A Model for Assessing Ignition, Flame Spread, and Burn Hazard Potential of a Multilayered Jacket

Ofodike A. Ezekoye, PhD,* Kenneth R. Diller, ScD†

An analysis is presented of ignition, flame spread, and skin burn associated with the ignition and burning of a multilayered jacket. The important physical processes can all be detailed based on simple thermophysical modeling. The ignition process associated with proximity to a radiant heat source is analyzed to see how a change in external (outer) fabric could have diminished the likelihood of ignition. Once the composite jacket has been ignited, the flame spread process is responsible for the heat transfer to the skin that causes the burn. We analyze the effects of the jacket innermost material on flame spread and on possible burn damage. We show how available thermophysical property data can be used to estimate the effect of inner layer material on burn event duration. Finally, given best-available data on the heat transfer rates between a burning inner layer and skin, we examine the kinetics of skin burn damage to determine the most likely injury that would result. (J Burn Care Res 2006;27:487–495)

Predicting the likely thermal insult from a particular ensemble of garments that has been ignited is a complex analysis challenge. The processes of ignition, flame spread, and heat transfer between the burning garments and tissue are coupled, multiple-physics problems. Furthermore, knowledge of the important characteristics (property data) of any particular textile material in specifying the likely damage impact is not obvious. In some accident scenarios, it is of interest to know how relatively simple changes in the layering of the cloth could have adversely or positively influenced the severity of burn injury.

In this report, we present a methodology to assess the impact of ignited clothing layers on burn severity. The methodology evaluates the most important effects of the various physical processes that impact burn severity. The specific scenario we examine is the burn severity that would result from a composite (layered) clothing assembly that is subjected to a radiant source. We ask whether reversal of the layers would have any impact on the severity of a burn to a person wearing the assembly. Both the control and reversed layer structures are jacket styles that are marketed widely.

We address the ignition and burning characteristics of a garment with a cotton outer cover, polyester batting, and a polyester inner layer overlaid on a twoply cotton layer on a skin surface. Garments like this are commonplace and provide good thermal insulation at reasonable prices. We also exchange the layers of clothing and ask if there could be a change in the ignition and potential burn characteristics of the reversed system. In particular, we ask if the exchange of a cotton outer layer for a polyester or nylon outer layer and the exchange of a polyester inner layer for a cotton inner layer would affect the burn characteristics of the garment.

The basis for this analysis is an actual accident. A middle-aged man suffered third-degree burns over most of his back when a composite jacket that he was wearing ignited as he sat by a gas log fireplace (Figure 1). A picture of the burned composite jacket is shown in Figure 2. The jacket had a layered construction with a heavy weight, 0.41 kg/m² (12 oz/yd²), cotton outer layer, quilted polyester batting, and a poly-
ester inner layer. The jacket was worn over a cotton shirt and cotton undershirt.

The accident in question can be analyzed by focusing on the requirements for the injury to have occurred. The analysis is characterized in terms of a fault-tree type model as shown in Figure 3. We show three basic steps required for the damage to have occurred.

1. The critical first step labeled 1 is a radiant ignition process that must occur for the accident to take place. This ignition process is for the outer layer. Apart from ignition, no burn will occur.

2. Steps 2.1 through 2.n represent the ignition processes for the multiple inner layers that were worn by the injured party. Note that thermal injury may not require that all of these layers be ignited for the damage to take place. Damage to tissue, which is represented by the heat flux assault shown in step 3, may occur at temperatures lower than the ignition temperature for a particular layer. As an example, a hot molten layer of a polymer dropped on a thin cloth layer adjacent to skin may cause a considerable burn injury without ignition of the cloth layer.

3. Step 3 represents the heat flux assault that would be consistent with the thermal damage that occurred to the victim.

To analyze each of the foregoing steps, we refer to the literature to clarify the underlying physics and also to find representative properties for the materials being analyzed.

RADIATIVE HEAT FLUX ANALYSIS

Radiation heat transfer is thermal energy conveyed by electromagnetic waves. No intermediary medium is required for radiative heat transfer, and radiation heat transfer can occur over very large length scales (such as from the sun to the earth). Radiation is the dominant mechanism for transferring heat from high-temperature sources and is very important in analyzing flame and fire problems. In the absence of performing a detailed analysis of the geometric configuration between the source and the subject, soot loading phenomena, and temperatures of the flames in the fire place, a simple overall energy balance bounds the relative magnitude of radiative heat flux from gas log fireplaces of various sizes.

Given the thermal energy of the fireplace and the area of the fireplace window, one can estimate the radiant flux produced. Table 1 shows the radiant flux (kW/m²) for various heat release rate burners in different sized fireplaces. Typical values for power input and sizes of gas log fireplaces are shown.

We see that the heat flux from a gas log fireplace is
effectively bounded on the low side by approximately 3 kW/m² for a low output burner in a large assembly and on the high side by approximately 70 kW/m² for a large output burner in a small assembly. More typical and representative fluxes are values in the teens (approximately 12 kW/m² to 17 kW/m²). Recognizing that the calculation does not consider an efficiency of conversion of chemical energy to thermal radiative energy, we use the product literature to find that typical radiant thermal efficiencies are approximately 80%. The efficiency places the representative radiative flux at approximately 10 kW/m² to 14 kW/m².

RADIATIVE IGNITION OF SOLIDS

Radiative ignition of solids can proceed either through the application of a pilot (a high-temperature source capable of initiating gas phase reactions) or through autoignition processes. Autoignition of solids can be further classified based as either being a flaming autoignition or being a glowing autoignition. Flaming autoignition takes place at very high external heat fluxes and is characterized by thermal runaway beginning in the gas phase. Glowing autoignition, in comparison, occurs as a result of char oxidation reactions occurring on the surface of the solid. The exothermic char oxidation process leads to local hot spots that are capable of initiating the gas phase reaction. Some similarity exists between glowing autoignition and piloted ignition in that the glow points are in effect the pilots for the subsequent flaming ignition process, although significant differences exist in the time required to achieve glowing autoignition as compared with the time required to achieve a piloted ignition. The ignition process in the actual case was likely a glowing autoignition process, although this is not clear. Babrauskas points out in his review of ignition of wood that only charring materials can achieve the relatively low-heat flux glowing autoignition mode, whereas thermoplastics that melt cannot be ignited in this low heat flux mode. The complexity of radiant ignition of solids is presented by Atreya as he details the theoretical basis for the ignition conditions in question.

Among other issues, it becomes clear from reviews of solid ignition by radiation that the ignition process of most interest to this study, glowing autoignition, has been studied the least and has the least theoretical basis for understanding. Piloted radiative ignition, during which an ignition source (pilot) sits in close proximity to the solid fuel in question, has received far more scrutiny and has a richer data base and theoretical basis. One of the questions that we raised initially in this work was the relative ease or difficulty in igniting a cotton outer layer as compared with a nylon or polyester outer layer. For glowing autoignition, we can only qualitatively state that charring materials such as cotton are easier to ignite in this mode because the char forms glowing hot spots that eventually lead to a flaming ignition. For the sake of more quantitatively assessing the relative ignition hazard, we assume that an ignition pilot source existed and use the literature to guide us in understanding the relative ignition hazards.

A typical minimum value of radiative heat flux required for piloted ignition of fabrics is approximately 10 kW/m². Nazare et al provide the critical heat flux for a number of materials and show that the critical heat flux for a heavyweight cotton material is 10 kW/m². Of their tested materials, which include acrylic, light cotton, light and heavy silk, wool, and a polyester-cotton blend, only acrylic had a lower critical heat flux (9 kW/m²) than heavy weight cotton. Given the values of heat flux from Table 1, we can infer that the accident in question may have occurred on the edge of ignitability for a typical jacket outer material. The details of the relative ease/difficulty of ignition of various types of textile materials is a more complex issue but can be analyzed at an approximate level. Before detailing the analysis, it is worthwhile to examine the literature to get a broader picture of the relative ease of ignition of various types of textile materials.

Although no single fire test is considered definitive in

<table>
<thead>
<tr>
<th>Power Rating kW</th>
<th>Window Dimensions</th>
<th>Window Dimensions</th>
<th>Window Dimensions</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.258 m² (20° × 20°)</td>
<td>0.387 m² (20° × 30°)</td>
<td>0.58 m² (30° × 30°)</td>
</tr>
<tr>
<td>2.92</td>
<td>10000</td>
<td>11.3</td>
<td>7.56</td>
</tr>
<tr>
<td>4.39</td>
<td>15000</td>
<td>17.0</td>
<td>11.3</td>
</tr>
<tr>
<td>8.78</td>
<td>30000</td>
<td>34.0</td>
<td>22.7</td>
</tr>
<tr>
<td>17.57</td>
<td>60000</td>
<td>68.1</td>
<td>45.4</td>
</tr>
</tbody>
</table>

Table 1. Estimated radiant heat fluxes (kW/m²) for various combinations of gas log burner energy output and fireplace window size.

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establishing the relative ease/difficulty of ignition of a material, there is consensus that the Limiting Oxygen Index (LOI) has a strong correlation to ease of ignition. LOI is found by a simple test, which monitors the burning behavior of a material at various oxygen levels. The LOI is the percentage oxygen concentration associated with limited flame spread. Table 2, taken from Plastics Flammability Handbook, states in section 6.1 (Burning Behavior of Textiles) that “Fibers having LOI values of 21% or below ignite easily and burn rapidly in air. Those with LOI values above 21% ignite and burn more slowly, and generally when LOI values rise above values of 26–28%, fibers and textiles may be considered to be flame retardant . . .”

We see that cotton and acrylic have the two lowest LOI values, implying that they are the two easiest-to-ignite materials tested. Recall that the study of Nazare et al4 independently determined acrylic and cotton to be the two easiest-to-ignite materials of their sample. Also note that the ignition temperature TIGN of cotton is quite low relative to all the synthetics. Also note that the ignition temperature TIGN of cotton to be the two easiest-to-ignite materials of these fabrics. As an example of a statement in the literature, the Plastics Flammability Handbook states in section 6.1 (Burning Behavior of Textiles) that “Fibers having LOI values of 21% or below ignite easily and burn rapidly in air. Those with LOI values above 21% ignite and burn more slowly, and generally when LOI values rise above values of 26–28%, fibers and textiles may be considered to be flame retardant . . .”

For these thermal models, effective property values are used to take into account the kinetic differences between materials. There are two limiting thermal models that are used. These are the “thermally thick” and “thermally thin” models of ignition. In the thermally thick model of ignition, the ignition time is specified in terms of a critical ignition heat flux, an ignition temperature, and a thermal inertia parameter that is the product of thermal conductivity, specific heat capacity, and density. A thin fabric used as a drapery would likely be modeled as a thermally thin material because the temperature is likely to be uniform throughout its thickness. However, if the same material was used as part of a composite such as an upholstered chair seatback, the composite system would be treated as a thermally thick material. The thermal models provide estimates of the time required for ignition of the samples. Whether the sample is thermally thin or thick, a steady state energy balance on the surface of the material is useful in determining the critical (minimum) heat flux for ignition. The energy balance is of form:

\[ q_{\text{MIN}} = e\sigma(T_{\text{IGN}} - T_s) + h(T_{\text{IGN}} - T_w) \]  

This balance states that the minimum heat flux, \( q_{\text{MIN}} \), that must be incident on the surface should equal the reradiated power (first term on right-hand side) and convective losses (second term on right-hand side). We assume that the emissivity, \( e \), is unity, which is appropriate for a thermally black body, and calculate critical heat fluxes of 5.4 kW/m² for acrylic, 10 kW/m² for cotton, 20 kW/m² for polyester, and 27 kW/m² for nylon 6.6 using the ignition temperature data presented by Troitzsch.

Table 2. Selected flammability properties of various fabrics (from Troitzsch)

<table>
<thead>
<tr>
<th>Fiber</th>
<th>TIGN (°C)</th>
<th>LOI (%)</th>
<th>ΔHc (kJ/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>600</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>Cotton</td>
<td>350</td>
<td>18.4</td>
<td>19</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>450</td>
<td>20–21.5</td>
<td>39</td>
</tr>
<tr>
<td>Polyester</td>
<td>480</td>
<td>20–21</td>
<td>24</td>
</tr>
<tr>
<td>Acrylic</td>
<td>&gt;250</td>
<td>18.2</td>
<td>32</td>
</tr>
<tr>
<td>Nomex</td>
<td>&gt;500</td>
<td>29–30</td>
<td>30</td>
</tr>
</tbody>
</table>
blend is 20 kW/m², one expects the critical flux for a pure polyester sample to be of comparable magnitude. Using these estimates for the critical heat flux for polyester, we see from Table 1 that very few fire log configurations are capable of supplying the required heat flux to ignite a polyester outer layer of a jacket. With the ignition of the outer material layer, the resulting flame serves as a pilot for the secondary ignition of the adjacent inner layers. Secondary ignition processes are very high probability events. Thus, the next critical step is related to causation of the burn. Focusing on the last inner layer of the jacket, we will analyze the flame spread process and consider its potential for producing a thermal injury. We consider the flame spread process to be an important factor in the injury process, although it may not always be the case. For some materials, the flame transport process might be affected by the material structural integrity after ignition. In some cases, if the material were to retract, melt, or behave in any way not consistent with linear flame spread, the following analysis would not be valid.

**UPWARD FLAME SPREAD ANALYSIS**

Flame spread refers to the continuous ignition process that takes place over a condensed phase substrate that supports a flame. In a flame spread process, the heat flux from the flame warms the virgin solid and pyrolyzes it to liberate flammable vapor. The reacting flame front then ignites the flammable mixture. For a given material, the available engineering flammability data can be applied to predict the flame spread rate for the material and also the heat flux during the spread process into substrate material. Normally flame spread is discussed in two configurations: opposed flow flame spread and wind aided flame spread. Opposed flow spread occurs in a downwardly propagating flame where the buoyant plume opposes the direction of flame spread. Wind-aided spread occurs in an upwardly propagating spread process where the buoyant plume helps drive the flame and hot products ahead of the pyrolysis front such that the flame heat transfer creates a much faster spread rate than is seen in opposed flow conditions.

We will focus on the wind-aided spread process here because photographic evidence from the accident in question shows burn injury and burned clothing that appear to more consistent with wind-aided than with opposed flow spread. A schematic of a wind aided flame spread is show in Figure 4.

A further classification of flame spread problems is in terms of thermally thin (lumped) vs thermally thick (semi-infinite). The problem of interest can be thought of as a thermally thin fuel sitting on a semi-infinite substrate (ie, the skin). The transfer of heat is from the flame, and there are several possible scenarios:

1. The flame length \((x_f - x_b)\) grows with time. This is the worst situation in causing a burn.
2. The flame length \((x_f - x_b)\) shrinks with time. This is a good situation to limit the burn extent.
3. The flame length \((x_f - x_b)\) is constant with time has the possibility for both fast or slow flame spread rates. The fast spread rate is good, and the slow spread rate is bad for fixed flame length in terms of controlling the duration of the event.

We will analyze these problems using standard mathematical models to determine what affect the inner layer material has on heat transfer to the skin. The steady burning configuration can provide insights about differences in burn injury as a function of material composition. Janssens\(^8\) points out that it is common to assume a net heat flux from the flame to the surface of approximately 25 kW/m² and that for a thin fuel layer over a thick substrate, it is appropriate to assume that the thermophysical properties are the same as those of the substrate. In the case of interest, we will use the thermal properties of skin for the substrate. For purposes of modeling we can change coordinate systems to one where the flame is stationary, and the fabric and substrate translate at a velocity \(U\). For the steady problem, the problem is mathematically stated as:

\[
\frac{\partial T}{\partial x} = \alpha \frac{\partial^2 T}{\partial y^2} \quad \text{with boundary conditions}^3 \quad (2)
\]

\[
-k \frac{\partial T}{\partial y} = q_0 (H_s (x - x_b) - H_s (x - x_f)) \quad (2a)
\]

\[
T(x, y \to \infty) = T_e \quad (2b)
\]
\[ T(x \to -\infty, y) = T_w \] (2c)

where \( \alpha \) is the thermal diffusivity, \( k \) is the thermal conductivity, and \( H_2 \) is a Heaviside step function. The problem of interest can be stated by asking, what is the maximum damage that might occur from this flame spread process? It is important to note that the maximum burn injury would take from this flame spread process? It is important to note that the maximum burn injury would take place at \( x = x_b \), which will have been subjected to the longest exposure to the incident heat flux. For a constant translation velocity \( U \), the duration of the flame at \( x_b \) is given by:

\[ t_d = \frac{x_f - x_b}{U} = t_{ign} = \pi k pc \left( \frac{T_{ign} - T_w}{2q_o} \right)^2 \] (3)

We see that the burn duration ratio for two thin fibers over the same substrate scales like

\[ \frac{t_d_{cotton}}{t_d_{polyester}} = \left( \frac{T_{ign, cotton} - T_w}{T_{ign, polyester} - T_w} \right)^2 \] (4)

Using the ignition temperature data in Table 2 we see that the burn duration for polyester is twice as long as that for cotton.

**RADIATION THERMAL BURN INJURY ASSESSMENT**

ASTM F1939-99\(^a\) provides the Stoll and Chianta time criterion\(^10\) for a second-degree burn from a heat flux source as

\[ q = 1.1971t^{0.787} \]

where the heat flux is in Cal/(cm\(^2\)s). We can use alternate methodologies (eg, the Henriques damage integral) to determine the extent of burn injury that would result from a flame spread process of given intensity.

Tissue thermal injury occurs to skin when its temperature is raised to a value sufficient to cause irreversible denaturation of structural proteins. The extent and severity of injury are dependent on the temperature and duration of exposure. The rate of injury accelerates exponentially with increasing temperature, and the total injury accrues linearly with advancing time. This injury process has been expressed for a rather broad range of thermal damage scenarios for more than a half century, based on adaptation of an Arrhenius chemical kinetics rate process model. Henriques and Mortiz were the first to publish a formal description of the thermal burn process in terms of a kinetic rate model.\(^11,12\) The quantita-

The rate of accumulation of injury is calculated in terms of a dimensionless damage function denoted by \( \Omega \).

\[ \frac{d\Omega(y, \tau)}{dt} = Ae^{-\frac{\Delta E}{RT_{ign, y}}} \] (5)

The definitions of the symbols are: \( x \) is distance into the skin (m); \( \tau \) is elapsed time from initiation of the insult (s); \( A \) is a scaling factor for the injury process (s\(^{-1}\)); \( \Delta E \) is the activation energy for the protein unfolding event (J/kmol); \( R \) is the universal gas constant (J/kmol.K); and \( T \) is the local tissue temperature expressed in absolute units (K).

The values for the scaling factor, \( A \), and the activation energy, \( \Delta E \), are derived from experimental data for thermal damage processes executed over the range of temperatures of interest. These types of experiments and analysis have been conducted by numerous investigators since the initial work of Henriques and Moritz.\(^11,12\) Although many alternative sets of coefficients exist and have been compared,\(^13,14\) the most frequently applied set for relatively low-temperature injuries is that of Henriques and Moritz, which will be used here. These values along with that of the universal gas constant, \( R \), are given in Table 3.

The total injury after an elapsed time \( \tau \) of thermal insult is obtained by integrating Eq (10) over that period.

\[ \Omega(y, \tau) = \int_0^\tau \int_0^\tau d\Omega(y, \tau) dt = A \int_0^\tau e^{-\frac{\Delta E}{RT_{ign, y}}} dt \] (6)

The value of temperature applied in Eq (11) to predict the level of burn injury can be determined by analysis of the heat transfer process at the skin surface that is propagated as a heat wave into the underlying tissue. In an accidental burn injury the duration of the insult is nearly always short enough to that the thermal response is limited to a finite depth within the skin. Therefore, the skin can be considered for purposes of the model as a semi-

<table>
<thead>
<tr>
<th>Table 3. Constitutive property values applied in the thermal damage model, eq (10)</th>
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<tbody>
<tr>
<td><strong>Property</strong></td>
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<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>Universal gas constant, ( R )</td>
</tr>
<tr>
<td>Activation energy for thermal injury, ( \Delta E )</td>
</tr>
<tr>
<td>Scaling factor for Arrhenius injury function, ( A )</td>
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</table>
infinite system for which thermal events at the surface are not realized beyond the superficial layers of tissue. If the skin is assumed to have uniform properties, which is often taken as being valid during a burn, then the mathematical description of the variation of temperature in the skin as a function of depth and time is given by the well-known error function. The exact form of this expression is dependent on how the appropriate boundary conditions are defined. Many of the classical studies in burn injury, including those of Henriques\textsuperscript{12} in which Eqs (5) and (6) were developed, have focused on contact insult in which a constant temperature is imposed on the skin surface by either a solid substrate or a liquid immersion. Alternatively, when the source of thermal insult is exposure to a fire, an applied heat flux defines the surface boundary conditions. This type of burn scenario has been investigated most completely in human subjects by Stoll and her coworkers.\textsuperscript{15,16} Under these conditions, the temperature at the surface of the skin will increase over time rather than being maintained constant, resulting in a unique thermal history in the deeper tissues. If the magnitude of the surface heat flux remains constant during the insult process, then the temperature variation in the skin is described as

$$T(y, t) - T_i = \frac{2q_o\left(\alpha t/\pi\right)^{1/2}}{k}\exp\left(-\frac{y^2}{4\alpha t}\right) - \frac{q_o y}{k} \text{erfc}\left(\frac{y}{2\sqrt{\alpha t}}\right)$$

where $T_i$ is the initial uniform temperature of the skin (K); erfc is the complementary error function; $q_o$ is the constant surface heat flux (W/m\textsuperscript{2}); $k$ is the thermal conductivity of skin (W/mK); and $\alpha$ is the thermal diffusivity of skin (m\textsuperscript{2}/s). In the present adaptation of this model the value of the heat flux is determined from analysis of the combustion of the jacket overlaying the skin surface. For the condition of the thermal insult resulting from the burning jacket, $q$ is assumed to take the 25 kW/m\textsuperscript{2} value for heat flux in a flame spread process as specified by Janssens.\textsuperscript{8}

The numerical value of $\Omega$ as calculated by Eq (6) provides a quantitative measure of the severity of a thermal injury. The threshold values as defined by Henriques\textsuperscript{12,17} and other are: $\Omega = 0.53$ for 1\textdegree; $\Omega = 1.0$ for 2\textdegree; $\Omega = 1.5$ for 3\textdegree. These values were developed for wounds caused by constant (steady state) surface temperature. Stoll\textsuperscript{15,16} has demonstrated differences in the injury outcomes for steady state and transient surface temperature (characteristic of radiation) burns, the rate of damage being higher for the transient case, thereby reducing the time to achieve a threshold injury by a factor of 2 to 5. Stoll's studies were restricted to second-degree wounds. Application of the model to predict third-degree wounds requires extrapolation, as has been performed often in the case of steady state surface temperature burns.

**ANALYSIS OF CASE-SPECIFIC BURNS**

The burns suffered by the wearer of the multilayered jacket that ignited and burned were beyond threshold third degree (medical report indicates full thickness necrosis of dermis and superficial subcutaneous fat). The net heat flux from the flame to the skin surface was estimated earlier to be 25 kW/m\textsuperscript{2}, which is approximately 600 mcal/cm\textsuperscript{2}.s. The maximum experimental flux reported by Stoll\textsuperscript{16} is 400 mcal/cm\textsuperscript{2}.s.

The temperature function in Eq (7) was computed for the standard thermal transport properties of skin (matching those used by Stoll) and for a radiative flux of 25 kW/m\textsuperscript{2} for a 10-second burn at incremental depths into the skin. The transient temperature curve is shown in Figure 5 at each of the computed depth locations.

The temperature plots shown in Figure 5 were applied to the calculation of the injury function in Eq (6) to estimate the time wise development of thermal injury at each of the indicated depths. The injury function $\Omega$ is plotted over the course of a 10-second burn in Figure 6.

The simulation also was run for some of the conditions calculated and measured by Stoll,\textsuperscript{14} specifically for radiation fluxes of 16.7 and 12.5 kW/m\textsuperscript{2}, identical to those that she studied. Her study focused on analysis of second degree rather than third degree burns. She also measured a threshold value of $\Omega$ that was somewhat less than the value of 1.0 defined by Henriques\textsuperscript{12} for constant surface temperature insults. For the present case, a second degree threshold $\Omega$ value of 0.8 was applied. For a radiation flux of 16.7 kW/m\textsuperscript{2}, Stoll measured causation of a second-degree burn in 5.6 sec and predicted it in 5.8 sec. The present model predicts 5.4 sec. For a flux of 12.5 kW/m\textsuperscript{2}, these three values are 7.8, 7.6 and 8.5 seconds, respectively. Thus, confidence in the present model is verified. For comparison, at the flux associated with the burning of the composite jacket, the time to a threshold second-degree injury is 2.6 seconds and to a third-degree injury is 4.9 seconds. The data in Figure 5 show that the temperature is increasing very rapidly at a depth of 80 $\mu$m during the time period, which depth is often used as a reference site of evaluation for computational studies.
CONCLUSIONS

In this work, we have analyzed the ignition and inner layer flame spread characteristics of a composite cotton outershell jacket relative to a comparable jacket in which the outer layer and inner layer materials are reversed. We find that the construction of the composite cotton outershell jacket poses a greater burn hazard than the reversed construction jacket because of the ignition potential of the cotton relative to the ignition potential of polyester. Further, we find that the burn severity for a polyester layer close to the skin is greater than that from a cotton layer equally close to the skin. The conclusions are also consistent with other studies. For example, the recent study by Sachdev et al\textsuperscript{18} of protective clothing for aviators states: “Ignition, being a surface phenomenon, is governed by the material on the top layer and the material on the bottom layer does not influence ignition.

Figure 5. Transient temperature increase at incremental depths in the skin during irradiation at a flux of 25 kW/m\textsuperscript{2}. The depth of 80 \(\mu\)m (0.0008 m) corresponds to the assumed interface between the epidermis and dermis.

Figure 6. Calculated values of the thermal injury function \(\Omega\) at the indicated depths during a 10-second radiation burn at 25 kW/m\textsuperscript{2}. The threshold value of \(\Omega\) for a third-degree burn (10\textsuperscript{4}) is indicated by the broken line.
time; however, the bottom layer influences the total heat released . . ."

One very strong conclusion from this study is that once the subject jacket of the analysis ignites, it would be very difficult to remove it before sustaining at least a deep second-degree thermal injury and, most probably, a third-degree burn would occur. In the case in question, the burn exceeded third degree, with the damage zone extending into the subcutaneous fat, as the model predicts.

Explicit conclusions derived from this study are as follows. They can be applied directly to selection and/or design of insulating jackets to reduce the risk of ignition flame injury.

1. Jacket design and construction influence the relative ease or difficulty of ignition and the severity of burns to a person wearing the jacket.
2. A jacket can be designed and constructed to provide greater fire and burn hazard protection without a significant effect on the warmth/comfort and cost effectiveness of the jacket.
3. A jacket design in which the construction materials produced a fractional lower radiant heat flux during combustion than does the present design would result in a significant safety for the wearer in the event of accidental ignition.
4. A redesign of the subject jacket with a nylon outer material would have provided greater protection against ignition.
5. A redesign of the subject jacket with a cotton inner layer would have resulted in a less-severe burn when the primary mechanism for heat transfer is a linear flame spread process.
6. When the subject jacket ignites, it is capable of producing a deep second- or third-degree injury or worse within the time frame in which the jacket could be anticipated to be removed or the fire extinguished.
7. The subject jacket design poses a significant injury threat to the wearer in the case of an accidental ignition.

This study had the primary goal of discussing how modeling can be used to assess the design of garments and the effect of these designs on burn severity. As such, we note that improved design of garments is an important step towards burn prevention for clothing-related burns.

REFERENCES