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A NEW METHOD FOR ESTIMATING THE EFFECTS OF THERMAL RADIATION FROM FIRES ON BUILDING OCCUPANTS

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ABSTRACT

A new model for estimating the effects of high thermal radiation heat fluxes on occupants has been developed. This model allows the user to specify the type of clothing worn by typical occupants (e.g., street clothing or protective clothing), percentage of body covered by clothing, and occupant characteristics (e.g., age). Numerical models of heat transfer in fabrics and skin are used to estimate the times required to produce burn damage to bare and clothed skin. These skin burn estimates are used along with occupant characteristics to estimate the time-dependent probability of death from a fire. This paper reviews existing models for estimating the effects of high heat fluxes on occupants, describes the heat transfer models used to make skin burn estimates, and compares the results of the new model with those from existing models.

INTRODUCTION

One of the most active areas of research in fire science is the development of computer models to evaluate fire protection systems in buildings. This has been fueled to a certain extent by the movement in Canada and other countries from prescriptive to objective or performance-based building codes. These types of building codes provide greater flexibility in design by allowing engineers to demonstrate the performance of fire protection systems to building officials using engineering calculations. In order to evaluate the impact of design features on life safety in objective or performance-based codes, models are needed to evaluate the effects of fires on people, especially the high thermal radiation heat fluxes from fires.

One computer fire model that has recently been developed is the National Research Council of Canada's (NRC's) FIERAsystem (Fire Evaluation and Risk Assessment system), which uses time-dependent deterministic and probabilistic models to evaluate the impact of selected fire scenarios on life, property and business interruption (Hadjisophocleous, et al., 1999). The current FIERAsystem Life

Hazard Model calculates the time-dependent probability of death due to being exposed to high thermal radiation heat fluxes from a fire in a building, and breathing or being exposed to hot or toxic gases. This model is based on techniques commonly used to estimate hazards in industry. However, when it comes to assessing the effects of high thermal radiation heat fluxes, most existing techniques do not take into account advances in medical treatment for burn victims, the characteristics of different occupant groups in buildings, and advances in industrial protective clothing. Therefore, a new model for estimating the effects of high thermal radiation heat fluxes has been developed. Results from this new model can be combined with results from existing models in FIERAsystem for assessing the effects of hot and toxic gases in order to estimate the total probability of death in a building fire.

In this paper, existing models used to estimate the probability of death due to high thermal radiation heat fluxes are first reviewed, along with concerns about using these methods in computer fire models, such as FIERAsystem. Techniques used by the new model to estimate burn damage to bare and fabric-covered skin are described, along with methods used to estimate probabilities of death based on these burn damage estimates and occupant characteristics. Results from the new and existing models are then compared. Issues in implementing the new model within computer fire models are also identified, along with areas of further research needed to improve life hazard models.

NOMENCLATURE

AG	age (years)
AREA	percentage of body's surface area with at least second degree burn damage
C ^A	apparent heat capacity (J/m ³ .°C)
c _p	specific heat (J/kg.°C)
G	blood perfusion rate (m ³ /s/m ³ tissue)
h	convection heat transfer coefficient (W/m ² .°C)

k	thermal conductivity (W/m·°C)
P	probability (dimensionless)
PF	pre-exponential factor (s ⁻¹)
q"	heat flux (kW/m ²)
R	universal gas constant (8.314 J/kg·mol·°C)
T	temperature (°C, K)
t	time (s)
V	thermal load ((kW/m ²) ^{4/3} ·s or (kW/m ²) ² ·s)
x	distance from surface (m)
Y	probit function (dimensionless)
Z	function of age and percentage of body's surface area with at least second degree burn damage

Greek Letters

ΔE	activation energy (J/mol)
Φ	factor to account for various levels of exposed skin area (dimensionless)
γ	the extinction coefficient for the fabric (m ⁻¹)
ρ	density (kg/m ³)
ξ	dummy variable for integration
Ω	value of Henriques' burn integral (dimensionless)

Subscripts

b	blood
c	core
conv	convective
ex	exposure
fl	flame
g	hot gases
i	initial
Lees	method used in Lees (1994)
o	outside surface
rad	radiative
s	skin
TNO	method used in TNO Green Book (1992)

CURRENT METHODS FOR PREDICTING THE EFFECTS OF HIGH HEAT FLUXES ON OCCUPANTS

Good reviews of current methods for predicting the effects of high heat fluxes on occupants can be found in Hockey and Rew (1997), Rew (1997), and Hymes, et al. (1996). Current methods use either thermal load criteria, or specific heat flux thresholds. Single heat flux thresholds specify a maximum heat flux that can be tolerated by individuals. However, these thresholds ignore transient heat transfer in the skin, and the non-linear nature of Henriques' burn integral (Henriques, 1947) and other techniques used to predict burn damage. As FIERAsystem is concerned with calculating time-dependent probabilities of death, only models based on thermal load criteria will be discussed in this section.

Many of the thermal load criteria are based on the work of Eisenberg, et al. (1975), who developed a probit relation using data from the atomic explosions in Hiroshima and Nagasaki. Estimates of the heat fluxes at different distances from the nuclear blasts, population data and distributions of deaths were used to develop the following probit function, Y:

$$Y = 14.9 + 2.56 \ln V \quad (1)$$

The thermal load, V, for a particular exposure duration, t, is calculated using the following equation (Tsao and Perry, 1979):

$$V = \int_0^t (q'')^{4/3} dt \quad (2)$$

The probit can then be used to determine the probability of death, using the following equation:

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \frac{\exp(-t^2)}{2} dt \quad (3)$$

There are several differences between the conditions associated with Eisenberg's data and modelling the effects of an industrial hazard today (Hockey and Rew, 1997). Deaths during the nuclear blasts may have been due to pressure effects as well as high heat fluxes. The medical treatment for burns has improved substantially since 1945. The population exposed to the nuclear blast would likely contain a much larger percentage of both very young and very old people than in an industrial setting today. As well, the exposed population likely had a lower level of clothing (coverage, thickness and mass/unit area) than in a typical industrial setting today.

On the other hand, for the same heat flux, radiation from a nuclear blast should inflict less damage to human skin than radiation from a fire. Radiation from a fire is primarily infrared, while radiation from a nuclear blast is primarily ultraviolet. Human skin will absorb practically all of the incident infrared radiation, but will absorb a substantially smaller percentage of incident ultraviolet radiation. Therefore, some believe that Eisenberg's model may still be used today, as the conservative assumptions may balance out the non-conservative assumptions.

Tsao and Perry (1979) revised the Eisenberg model to account for the differences between primarily infrared and ultraviolet exposures. Tsao and Perry's probit function for fatalities is:

$$Y = -12.8 + 2.56 \ln V \quad (4)$$

where V is given by Eq. (2). Many of the same comments on the Eisenberg, et al. model are also applicable to the Tsao and Perry model.

The models developed by Eisenberg, et al., and Tsao and Perry do not consider occupant characteristics. The data used to develop the probit function was based on males and females of all ages and physical abilities. In reality, occupant characteristics will vary by building. For example, occupant characteristics will be considerably different in seniors residences, aircraft hangars, shopping centres and industrial settings. Hymes, et al. (1993) indicated that the two most important factors in predicting deaths from burn injuries are the patient's age and area of skin burn.

Neither of the two models consider the effects of clothing. Clothing can be beneficial or detrimental, depending on whether the incident heat fluxes are high enough to ignite the clothing. If they are smaller, then the clothing can protect the underlying skin by slowing the rate of heat transfer to the skin and thus reducing burn injuries. If the heat fluxes are high enough to ignite the clothing, then burn injuries can be more severe than those caused to bare skin by heat fluxes from the original hazard.

One model that does include the effects of clothing is described in the TNO Green Book (1992). This method first calculates the probability of burn damage to bare skin. This probability is used

along with an assumed age distribution of the population and percentage of skin that is exposed, and the burn mortality charts of Bull (1971), to calculate the probability of death. For example, for the same age distribution as the Dutch population as a whole, a probability of death of 14% is calculated when 20% of the total skin is damaged. The TNO Green Book method treats clothing by assuming that no burn damage occurs to clothed skin unless the clothing ignites. If clothing does ignite, the probability of death is assumed to be 100%. Ignition of clothing is predicted to occur for a thermal load, V_{TNO} between $2.5(10)^4$ and $4.5(10)^4$ (kW/m²)²s, where:

$$V_{TNO} = \int_0^t (q'')^2 dt \quad (5)$$

Some of the assumptions in the TNO method may be overly conservative. As medical treatment for burns has improved in the last 30 years, using Bull's mortality charts may overpredict the probability of death for given burn damage. Assuming a probability of death of 100% when clothing ignites may also be very high. For example, Lawrence (1991) presents data from the Birmingham Accident Hospital in the UK between 1981 and 1987 that indicates that only 20% of patients whose clothing caught on fire actually died. On the other hand, the TNO method assumes that unless clothing ignites, there is no burn damage to clothed skin. In reality, there may be some damage. For example, thermal mannequin tests of flame resistant garments, such as ASTM F1930-99 (American Society for Testing and Materials, 1999), indicate that for high heat flux exposures, skin burns may occur even if the garments do not ignite. In addition, the probability of death calculated using the TNO approach would be a step function: a small change in the thermal load from just below to just above the ignition criteria will increase the probability of death from 14% to 100%. This would make it difficult to apply this method in computer fire models.

Lees (1994) also developed a model that accounts for the effects of clothing. The probit equation used in this model is based on experimental data from skin burn experiments using pigs:

$$Y = -10.7 + 1.99 \ln V_{Lees} \quad (6)$$

where:

$$V_{Lees} = \Phi \int_0^t (q'')^{4/3} dt \quad (7)$$

and Φ = a factor to account for various levels of exposed skin area
 = 0.5 (for a normally clothed population), or
 = 1.0 (when ignition of clothing is predicted)

Ignition of clothing is predicted to occur at a thermal load, V_{Lees} , of 1800 (kW/m²)^{4/3}·s. This value was calculated by converting the lower value of the TNO criterion (used with Eq. (5)), so that it can be used with Lees' definition of the thermal load (Eq. (7)). Lees' model was derived using the burn mortality data in Lawrence (1991), assumptions about the age distribution of occupants, percentage of body that is bare skin, and relationships between the thermal load (Eq. (7)), the depth of skin burn damage and the probability of death. This may make the model, as it is described in the reference, difficult to use in cases where occupant ages and types of clothing are quite different from the assumptions in the model. For example, in Lees' model, the age distribution is assumed to be equally distributed from

10-69 and ordinary clothing is used. In an industrial setting, the age distribution will likely be narrower and specialized protective clothing may be used. However, the general approach described in the reference could still be used to derive a model for the specific scenario of interest. The factor, Φ , is used in Eq. (7) to account for the assumption that only one half of the surface of the body will be exposed at a time to thermal radiation, until the point where the clothing ignites, thus exposing the entire body.

Rew (1997) compares predictions for the duration of a given heat flux necessary to cause ignition of clothing materials made using various models in the literature. Besides the two models described above, a model developed by Hymes, et al. (1996), is also examined. Hymes, et al.'s model predicts the time to ignition of various fabrics for a given heat flux, based on simple heat transfer theory and experimental results. Rew found that the TNO criterion was more conservative than the model of Hymes, et al. for exposures of durations between 10 and 30 s. For exposures greater than 10 s, the Lees criterion was more conservative than either the TNO or the Hymes, et al. models.

The FIERASystem Life Hazard Model (Hadjisophocleous, et al., 1999) calculates the time-dependent probability of death for occupants in a compartment due to the effects of being exposed to high heat fluxes, and hot and/or toxic gases. This model uses input from other FIERASystem models that calculate the heat fluxes in the compartment, and the temperature and chemical composition of hot gases. In this paper, only the portion of the model that deals with high thermal radiation heat fluxes will be discussed.

The time-dependent probability of death from exposure to high thermal radiation heat fluxes, at a given location in the compartment, is calculated using the sum of the heat fluxes from the fire and the heat fluxes from the hot smoke layer. Heat fluxes are calculated at a height of 1.0 m off the ground, approximately at the mid-section of most occupants. Tsao and Perry's (1979) model is used to calculate the probability of death from the heat flux data. The decision to use this model was made because of the fact that the revised vulnerability model of Tsao and Perry does consider the differences between the nuclear blasts, which the Eisenberg vulnerability model is based on, and fires, which are being modelled here. In addition, it is more conservative than the Eisenberg model.

A NEW MODEL FOR ESTIMATING THE EFFECTS OF THERMAL RADIATION ON OCCUPANTS

As Tsao and Perry's model does not consider clothing or occupant characteristics, an improved model for high heat flux exposures has been developed. In order to model occupants in a variety of buildings, this model allows the user to specify the type of clothing worn by typical occupants (e.g., ordinary street clothing or protective clothing), the percentage of body covered by clothing, and the age of occupants. The model calculates the overall probability of death to occupants with time based on burn damage to bare skin, burn damage to clothed skin, and burn damage to skin after the destruction of clothing. Techniques used to calculate each of these three types of burn damage are discussed in the following sections.

Burn Damage to Bare Skin

Burn damage to bare skin is estimated using a finite element heat transfer model of bare skin, developed by Torvi and Dale (1994). Heat transfer in the skin is assumed to be transient and

one-dimensional. There are three layers of skin: the epidermis, dermis and subcutaneous layer, each with its own thermal properties. The bioheat transfer equation for blood perfused skin, first proposed by Pennes (1959), is used to calculate the temperature within the skin:

$$(\rho c_p)_s \frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial x^2} - G(\rho c)_b (T - T_c) \quad (8)$$

The boundary conditions are:

at the heated surface ($x = 0$), for $t > 0$

$$-k_s \frac{\partial T}{\partial x} = q''(t) \quad (9)$$

where

$q''(t)$ = the time dependent heat flux on the surface of the skin.

and at the base of the subcutaneous layer of the skin ($x = L$), for $t > 0$

$$T = T_c \quad (10)$$

The core temperature of the body, T_c , is assumed to be 37°C.

The initial condition is a given temperature distribution in the skin, $T_i(x)$, at time zero.

$$T(x, t = 0) = T_i(x) \quad (11)$$

Five finite elements, which use cubic Hermitian temperature interpolation polynomials, are used to represent the skin: one element for the epidermis, two for the dermis, and two for the subcutaneous layer. It was found in previous research that five Hermitian elements provided the same or better accuracy as nine quadratic or eighteen linear elements (Torvi and Dale, 1994). Once the temperatures within the skin are determined using the finite element model, the times required to produce second and third degree burn damage are calculated using Henriques' skin burn integral (Henriques, 1947):

$$\frac{d\Omega}{dt} = PF \exp\left(-\frac{\Delta E}{RT}\right) \quad (12)$$

The temperature, T , in Eq. (12) is the absolute temperature at the basal layer (base of the epidermal layer of the skin) for second degree burns (K), and is the absolute temperature at the base of the dermis for third degree burns (K).

Equation (12) can be integrated to produce

$$\Omega = \int_0^t PF \exp\left(-\frac{\Delta E}{RT}\right) dt \quad (13)$$

This integration is performed over the time the basal layer or dermal base temperature, T , is greater than or equal to 44°C for second and third degree burns, respectively. This temperature was found to be the threshold temperature for thermal damage. Second degree burns are said to occur when Ω is unity at the basal layer, while third degree burns are said to occur when Ω is unity at the dermal base. Further information on this skin burn model, including the values of the individual thermal properties used in the model, can be found in Torvi and Dale (1994).

Burn Damage To Clothed Skin

In order to evaluate the damage to clothed skin, heat transfer models of clothing and the underlying skin must be used. These models are very reliant on the boundary conditions used to represent

the fire hazard under consideration, and the modes of energy transfer which must be considered. For example, a heat transfer model for firefighters' protective clothing, exposed for a relatively long period of time to thermal radiation at a distance, will be different from a model of a lightweight protective coverall engulfed in a flash fire.

Therefore, a general model of heat transfer in clothed skin, which will be suitable for all exposures, cannot be specified. A module must be developed for each particular hazard of interest. For demonstration purposes, a finite element heat transfer model developed by Torvi and Dale (1999) of a single fabric layer (0.7 mm thick), an air space (6.4 mm thick), and skin under bench top test conditions used to simulate a flash fire, will be used in this paper. Heat transfer in the clothing and skin is assumed to be transient and one-dimensional. Five cubic Hermitian elements are used to represent the fabric, one element is used to represent an air space between the fabric and the skin, and five elements are used to represent the three layers of skin described in the section on the bare skin heat transfer model. Details about the assumptions made in developing the heat transfer model, and about the techniques used to treat various modes of heat transfer can be found in Torvi and Dale (1999). The following differential equation was developed for the temperature distribution in the fabric-air gap-test sensor system.

$$C^A(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k(T) \frac{\partial T}{\partial x} \right) + \gamma q_{rad} \exp(-\gamma x) \quad (14)$$

where

C^A = the apparent heat capacity of the fabric, and

q''_{rad} = the portion of the net radiative heat flux on the surface of an infinitesimal element of fabric.

The initial condition is a given temperature distribution in the fabric, air gap and skin, $T_i(x)$, at time zero.

$$T(x) = T_i(x) \quad (15)$$

The boundary condition at the heated surface, $x = 0$, during the exposure, (i.e., for $0 < t \leq t_{ex}$) is

$$-k \frac{\partial T}{\partial x} = q''_{conv} = h_{fl}(T_g - T_{x=0}) \quad (16)$$

where

q''_{conv} = the convective heat flux,

h_{fl} = the convective heat transfer coefficient for the hot gases from the burner, and

T_g = the temperature of the hot gases from the burner.

The boundary condition at the base of the subcutaneous layer was given earlier as Eq. (10).

Burn Damage After Destruction of Clothing

In addition to burn damage caused by heat transfer through clothing to the underlying skin, burn damage can occur after the destruction of clothing. If this clothing is flammable, then severe burn damage can occur to large portions of a person's skin due to burning fabric being in close proximity to, or in contact with, the skin. This damage can be reduced if a person takes evasive action, such as stopping, dropping and rolling. For clothing that is flame resistant, exposure to bare skin can occur if the clothing is weakened by the exposure to the point that it can break open when a person takes evasive actions.

The program assumes that destruction of the clothing occurs when the surface temperature of the fabric reaches the fabric destruction temperature, which is specified by the user of the model. For a flammable fabric, this would be the ignition temperature, whereas for a flame resistant fabric this would be the temperature beyond which the fabric is weakened to the point where it can break open. As mentioned earlier, most current models assume a probability of death of 100% as soon as the clothing ignites, which may be overly conservative. Therefore, to take into account that a person can take evasive action when their clothing is on fire, and that less than 100% of people whose clothing catches on fire will die, the model assumes that there will be a time delay after the fabric reaches the destruction temperature before all of the underlying skin is damaged. The time for burn damage to the underlying skin is calculated as the sum of the time required to destroy the fabric and the time required to produce burn damage to the underlying skin from the incident heat flux. This latter time is taken to be equal to the time required to produce third degree burns to bare skin for the same incident heat flux, as calculated by the bare skin heat transfer model described earlier in the paper.

Total Probability of Death Due to High Thermal Radiation Heat Fluxes

Based on information on burn damage to clothed and unclothed skin and the percentages of clothed and bare skin, the total time-dependent skin surface area that receives burn damage is calculated. The model assumes that unless clothing ignites, only one half of the body will be exposed to the high thermal radiation heat fluxes from the fire. This will be the case as a person attempts to escape from a hazard, such as a pool fire, and this logic was also used by Lees (1994) in developing his model. Once the clothing ignites or is destroyed, it is assumed that the person's entire body will be burned. Therefore, the total area of the body with burn damage is:

- half of the percentage of bare skin area when second degree burns occur to bare skin,
- 50% of the total area when second degree burns occur to clothed skin, and
- 100% after fabric ignition and the subsequent time delay.

The total surface area of skin receiving at least second degree burns is then combined with the age of the occupant to determine the probability of death using the burn mortality information from Hymes, et al. (1993). Hymes, et al. presented the following model of burn injury mortality, based on a logit analysis of data from over 3000 burn injury patients treated between 1971 and 1980 in the West Midlands Regional Burns Unit in Birmingham, U.K.:

$$P = \frac{e^Z}{1 + e^Z} \quad (17)$$

where:

- P = the probability of an individual's death ($0 \leq P \leq 1$)
Z = $-7.575 + 0.07184 (AG) + 0.1135 (AREA)$
AG = the age of the patient + 0.5 (years)
AREA = the percentage of the body's surface area with at least second degree damage ($0 \leq AREA \leq 100$)

As an example of the use of Eq. (17), Fig. 1 shows the probability of death as a function of percentage body burns for a 35 year old person. Hymes, et al. presented a second model, which also takes into account factors such as the type of injury (burn, scald or inhalation)

and predisposing factors (e.g., drugs or alcohol¹). However, this second model was only marginally better in fitting the statistical data.

Fig. 1 Probability of Death As a Function of Area of Second Degree Burn Damage Calculated Using Hymes, et al. (1993) Model for a 35 Year Old Person

In order to use Eq. (17) in this model, a function must also be specified to account for changes in the area term with time. In between the times of the specific events calculated by the various modules (e.g., time to second degree burn of bare skin), the area term is assumed to vary directly with the depth of burn damage. This allows the model to allow for variations in skin and fabric thickness, and fabric-skin spacing, over an individual's body, and from individual to individual. During the development of the single layer fabric heat transfer model, it was found that the time required to produce burns was a linear function of fabric thickness, within reasonable limits of the nominal thickness of a fabric (Torvi and Dale, 1998). During the development of this life hazard model, the time required to produce second or third degree burn damage was also found to be a linear function of the epidermis and dermis thickness, respectively. Therefore, this life hazard model assumes that the depth of burn, and hence the area of the body receiving at least second degree burn damage, is a linear function of time in between the specific events, which are calculated by the heat transfer models of bare and clothed skin.

For some applications, criteria based on burn injuries are used, rather than the probability of fatality. For example, Hymes, et al. (1993) state that criteria should "consider not only lethality but also disfigurement in survivors", because of the large physical and emotional effects of burn injuries on patients. If an engineer wishes to set fire safety objectives based on preventing any injury to occupants, rather than objectives based on avoiding fatalities, then the new model can be used to estimate when second degree burn damage would occur to bare and clothed skin.

COMPARISON OF NEW AND EXISTING MODELS

In order to demonstrate the new life hazard model, four constant heat flux exposures were selected: 80, 60, 40, and 20 kW/m². These heat fluxes represent a range of hazards from a direct exposure to a flash fire (80 kW/m²) to the expected heat fluxes to workers who may be in the vicinity of the flash fire. The heat flux in the model was varied through the selection of the convective heat transfer coefficient in Eq. (16), which simulates altering the height of the

¹ Hymes, et al. also argued that these factors likely affect the probability of a fire occurring more than they affect the probability of survival from burn injuries.

flame from a laboratory burner in a bench top test of a flame resistant fabric. The results from the new life hazard model were compared with results using three existing models, described earlier in this paper: Eisenberg, et al. (1975), Tsao and Perry (1979) and Lees (1994). The TNO model was not included in this comparison, as the portion of Lees' model for ignition of clothing is based on the TNO ignition criteria. As a test case, a 35 year old person was chosen, with 20% bare skin, and clothing with a destruction temperature of 400°C.

The times to the three events of interest for the four different heat fluxes are shown in Table 1. As mentioned earlier, It is assumed that only the side of the person facing the fire can be burned, until the point at which the fabric is destroyed and burn damage can then occur to the rest of the person, due to ignition and fire spread on the fabric. Based on these assumptions, 10% of the body will have burn damage when second degree burn to bare skin is predicted. For a 35 year old person, the corresponding probability of death predicted by Eq. (17) is 0.020. When second degree burn to clothed skin is predicted, 50% of the body will have burn damage, and the corresponding probability of death is 0.657. After the destruction of clothing, when 100% of the body has burn damage, the probability of death is 1.000.

The time-dependent probabilities of death for a 35 year old person calculated using the different methods are shown in Fig. 2. For most of the heat flux levels, the probabilities of death predicted using the new model were between the probabilities predicted using Tsao and Perry's and Eisenberg, et al.'s models. This allows the model to account for the fact that medical treatment has improved since the data from the nuclear explosions, yet also demonstrates that a primarily ultraviolet exposure will be less severe than a primarily infrared exposure. At the lowest heat flux level (20 kW/m²), predictions made by the new model were even more conservative than the Tsao and Perry model. This may be because the heat transfer model of the fabric was developed for higher levels of thermal radiation (the model was validated with experimental data for a nominal heat flux of approximately 80 kW/m² – Torvi and Dale (1999)). Thus, it may be used outside of its range of validity in the 20 kW/m² case. Physiological changes such as increased sweating and blood flow rates, that would help to protect the skin under these lower heat flux conditions, were not included in the heat transfer models of bare and clothed skin. In addition, the new model initially predicts a higher probability of death than Tsao and Perry's, or Eisenberg, et al.'s model. This may be due to the skin burn model predicting the onset of second degree burns relatively quickly, as compared with other models that are found in the literature. For example, Rew (1997) compares the different thermal doses used by various authors to predict first, second and third degree burns. There is also a difference between predicting threshold and deep second degree burns. It should also be noted that only a single layer fabric,

0.7 mm thick, was used in the heat transfer model. In many cases, a person would wear multiple layers of clothing, which would help to increase the time required to produce second degree burns to clothed skin.

Lees' model was much less conservative than the new model or the other two existing models. Lees notes this in the paper describing his model (Lees, 1994). Much of the difference between Lees' model and the new model is due to the ways in which fabric ignition and subsequent skin damage is handled. In addition, the new model also considers damage to clothed skin that does not ignite, which is not considered by Lees. The examples given in Lees' paper are for very high heat flux exposures, between 72 and 173 kW/m², which are more severe than the cases studied here, or in most building fires. For the 80 kW/m² case, there was more agreement between the new model and Lees' predictions than for the lower heat flux cases. It may be that Lees' model is more suitable to higher heat flux exposures. In addition, if appropriate clothing for these higher heat flux exposures (e.g., higher destruction temperatures and thicker fabrics) was included in the fabric heat transfer model, this should also result in less conservative predictions, which will be closer to those made by Lees' model. This will be discussed in the next paragraph. It should be noted that Lees' model also assumes evenly distributed ages of occupants between 10 and 69, whereas a 35 year old person was assumed for the new model. Age has a significant effect on the predictions made by the new model, as shown in Fig. (1).

As an example of how fabric and occupant parameters affect the results of the new model, the percentage of bare skin, and fabric destruction temperature were varied in the new model for a heat flux of 80 kW/m². Increasing the fabric destruction temperature will decrease the probability of death, once second degree burns occur to clothed skin (Fig. 3). This demonstrates the importance of using protective clothing in an industrial setting. Protective fabrics may have a destruction temperature of 500°C or more, as compared to ordinary fabrics, whose destruction temperature may be of the order of 300-350°C (e.g., Hymes, et al. (1996) lists a piloted ignition temperature of 285°C for a denim fabric sample). Besides age (Fig. 1), the percentage of bare skin has a significant effect on the probability of death (Fig. 4). This demonstrates the importance of occupant characteristics. For example, the same fire will have a much larger effect on people dressed in shorts and t-shirts in a shopping mall than the employees of an industrial facility who are provided with proper protective clothing. In addition, the population distributions in the two buildings will also affect the probability of death from the fire. The ability to include these occupant and fabric factors, is a very big advantage of the new model over existing models, which cannot easily account for all of these factors when estimating the effects of fire in a wide range of occupancies.

Table 1. Times to Key Events as Calculated by the New Life Hazard Model

Heat Flux (kW/m ²)	Time for 2nd Degree Burns to Bare Skin (s)	Time for 2nd Degree Burns to Clothed Skin (s)	Time for Destruction of Fabric (s)	Time for 3rd Degree Burns to Bare Skin (s)	Time to Skin Burn Damage after Destruction of Fabric (s)
20	3.60	19.80	23.00	21	44.00
40	1.36	10.95	4.90	13	17.90
60	0.80	7.95	2.80	11	13.80
80	0.56	6.30	1.85	9	10.85

Fig. 2 Probability of Death Estimated Using Existing Models and New Life Hazard Model (35 Year Old Occupant, 20% bare skin, Incident Heat Fluxes of 20, 40, 60, and 80 kW/m²)

Fig. 3 Probability of Death Estimated Using New Life Hazard Model for Various Fabric Destruction Temperatures (35 Year Old Occupant, 20% Bare Skin, Incident Heat Flux of 80 kW/m²)

Fig. 4 Probability of Death Estimated Using New Life Hazard Model for Various Percentages of Bare Skin (35 Years Old, Incident Heat Flux of 80 kW/m², Fabric Destruction Temperature of 400°C)

CONCLUSIONS AND FUTURE WORK

A new model for estimating the effects of fire on building occupants has been described in this paper. The model uses numerical models of heat transfer in fabrics and skin to estimate the times required to produce burn damage to bare and clothed skin. These skin burn estimates are used along with occupant characteristics to estimate the time-dependent probability of death from a fire. Results from the model are more conservative than some existing models, and less conservative than others.

The main area of future work needed to increase the utility of this life hazard model is the development of heat transfer models of fabric-covered skin for a larger number of hazards. The model described in this paper has been derived and validated for simulated flash fire conditions. New models for fabric-covered skin should continue to be derived and validated under other conditions, such as primarily radiant exposures to building fires for ordinary and protective clothing. In order to use these models, information on thermal properties of different fabrics over the wide ranges of temperatures expected in these exposures will also be needed.

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REFERENCES

- American Society for Testing and Materials, 1999, ASTM F1930-99, "Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Flash Fire Simulations Using an Instrumented Manikin," West Conshohocken, PA.
- Bull, J.P., "Revised Analysis of Mortality Due to Burns", 1971, *The Lancet*, pp. 1133-1144.
- Eisenberg, N.A., et al., 1975, "Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills (VM1)", ADA-0150245, Coast Guard NTIS Report No. CG-D-137-75.
- Hadjisophocleous, G.V., Torvi, D.A., Fu, Z. and Yager, B., 1999, "FIERAsystem: A Computer Model for Fire Evaluation and Risk Assessment," Proceedings, ASME Offshore Mechanics and Arctic Engineering (OMAE) 18th International Conference, St. John's, NF, Paper Number OMAE99-6016.
- Henriques, F.C., Jr., 1947, "Studies of Thermal Injuries V. The Predictability and the Significance of Thermally Induced Rate Processes Leading to Irreversible Epidermal Injury," *Archives of Pathology*, Vol. 43, pp. 489-502.
- Hockey, S.M. and Rew, P.J., 1997, Review of Human Response to Thermal Radiation, HSE Contract Research Report No. 97/1996, Health and Safety Executive (HSE) Books, Suffolk, U.K.
- Hymes, I., Brearley, S., Prescott, B.L. and Zahid, M., 1993, "The Prognosis of Burn Injury Victims," SRD/HSE Report R600, Safety and Reliability Directorate, Culcheth, Cheshire, U.K.
- Hymes, I., Boydell, W. and Prescott, B., 1996, "Thermal Radiation: Physiological and Pathological Effects," Major Hazards Monograph, Institution of Chemical Engineers, Rugby, Warwickshire, U.K.
- Lawrence, J.C., 1991, "The Mortality of Burns", *Fire Safety Journal*, Vol. 17, pp. 205-215.
- Lees, F.P., 1994, "The Assessment of Major Hazards: A Model for Fatal Injury from Burns," *Transactions of the Institution of Chemical Engineers*, Vol. 72, Part B, pp. 127-134.
- Pennes, H. H., 1959, "Analysis of Tissue and Arterial Blood Temperatures in Resting Human Forearm," *Journal of Applied Physiology*, Vol. 14, 1959, pp. 93-122.
- Rew, P.J., 1997, "LD₅₀ Equivalent for the Effects of Thermal Radiation on Humans," HSE Contract Research Report No. 129/1997, Health and Safety Executive (HSE) Books, Suffolk, U.K.
- TNO, 1992, "Methods for the Determination of Possible Damage to People and Objects Resulting from Releases of Hazardous Materials (The Green Book)," Report CPR 16E, The Netherlands Organisation of Applied Scientific Research, Voorburg, The Netherlands.
- Torvi, D.A. and Dale, J.D., 1994, "A Finite Element Model of Skin Subjected to a Flash Fire," *ASME Journal of Biomechanical Engineering*, Vol. 116, pp. 250-255.
- Torvi, D.A. and Dale, J.D., 1998, "Effects of Variations in Thermal Properties on the Performance of Flame Resistant Fabrics for Flash Fires," *Textile Research Journal*, Vol. 68, pp. 787-796.
- Torvi, D.A. and Dale, J.D., 1999, "Heat Transfer in Thin Fibrous Materials Under High Heat Flux," *Fire Technology*, Vol. 35, pp. 210-231.
- Tsao, C.K. and Perry, W.W., 1979, "Modifications to the Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills (VM4)," ADA 075 231, US Coast Guard NTIS Report No. CG-D-38-79.