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Effects of Variations in Thermal Properties on the Performance of Flame Resistant Fabrics for Flash Fires

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ABSTRACT

A numerical model of heat transfer in thermal protective fabrics under high heat flux conditions is used to determine the effects of varying individual thermal properties and boundary conditions on the predicted performance of single layer fabrics during bench top tests simulating flash fire conditions. The fabric thermal properties with the largest effects are thermal conductivity and specific heat. The boundary conditions, *i.e.*, flame temperature and emissivity and convective heat transfer coefficient, have an even larger effect on predicted bench top test results. The results of the parametric studies are described in this paper, along with a discussion about how these results may be used to design thermal protective fabrics.

When designing thermal protective clothing, it is important to know which thermal properties affect its performance. Basic heat transfer theory suggests properties that are important to the performance of protective garments, such as thickness, thermal conductivity, and specific heat. The roles of other properties, such as thickness and moisture regain (*e.g.*, Baitinger and Konopasek [2] and Lee and Barker [4]), have been studied extensively, so the qualitative effects of increases or decreases in certain thermal properties on the thermal protection offered by a fabric or garment are known. For example, Lawson [3] recommends the following to improve the thermal protection of clothing for fire fighters: reduce and control moisture inside the clothing, decrease the thermal conductivity of the materials used in the garment as well as that of the finished garment, and reduce the heat capacity of the garment so as to reduce its ability to store energy. For other applications, this list may be different.

It is important not only to know qualitatively how changes in thermal properties can affect the protection offered by clothing, but also to know these effects quantitatively. As well, many of the thermal properties of fabrics are interdependent or can only be varied within certain limits. For example, while increasing the thickness of a garment may be beneficial in terms of thermal protection, it may also decrease the comfort of those using it. It is important to be able to optimize the combination of important thermal properties to produce the best possible thermal protective clothing.

In an earlier paper, we developed a model of heat transfer in inherently flame resistant fabrics [9]. This model accurately predicts temperatures in these fabrics for the high heat flux exposures of bench top test methods such as ASTM D 4108 [1]. We have used this model to conduct a series of parametric studies to quantitatively describe the effects of various thermal properties of single layer fabrics on the heat transfer in these fabrics and their performance in bench top tests used to simulate flash fires. The model did not include mass transfers, so we did not include the effects of these thermal properties on mass transfers in the parametric studies. The results of our studies demonstrated the utility of the numerical model to designers of protective clothing. Because some of the thermal properties of these fabrics are difficult to measure, our results should also indicate the accuracy to which these properties need to be determined for inclusion in the model.

In this paper, we review the heat transfer model used for these parametric studies and present our results. We also discuss the relative magnitudes of the effects of varying individual thermal properties on the predicted performance of flame resistant fabrics.

Fabric/Air Gap/Test Sensor System

The experimental apparatus used in ASTM D 4108 and some other bench top fabric tests and modeled here is shown in Figure 1. The test arrangement consists of a fabric heated from below by a Meker burner using premixed reactants (propane and air), a copper calorimeter test sensor mounted in an insulating block, and a completely enclosed air space with a thickness δ of about 6 mm between the fabric and test sensor. The dimensions of the apparatus (looking from above) are 150×150 mm. The fabric specimen is 100×100 mm, while the portion of the fabric specimen exposed directly to the flame is 50×50 mm.

The convective heat fluxes from the hot gases from the burner to the fabric and from the fabric to the test sensor are indicated in the figure by q_{conv}, while the net heat fluxes due to thermal radiation exchanges between the burner head, fabric, and ambient and between the fabric and test sensor are indicated by q_{rad}. We used an exposure of 82 kW/m^2 for 10 seconds, which is similar

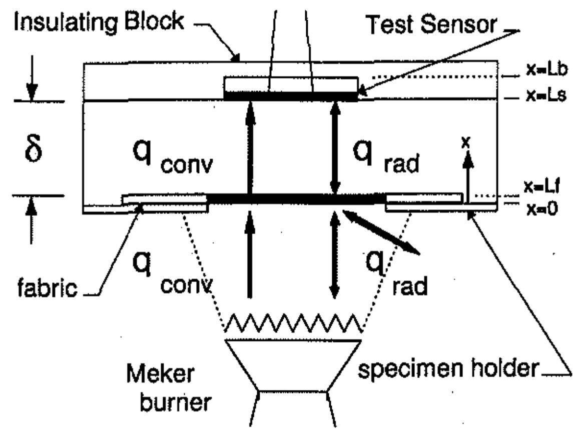

FIGURE 1. Fabric-air gap-test sensor system.

to many bench top tests of single layer fabrics. Because many of the fabric's thermal properties are only determined during fabric heating, we did not include fabric cooling after exposure in the model.

Heat Transfer Model

We developed a one-dimensional heat transfer model of the flame resistant fabric-air gap-test sensor system described above. Using assumptions and methods outlined in Torvi [8], we developed the following differential equation for the temperature distribution in the fabric-air gap-test sensor system:

$$C^A(T)\frac{\partial T}{\partial t} = k(T)\frac{\partial^2 T}{\partial x^2} + \gamma q_{\text{rad}} \exp(-\gamma x) \quad , \quad (1)$$

where C^A is the apparent heat capacity,[1] $k(T)$ is the temperature dependent thermal conductivity, q_{rad} is the portion of the net radiative heat flux on the surface of an infinitesimal element of fabric,[2] γ is the extinction coefficient for the fabric, and the rest of the symbols have their usual meanings.

We solved the equation subject to the following initial and boundary conditions:

Initial condition, $t = 0$:

[1] The apparent heat capacity is the product of the density and the temperature-dependent apparent specific heat. Temperature-dependent apparent specific heat values include energies associated with thermochemical reactions, which are determined using a thermogravimetric analyzer and a differential scanning calorimeter. More details on this method of treating thermochemical reactions in heat transfer problems can be found in Torvi [8].

[2] For the element on the exposed surface of the fabric, this is the net radiative flux incident on that fabric surface. For interior elements, this is the amount of the net radiative flux that is transmitted to the surface of that particular interior element (*i.e.*, the portion that has not been absorbed in the previous elements).

$$T(x) = T_i(x) \quad , \qquad (2)$$

where $T_i(x)$ is the initial temperature distribution in the fabric, air gap, and test sensor.

Boundary condition at the heated surface, $x = 0$, for $t > 0$:

$$-k(T)\frac{\partial T}{\partial x} = q_{\text{conv}} = h_{fl}(T_g - T_{x=0}) \quad , \qquad (3)$$

where h_{fl} is the convective heat transfer coefficient for the hot gases from the burner, and T_g is the temperature of the hot gases from the burner.

Boundary condition at the back of the air space between the test sensor and the back of the insulating block (see Figure 1), $x = L_b$, for $t > 0$:

$$T(x = L_b) = T_{\text{amb}} \quad , \qquad (4)$$

where T_{amb} is the ambient temperature, taken as 300 K.

We used the finite element method to solve Equation 1 and wrote a computer program based on this finite element model to solve for the temperatures at various locations within the fabric and corresponding temperatures of the copper test sensor during an exposure. We then used these copper test sensor temperatures to estimate the time required to produce second-degree burn damage to human skin placed in the same position as the test sensor using the data from Stoll and Chianta [7] (often referred to as the Stoll criterion—see ASTM D4108 [1] and Figures 3 and 6).

We validated the model using transient temperatures of the exposed and unexposed sides of fabric specimens measured with an infrared thermometer (Barnes Optitherm model 12-8762, Barnes Engineering Company, Stamford, CT) during 10-second exposures to a heat flux of 82 kW/m^2. The tolerance for this heat flux was ±2 kW/m^2. We also recorded temperatures of the copper disk test sensor. We used specimens of two common, inherently flame resistant fabrics, Kevlar®/PBI[3] (60% Kevlar and 40% PBI) and Nomex® IIIA as test cases for the model. Each had a nominal mass per unit area of 200 g/m^2 (6 oz/yd^2). The Kevlar/PBI samples were 2/1 twills, while the Nomex IIIA samples were plain weaves. There was an air gap of 6.4 mm (1/4 inch) between the fabric and test sensor, as in ASTM D 4108.

Temperatures and bench top test results predicted by the model were similar to those measured during actual tests. For example, Figure 2 compares the predicted and measured fabric temperatures for the Nomex IIIA fabric (the lower limit of the temperature range of the infrared thermometer is 200°C). Predicted fabric temperatures are close to those measured using the infrared thermometer, especially after the first few seconds of the exposure. The absolute temperatures predicted by the model are less than 4% different from those measured with the infrared thermometer during the latter portion of the 10-second exposures.

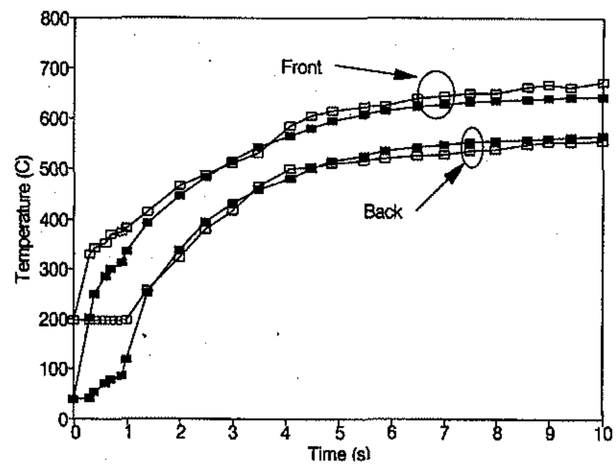

FIGURE 2. Comparison of temperatures of front and back of Nomex IIIA fabric specimens predicted using numerical model (■) and measured using infrared thermometer (□).

The model also accurately predicted copper disk test sensor temperatures and times required to exceed the Stoll criterion. For example, Figure 3 compares the predicted and measured temperatures of the bench top test

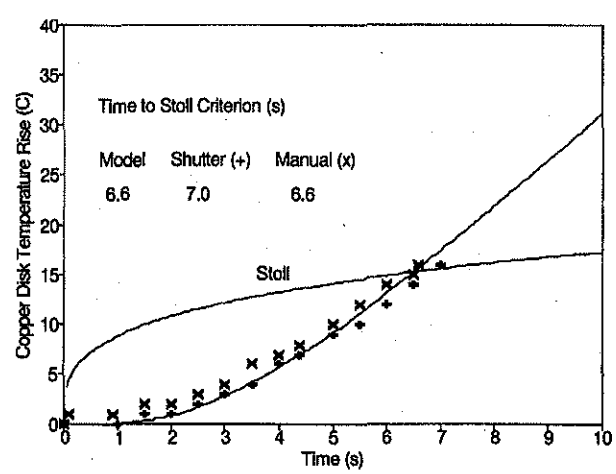

FIGURE 3. Comparison of predicted and measured copper disk temperatures and bench top results for Nomex IIIA fabric specimens.

[3] Certain commercial products are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendations or endorsement by the National Research Council of Canada, nor does it imply that the product or material identified is the best available for the purpose.

sensor mounted 6.4 mm (1/4 inch) behind a Nomex IIIA fabric specimen. Predicted times required to exceed the Stoll criterion are also given in the figure, along with data measured with the bench top apparatus, using either an automatic shutter to expose the fabric or manually moving the burner into place to begin the exposure. Predicted times required to exceed the Stoll criterion are within 6% of those measured during actual bench top tests.

In the numerical model, the high heat flux was imposed on the model exactly at time zero. With the manual tests, time zero was when a proximity sensor indicated that the burner was in place. Therefore, the fabric was preheated for a fraction of a second as the burner was moved into place before the computer began taking data. This was opposite the case of the bench top tests with the shutter, where the burner was in place at time zero when the computer sent a signal to the pneumatic shutter to open. It required up to 0.2 seconds for the shutter to open, so the fabric might not be exposed to the full flame for up to 0.2 seconds after time zero. Therefore, we would expect that the results of the numerical model, where the full flux is placed on the fabric at time zero, should be in between the two sets of experimental results. This is what Figure 3 shows.

Effects of Individual Thermal Properties on Bench Top Test Results

Designers of protective fabrics are interested in quantitatively knowing the effects of various thermal properties on the protection these fabrics may provide. In addition, many of the thermal properties used in numerical models of thermal protective fabrics are difficult to determine or are associated with much uncertainty. To determine the effects of varying these thermal properties on the results from the numerical model, we conducted a series of parametric studies using the properties of the Nomex IIIA fabric for the base cases. The range of values for the thermal properties in the parametric studies are given in Table I.

In many cases, we did not choose the range of values for the individual properties to reflect the anticipated range of values expected for these materials, but rather to determine the effects of individual parameters over a wide range of values. A summary of the results of these parametric studies is presented here in terms of times required to exceed the Stoll criterion. Further information on the effects of variations in the individual parameters on fabric and sensor temperatures can be found in an earlier work (Torvi [8]).

TABLE I. Ranges of values for thermal and other properties used in the parametric studies.

Property	Range of values used in parametric study (typical value for Nomex IIIA fabric during this bench top test)
Moisture regain, %	0–100 (5)
Thickness, mm	0.3–2.0 (0.7)
Thermal conductivity, W/m·°C	0.04–0.2 (0.04)
Specific heat, J/kg·°C	1000–3900 (1300)
Decomposition reaction temperature range, °C	initial temperature: 350–600 (425) ΔT for reaction: 100–300 (200)
Decomposition reaction energy, endothermic, kJ/kg·°C	30–300 (130)
Convective heat transfer coefficient, W/m²·°C	25–50 (40)
Flame temperature, K (corresponding emissivity)	1800–2200 K (2000 K) (0.018–0.022) (0.02)

MOISTURE REGAIN

We varied the initial amount of moisture in the fabric between 0 and 100%. The temperatures predicted for the front and back of a Nomex IIIA fabric are shown in Figures 4 and 5, while the temperatures predicted for the copper disk test sensor are shown in Figure 6. The times required to exceed the Stoll criterion for different initial amounts of moisture are given in Table II.

As the initial amount of moisture in the fabric increased, the predicted rates of temperature increase on the front and back of the fabric decreased (Figures 4 and 5). This was due to the increased amount of energy from the Meker burner, which was required to evaporate the water in the fabric. In turn, the decrease in the

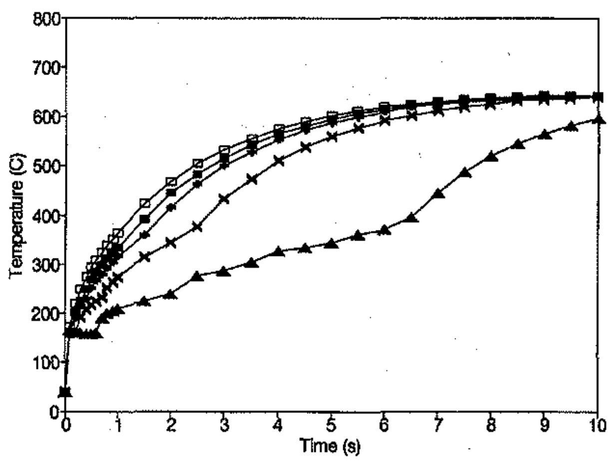

FIGURE 4. Temperatures of exposed side of fabric predicted by numerical model for various initial mass fractions of moisture (□ 0.01, ■ 0.05, + 0.10, × 0.25, ▲ 1.00).

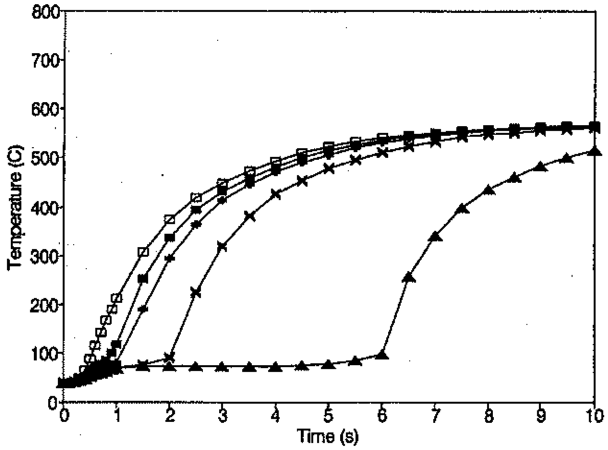

FIGURE 5. Temperatures of unexposed side of fabric predicted by numerical model for various initial mass fractions of moisture (□ 0.01, ■ 0.05, + 0.10, × 0.25, ▲ 1.00).

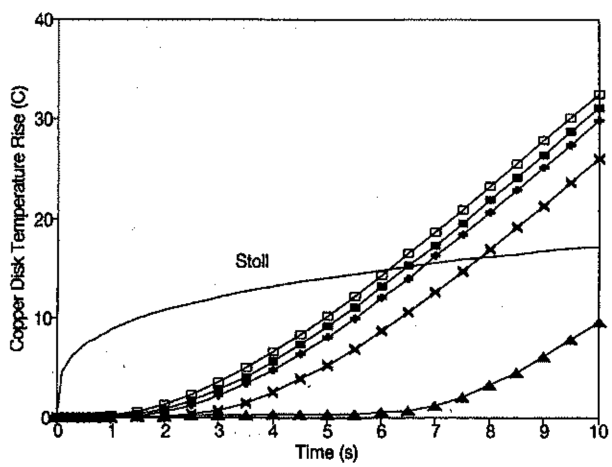

FIGURE 6. Copper disk temperature rises predicted by numerical model for various initial mass fractions of moisture (□ 0.01, ■ 0.05, + 0.10, × 0.25, ▲ 1.00).

TABLE II. Required times to exceed Stoll criterion predicted by numerical model for various initial mass fractions of moisture.

Moisture regain, %	Time required to exceed Stoll criterion, seconds
0	6.15
3	6.35
5	6.55
7	6.65
10	6.85
15	7.15
20	7.50
25	7.80
100	>10

rate at which the temperature of the back of the fabric (Figure 5) increased caused the copper disk temperature to increase more slowly (Figure 6), which increased the time required to exceed the Stoll criterion (Table II). The magnitude of the differences between the times required to exceed the Stoll criterion temperatures for tests of dry (0%) and conditioned (5–7%) fabrics were similar to the differences measured by Lee and Barker [4] for 50% convective/50% radiative bench top tests (the tests simulated in the model were nominally 75% convective/25% radiative[4]).

It would therefore appear that moisture enhances the performance of fabrics in bench top tests. In our study, however, only one parameter, moisture regain, was varied independently, and moisture transfer and the energy transfers associated with it were not included in the numerical model. In addition, we did not consider the effects of increased moisture regain on other thermal properties (*e.g.*, thermal conductivity). Morse *et al.* [5] found it difficult to determine whether water vapor from heated fabrics travels toward the skin or test sensor or toward the heat source. For the particular hazard they were modeling, a JP-4 fuel pool fire, the dynamic pressure across a fabric during an exposure and the internal pressures developed by the evaporation of moisture were similar in magnitude. If some of the moisture from the fabric does in fact travel toward the skin or test sensor, then there may be a point at which increases in the initial moisture content may, in fact, have a detrimental effect on the protection the fabric offers. This effect has been shown to be important when studying longer exposures to high heat fluxes. For example, many fire fighters suffer steam burns during the course of their duties [3]. However, moisture transfer in fire fighters' clothing will be different from the single layer fabrics we studied in this paper, due to the multiple layers, the presence of moisture barriers, and other factors.

THICKNESS

We varied the fabric thickness between 0.3 and 2.0 mm, and the times required to exceed the Stoll criterion for different thicknesses are shown in Figure 7. We found the relationship between the time required to exceed the Stoll criterion and fabric thickness to be linear for this range of fabric thicknesses, which agrees with

[4] When discussing the nominal percentages of the radiative and convective components of the heat flux, note that Lee and Barker [4] measured the total heat flux with a copper calorimeter and the contribution of the radiative portion of this total with a commercial radiometer. This procedure is also used in test standards specifying the portions of the flux that are convective and radiative. In this study, we calculated the nominal percentages from the values of the flame temperature, convective heat transfer coefficient, radiation view factors, etc.

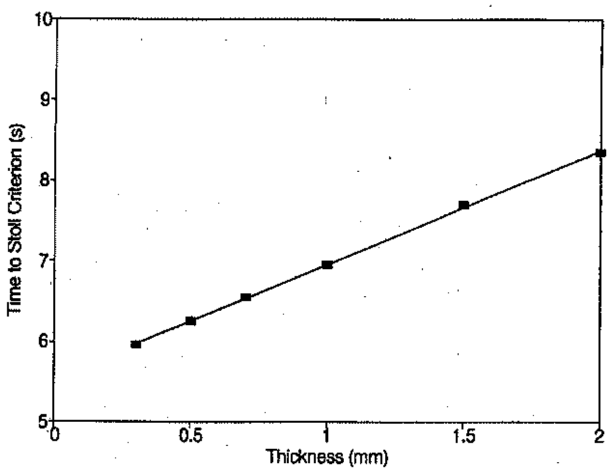

FIGURE 7. Times required to exceed the Stoll criterion predicted by numerical model for different fabric thicknesses.

the experimental work of other investigators (*e.g.*, Baitinger and Konopasek [2]).

We can explain the increased time required to exceed the Stoll criterion with thickness in terms of predicted fabric temperatures. As thickness increases, the temperature of the back of the fabric increases at a slower rate. This is expected because increasing fabric thickness increases the internal resistance to heat transfer within the fabric. This slower rate of temperature increase on the back of the fabric leads to a decrease in the rate of energy transfer between the fabric and the test sensor across the air space, which, in turn, increases in the time required to exceed the Stoll criterion.

THERMAL CONDUCTIVITY

The specific heat of the fabric was held constant at 1300 J/kg°C, the nominal value for a fabric at room temperature, while thermal conductivity was given constant values between 0.04 and 0.2. The times required to exceed the Stoll criterion for different values of thermal conductivity are given in Table III.

The value of thermal conductivity had a significant influence on the rate of temperature increase on the front of the fabric, and an even larger influence on the rate on the back of the fabric. The differences in the temperatures on the back of the fabric manifested themselves in differences in the copper disk temperatures, and hence the times required to exceed the Stoll criterion. An increase in the thermal conductivity of the fabric increases the rate of heat transfer in the fabric, causing the temperature of the fabric back to increase faster and thus increasing the energy transfer between the fabric and the skin or test sensor.

TABLE III. Required times to exceed Stoll criterion predicted by numerical model for various constant values of thermal conductivity.

Thermal conductivity W/m·°C	Time required to exceed Stoll criterion, seconds
0.04	>10
0.08	7.00
0.12	5.95
0.16	5.45
0.20	5.15

As a practical illustration of how thermal conductivity can vary from fabric to fabric, we varied the volume fraction of the fibers from 5 to 30%. We determined thermal conductivity at each time step using the weighted sum (by volume fraction) of the thermal conductivities of fibers and air calculated using expressions developed for the temperature-dependent thermal conductivity of each [8]. The times required to exceed the Stoll criterion are shown in Table IV.

TABLE IV. Required times to exceed Stoll criterion predicted by numerical model for various volume fractions of fibers.

Volume fraction of fibers, %	Time required to exceed Stoll criterion, seconds
5	7.80
10	7.10
20	6.55
30	6.25

As shown in the table, increasing the volume fraction of fibers in the fabric increases the thermal conductivity of the fabric and thus decreases the time required to exceed the Stoll criterion. This only takes into account the effect of an increased volume fraction of fibers on the thermal conductivity of the fabric, and does not account for effects on the mechanical stability of the fabric, other thermal properties, etc.

SPECIFIC HEAT

We allowed the thermal conductivity to vary according to fabric temperature using the equations normally employed in the numerical model. The specific heat was given constant values between 1000 and 3900 J/kg·°C. We also calculated temperature dependent specific heat values using the apparent heat capacity method in the numerical model and an empirical relationship given by Schoppee *et al.* [6] for an "average" polymeric material. Times required to exceed the Stoll criterion predicted using the various constant and temperature dependent specific heat values are shown in Table V.

TABLE V. Required times to exceed Stoll criterion predicted by numerical model for various constant values of specific heat.

Specific heat, J/kg·°C	Time required to exceed Stoll criterion, seconds
1000	4.45
1300	5.00
2600	7.25
3900	9.30
Schoppee *et al.* [6]	6.10
Apparent specific heat [8]	6.55

The value of specific heat significantly influenced the rate at which the front and back temperatures of the fabric increased, as expected from basic heat transfer theory. Differences in the predicted temperatures on the back of the fabric manifested themselves in differences in the rates of increased copper disk temperatures, and hence the times required to exceed the Stoll criterion. The equation based on the apparent heat capacity method accounts for energies associated with moisture evaporation and thermal decomposition reactions, whereas the constant values of specific heat and Schoppee's equation do not.

ENERGIES ASSOCIATED WITH THERMAL DECOMPOSITION REACTIONS

There are many difficulties and uncertainties associated with determining the energies connected with thermal decomposition reactions. For example, many differential scanning calorimeters can only be used to determine specific heat data up to a maximum temperature of 500°C, which is less than the upper bound of the temperature range over which thermal chemical reactions take place in the materials. Hence, the value of the apparent heat capacity often can only be estimated beyond this temperature. In order to determine the effect of variations in these energies on predicted fabric performance and how accurately these energies must be known, we varied the energy associated with thermal decomposition reactions between 30 and 300 kJ/kg. The temperature range over which this energy is released was set at 425–625°C. To determine the effect of varying the temperature range over which energy is released, we set the energy at 130 kJ/kg and varied the temperature range for the thermal decomposition reaction from 100–300°C. Differences in the temperatures of the fabric and the copper disk were minimal. The times required to exceed the Stoll criterion are shown in Tables VI and VII.

Changes in energy associated with thermal decomposition reactions had a minimal effect on the protection offered by the fabrics. This seems counter-intuitive, but while conditioned fabrics have small amounts of moisture (*e.g.*, 5–8% by mass), the amount of energy required to evaporate this water can be equal to or greater than the estimated amount of energy required for thermal decomposition reactions (*e.g.*, 125–200 kJ/kg for evaporation and moisture removal from the fabric as compared to 130 kJ/kg for thermal decomposition reactions). This is why the initial moisture in the fabrics had a much larger effect on the thermal response and protection offered by the fabrics.

The temperature range over which the reactions were assumed to occur had a relatively small effect on the protection offered by the fabrics. Reactions that occur at lower temperatures will "stall" the temperature rise on the back of a fabric, thus reducing the energy transfer to the skin or test sensor and increasing the time required to exceed the Stoll criterion. The magnitude of temperature range over which energy was released had a very minimal effect on the results of the numer-

TABLE VI. Required times to exceed Stoll criterion predicted by numerical model for various values of energy of thermal decomposition reaction.

Reaction energy, kJ/kg, endothermic	Time required to exceed Stoll criterion, seconds
30	6.35
60	6.40
80	6.45
100	6.45
130	6.55
150	6.55
200	6.65
300	6.85

TABLE VII. Required times to exceed Stoll criterion predicted by numerical model for various temperature ranges for thermal decomposition reaction.

(a) Effect of initial and final temperature (200°C temperature range)

Initial temperature, °C	Final temperature, °C	Time required to exceed Stoll criterion, seconds
350	550	6.65
425	625	6.55
500	700	6.40
600	800	6.25

(b) Effect of temperature range

Initial temperature, °C	Final temperature, °C	Temperature range, °C	Time required to exceed Stoll criterion, seconds
425	525	100	6.65
425	575	150	6.60
425	625	200	6.55
425	725	300	6.50

ical model. These results appear to indicate that further work is not required to refine the estimates of the energies associated with thermal decomposition reactions used in this model.

Our analysis does not include the effects of decomposition reactions on the mechanical integrity of fabrics, not do we consider mass transfer of decomposition products. Therefore, while the results of our parametric study indicate that it is desirable to have decomposition reactions occur at lower temperatures, caution must be exercised in applying these results. If these reactions severely damage or destroy the mechanical integrity of the fabric, cause it to shrink toward the skin or test sensor, or release large quantities of decomposition reaction products that can condense on the skin or test sensor, decomposition reactions that occur at lower temperatures will certainly decrease the protection a fabric offers.

BOUNDARY CONDITIONS

The convective heat transfer coefficient for the flow of hot gases from the Meker burner and the flame temperature are used to define the boundary condition and hence the heat flux incident on the fabric. We varied the convective heat transfer coefficient between 25 and 50 $W/m^2 \cdot °C$, and the temperature of the flame and its corresponding emissivity ε between 1800 ($\varepsilon = 0.022$) and 2200 K ($\varepsilon = 0.018$). The times required to exceed the Stoll criterion for different values of the convective heat transfer coefficient are given in Table VIII, and those required to exceed the Stoll criterion for different values of flame temperature and emissivity are given in Table IX.

TABLE VIII. Required times to exceed Stoll criterion predicted by numerical model for various values of convective heat transfer coefficient.

Convective heat transfer coefficient, $W/m^2 \cdot °C$	Time required to exceed Stoll criterion, seconds
25	8.30
30	7.55
35	7.00
40	6.55
45	6.15
50	5.75

TABLE IX. Required times to exceed Stoll criterion predicted by numerical model for various values of flame temperature and emissivity.

Flame temperature, K	Emissivity	Time required to exceed Stoll criterion, seconds
1800	0.022	7.60
2000	0.02	6.55
2200	0.018	5.75

The convective heat transfer coefficient and the flame temperature and emissivity each have a very large influence on the temperatures and bench top test results. In fact, as discussed below, the description of the front boundary condition is the parameter that has the largest effect of all the parameters we examined in this study.

Implications of Results to Fabric Design

The results of our parametric studies indicate the effects of varying individual thermal properties on thermal responses and bench top test results of single layer fabrics. Many of the qualitative results of the parametric studies are intuitively obvious from basic heat transfer theory. For fabric design, however, it is important to know the quantitative effects of these properties on fabric performance. Table X compares the effects of changes to each individual property. Fabric thermal properties that have the largest effect on the times required to exceed the Stoll criterion are thermal conductivity and specific heat. We expected this because, in conduction heat transfer, the key quantities are thermal diffusivity $(k/(\rho \cdot c_p))$ or thermal absorptivity $((k\rho c_p)^{1/2})$. Thickness is also an important property, which is also intuitively obvious. The moisture regain and energy associated with thermochemical reactions have minor effects on the predicted bench top test results.

In practice, certain properties of protective fabrics can be changed more easily than others. For example, increasing the thickness of a single layer fabric may be relatively easy, and is only limited by comfort. Fabric thermal properties are interdependent. The thermal conductivity of a fabric is very dependent on the amount of air in it. While an increase in the volume fraction of air will decrease thermal conductivity, it will also allow more incident radiation to penetrate completely through a fabric. As well, this work indicates that increasing the moisture in a fabric improves its performance under flash fire conditions, but increasing moisture content also increases thermal conductivity, which, in turn, decreases the protection a fabric offers. While these interactions of thermal properties were not considered in this study, correlations for thermal properties that take these interactions into account must be used when applying the numerical model to fabric and garment design.

The boundary conditions, flame temperature and corresponding emissivity, and convective heat transfer coefficient have an even larger effect on predicted bench top test results than any fabric thermal properties. This is to be expected, because they define the

TABLE X. Comparison of effects of individual thermal properties and boundary conditions on predicted times required to exceed Stoll criterion.

Property	Typical value	Change to typical value	Effect on time required to exceed Stoll criterion
Moisture regain	5%	double	increase 5%
Thickness	0.7 mm	double	increase 15%
Thermal conductivity	0.04 W/m·°C	double	decrease more than 30%
Specific heat	1300 J/kg·°C	double	increase 45%
Decomposition reaction energy (endothermic)	130 kJ/kg·°C	double	increase 4%
Convection heat transfer coefficient	40 W/m²°C	decrease 25%	increase 15%
Flame temperature	2000 K	decrease 10%	increase 15%

intensity of the thermal assult on the fabric. While a designer does not have control over the nature of the high heat flux a garment will be subjected to, this result shows the importance of setting appropriate exposures for test standards of protective fabrics or garments and the large effect this exposure has on test results for these materials.

The optimum values of fabric thermal properties may also change depending on the exposure of interest. Our parametric study indicates that increasing the specific heat has a large effect on increasing the time required to exceed the Stoll criterion for thin, single layer fabrics under simulated, short duration, high heat flux exposures. However, Lawson [3] states that an increase in the heat capacity of fire fighters' clothing, which is much thicker than the fabrics studied in this paper, can represent an increased hazard, because it allows more energy to be stored in the garment and released over long periods of time, possibly causing skin burns. This illustrates that the performance of protective clothing must be evaluated for the specific hazard faced, rather than being applied to all situations.

Conclusions and Recommendations

We have used a numerical model of heat transfer in thermal protective fabrics under high heat flux conditions to determine the effects of varying individual thermal properties and boundary conditions on the predicted performance of single layer fabrics during bench top tests. Fabric thermal properties with the largest effects are thermal conductivity and specific heat. Boundary conditions of flame temperature and emissivity and convective heat transfer coefficient have an even larger effect on predicted bench top test results.

Our results also indicate which thermal properties must be determined most accurately for inclusion in numerical models of fabrics. Developing better techniques to determine these properties over the wide fabric temperature ranges seen in bench top tests will help improve the results from this and other numerical models of these and similar materials. Relationships that include interactions of individual thermal properties should also be developed.

We have considered single-layer fabrics under short duration flash fire conditions in this paper. Parametric studies for longer term exposures, such as those encountered by fire fighters, should also be run in order to determine the effects of various parameters on the protection these fabrics can provide. Of particular interest are the roles of thermal properties both during and immediately after exposure, when the fabric is cooling but can still transfer large quantities of energy to skin behind it.

Numerical results provided in this paper are for bench top tests, which use a laboratory burner as a heat source. We have shown that the nominal heat flux from the burner is 75% convective and 25% radiative. Other bench top tests (and other industrial hazards) have heat sources with different percentages of convective and radiative incident energy. If a radiative heat source is used, oxygen may be available to support oxidative thermochemical reactions on the front surface of the fabric, which would be exothermic rather than endothermic like the reactions are modeled in this work. The effects of varying the thermal properties of a fabric subjected to a radiative exposure should therefore also be quantified.

Cautions

In applying the work in this paper, remember that our results are applicable only to common bench top tests of two particular protective fabrics. The numerical model discussed in this paper has certain limitations. Exposure to a laboratory Meker burner, used in the bench top tests here, is different from an actual flash fire or other industrial accident. We did not consider human response during an accidental exposure, so for these and other reasons, the results and discussion in this paper may not be applicable to the performance of actual protective fabrics or garments during actual flash fires or other industrial accidents. Our model should not be used to estimate the protection these or other materials can provide in a flash fire or other accident, but is only intended to be used to gain an appreciation for the physics involved in bench top tests of these particular fabrics.

In addition, our intention in this work was not to recommend either of the two fabrics used in this study, or any other particular fabric, for thermal protective clothing. Our results are based on tests of specimens from limited quantities of two fabrics supplied to us, and so they may not be representative of other specimens of the same fabrics or other bench top test results.

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