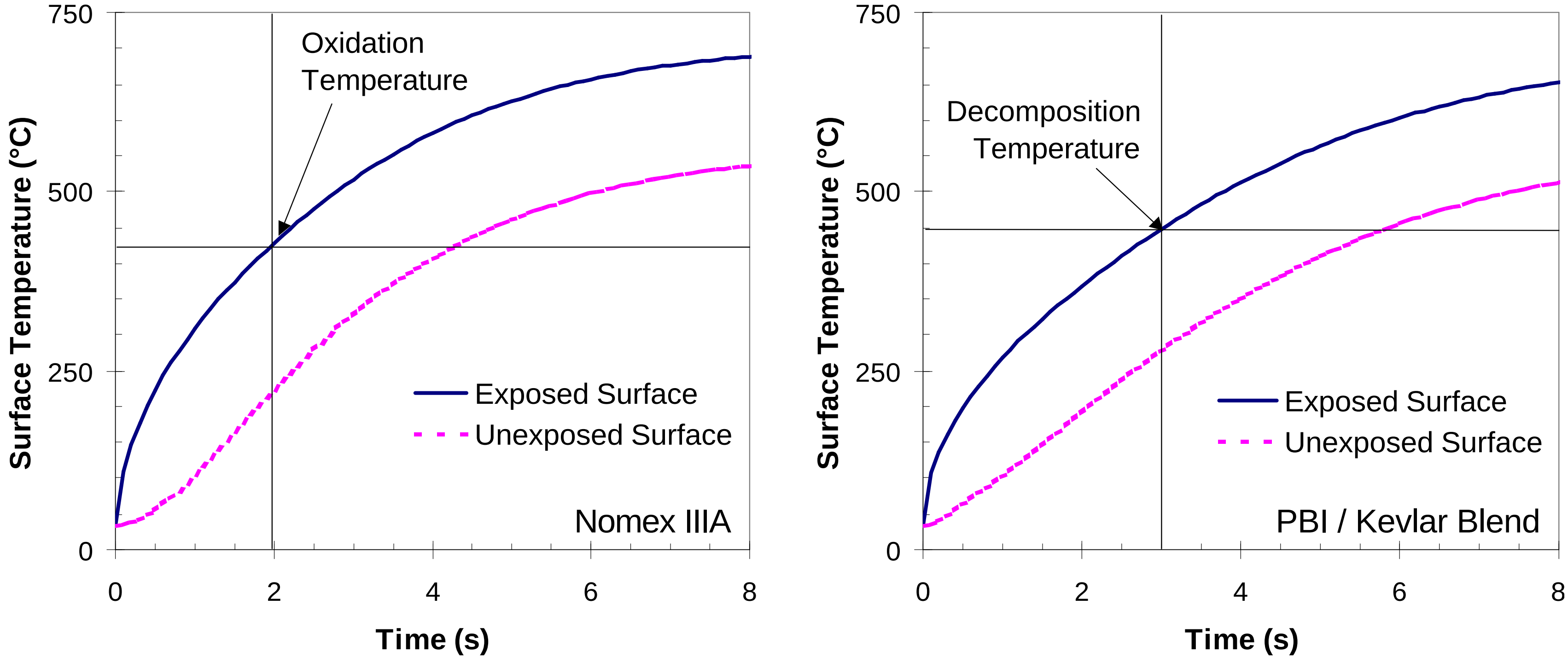
Figure 5 plots the surface temperatures of both the exposed and unexposed faces for each material. Also denoted on the figure are corresponding oxidation and decomposition temperatures for each of the materials. Nomex IIIA is composed primarily (93%) of Nomex fiber which begins to undergo oxidation at approximately 427°C [10]. For the PBI / Kevlar blend, the Kevlar fibers (60%) begin to thermally degrade between 427°C and 482°C [11]. Both of these reactions are endothermic, absorbing some of the incident heat energy and slowing the rate of heat transfer across the fabric and into the calorimeter. The Nomex fibers also swell as the oxidation reaction occurs, reducing the porosity of the material and further altering the heat transfer mechanisms. Kevlar fibers do not swell in this manner. From figure 5 we observe that at the approximate location of the inflection in the experimental data, the outer surface temperature of each of the fabrics has reached a temperature that is near either the oxidation point (for Nomex) or the degradation point (for Kevlar). The heat transfer across the fabric is thus alterred perhaps resulting in the measured inflection for each fabric.

5 Conclusion

We have summarized a series of simulations that have been performed to predict the response of a single layer fabric to the high intensity, short duration convective and radiant heat fluxes that may arise during fire exposures. The predictions have been compared with experimental measurements for two different fabrics utilized in firefighter protective garments. To compare predicted behavior to measured behavior we have chosen to simulate a Thermal Protective Performance test. The results show that the predicted response of the calorimeter sensor from the model system of equations closely matches with experimental results for the case of 50% convective and 50% radiative heat transfer mechanisms.

Predicted TPP ratings for the fabrics also yield good agreement with experimental results. For Nomex IIIA, the predicted value of 607 kJ/m^2 (14.5 cal/cm^2) is within 6% of the experimental result of (640±50) kJ/m^2 ((15.4±1.2) cal/cm^2). For the PBI / Kevlar blend the predicted value of 682 kJ/m^2 (16.3 cal/cm^2) was also within 6% of the the experimental result of (650±50) kJ/m^2 ((15.5±1.2) cal/cm^2). For both materials the predicted value fell within the range of uncertainty for the experimental measurements.

A possible explanation for observed inflections in the calorimeter response during the experimental measurements was also presented. Model results showed that approximately 2 seconds into the exposure, the outer surface temperature of the Nomex IIIA fabric had reached a temperature sufficient to begin oxidation of the Nomex fibers. Likewise, approximately 3 seconds into the exposure, the outer surface temperature of the PBI / Kevlar blend had reach a temperature sufficient to begin decomposition of the Kevlar fibers. Both of these times roughly correspond to the observed inflections of the experimental data, although more tests



(a)

(b)

Figure 5: Exposed and unexposed surface temperatures for (a) Nomex IIIA and (b) PBI / Kevlar blend. For Nomex IIIA the temperature at which the Nomex fiber undergoes oxidation is presented and for the PBI / Kevlar blend the approximate decomposition temperature of the Kevlar fiber is denoted.

showed be made to confirm this conclusion.

Typical simulations utilized in this work were performed in less than 10 minutes on a 933 MHz Pentium III desktop computer with 1GB of RAM. This performance implies a large potential for conducting more complete parametric analyses of fabric responses to various conditions. Physical parameters such as thickness and weight; thermal properties such as thermal conductivity and specific heat; and optical properties such as absorptivity and transmissivity can be systematically varied so as to determine the most efficient means of providing maximum protection while balancing undesireable quantities.

In addition to studying the physical characteristics of the fabrics utilized in protective clothing, the model can be used to determine how fabrics respond to the way in which the thermal energy is applied as well as how they respond to other environmental factors. Previous discussions on materials utilized for protective garments have centered on issues such as the effect of moisture upon the insulating characteristics of fabrics, the presence of stored heat from previous exposure, and the shape of the incident heat flux curve versus time [12, 13]. Any of these items may affect the performance of a firefighter's protective garment.

6 Future Research

Of particular interest is the effect of moisture on the insulating characteristics of protective fabrics. Prior results obtained with the model [3] have shown that the transport of moisture through a composite fabric and the adsorption / desorption of water within the fabric weave can have a dramatic effect on how heat is transported. While the added mass and the evaporative effect of water may slow the transport of heat across a fabric layer, the thermal conductivity of water compared to the base material can also increase the rate in which heat energy is transported across the fabric. An additional concern for wet fabrics is the transport of hot water vapor which may condense further into the fabric at say the surface of the wearer's skin. The possibility of not only dry burns but also scalding burns therfore must be considered for the case of wet fabrics.

While this work has restricted simulations to single layers of protective fabrics, similar work is needed for multilayer fabrics such as are utilized in complete firefighter turnout garments. These garments are composed of not only the outer shell, as utilized in this work, but also include a moisture barrier and thermal liner as well.

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