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Comparison of Methods Used to Predict the Burn Injuries in Tests of Thermal Protective Fabrics

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ABSTRACT: A study was conducted to compare the two methods, Henriques Burn Integral and Stoll criteria, in thermal protective performance evaluation on firefighter clothing composites exposed to various thermal hazards. The thermal hazards that the firefighter may encounter during fire fighting are low level thermal radiation and high intensity flashover fire. With the simulation of these thermal hazards in the lab, the heat flux behind exposed clothing composites are characterized with flux rise rate and peak heat flux. Comparisons were performed on the prediction differences of clothing system made using Henriques Burn integral and Stoll criteria under different conditions. The study demonstrated that in some cases less difference is predicted by the two methods, while in other cases a significant difference is observed. Several recommendations were made for the qualitative prediction of garment and fabric thermal protective performance under different situations.

KEYWORDS: thermal protective performance, radiant protective performance, Henriques Burn Integral, Stoll criteria, thermal radiation, flash fire, TPP, RPP

Introduction

Two methods are used as the basis for burn protections in evaluating garment and fabric thermal protective performance: Stoll criteria and Henriques Burn Integral (HBI). The Stoll criteria is used in ASTM F 1060, Test Method for Thermal Protective Performance for Protective Clothing for Hot Surface Contact; ASTM F1939, Standard Test Method for Radiant Protective Performance of Flame Resistant Clothing Materials (RPP); and NFPA 1971 Thermal Protective Performance (TPP) test. The Henriques Burn Integral is used in ASTM F 1930, Standard Test Method for Evaluation of Flame Resistance Clothing for Protection Against Flash Fire Simulation Using an Instrumented Manikin. The Stoll second-degree burn criteria derives from the work of Stoll and Chianta [1], which are based on the observed exposure time required to produce a second-degree burn in blackened human skin subjected to incident heat fluxes varying from 0.1 to 0.4 $cal/cm^2 \cdot s$ (4.2–16.8 kW/m^2) in intensity [2]. The Stoll curves were established by converting the total amount of energy that must be absorbed by the skin to sustain second-degree burn or cause pain for a given length of time to a temperature rise of copper calorimeter. Therefore, the Stoll curve can be used to predict second burn time and pain time by comparing with the temperature rise of copper calorimeter. Figure 1 shows the calculated Stoll curves (temperature rise) for prediction of second-degree burn time and pain time using the specific TPP sensor (see appendix). The Stoll method has advantage of simplicity; it does not need

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sophisticated numerical calculation to estimate burn injury. However, Stoll and Chianta state that in applying these data it is essential that the incident heat pulse must be rectangular, for any variation from this shape invalidates the data [1]. Additionally, use of these curves for extended exposures requires extrapolation and this method is limited to certain heat flux intensities [2].

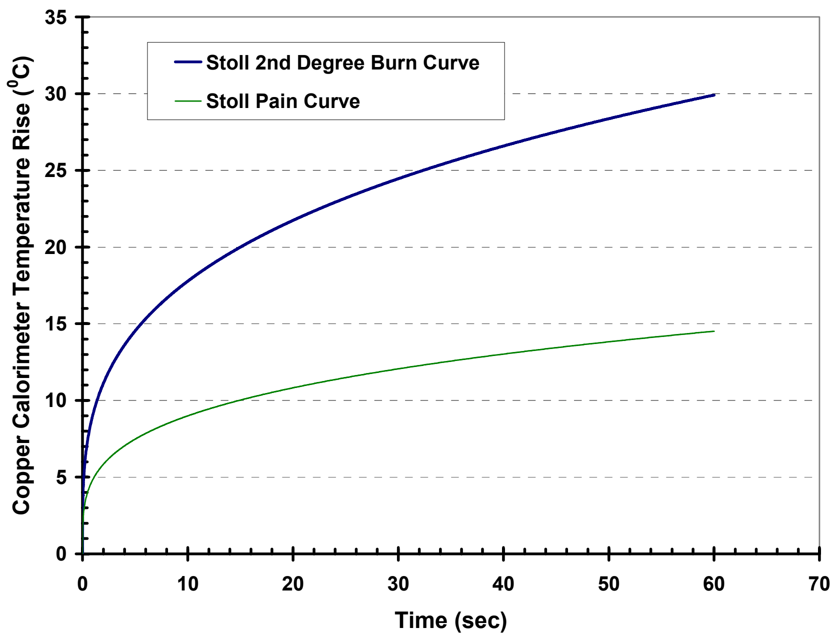


FIG. 1—*Calculated Stoll Curves for TPP Sensor.*

The Henriques Burn Integral is based on work by Henriques and Moritz [3]. Their work shows that destruction of the tissue layer located at the epidermis/dermis interface in human skin starts when the tissue temperature of the basal layer rises above 44°C. Therefore, the time that the temperature of the basal layer is above the damage temperature is critical. They found that the destruction rate can be modeled using a first order chemical reaction; that is:

$$\frac{d\Omega}{dt} = P\exp(-\frac{\Delta E}{RT}), \tag{1}$$

where

Ω = a quantitative measure of burn damage at the basal layer or at any depth in the dermis,

P = frequency factor, S^{-1},

ΔE = the activation energy for skin, J/mol,

R = the universal gas constant, 8.315 J/kmol.K,

T = the absolute temperature at the basal layer or at any depth in the dermis, K,

t = total time for which T is above 44°C (317.15K).

Integration of this equation yields:

$$\Omega = \int_0^t P \exp(-\frac{\Delta E}{RT}) dt \; . \tag{2}$$

The integration is performed from the time when the temperature of the basal layer of the skin, T, exceeds or equals 44°C. Henriques found that if Ω is less than, or equal to, 0.5, no damage will occur at the basal layer. If Ω is between 0.5 and 1.0, first-degree burns will occur, whereas if $\Omega > 1.0$, second-degree burns will result. The damage criteria can be applied to any depth of skin provided the appropriate values of P and ΔE are used. Mathematically, a second-degree burn injury has been defined as an $\Omega > 1.0$ at the epidermis/dermis interface and a third-degree burn injury as an $\Omega > 1.0$ at the dermis/subcutaneous tissue interface. This method is used in conjunction with temperature-time data from a skin model to predict times to second and third degree burns. This method is valid for any heat flux conditions. Details about the structure of skin model and the parameters used for Henriques Burn Integral are given in the Appendix.

Data produced by decades of fire research on structural fires show that most burn injuries sustained by firefighters occurred in the low level thermal environments [4,5]. This thermal environment could be outside of the flaming envelope, postflashover or preflashover fires. The thermal intensity for this thermal environment is in the range of 0.24–0.5 cal/cm^2·s (10 – 21 kW/m^2) [5,6]. Firefighters can be trapped in a flash fire or come into direct contact with flash fire for a few seconds in a rescue mission. The current firefighter turnout suits can provide 10 second protection or less to escape under most flashover conditions [7].

In this study, the two kinds of thermal hazards were simulated, and the heat flux behind the clothing composites when exposed to these hazards was characterized. The differences in times required to generate a second-degree burn made using Henriques Burn Integral and Stoll criteria in different conditions were examined.

Experimental

Materials

Two protective clothing composites, System A and System B, were selected in this study. The components of System A and System B are described in Table 1.

TABLE 1—*Protective clothing ensembles.*

Clothing System	System A	System B
Shell Fabric (g/m^2)	60% Kevlar ®/ 40% PBI, (254)	60% Kevlar ®/ 40%Nomex®, (237)
Moisture Barrier (g/m^2)	Higher THL Value Moisture Barrier (167)	
Thermal Liner (g/m^2)	One layer batting (237)	Three layer batting (271)

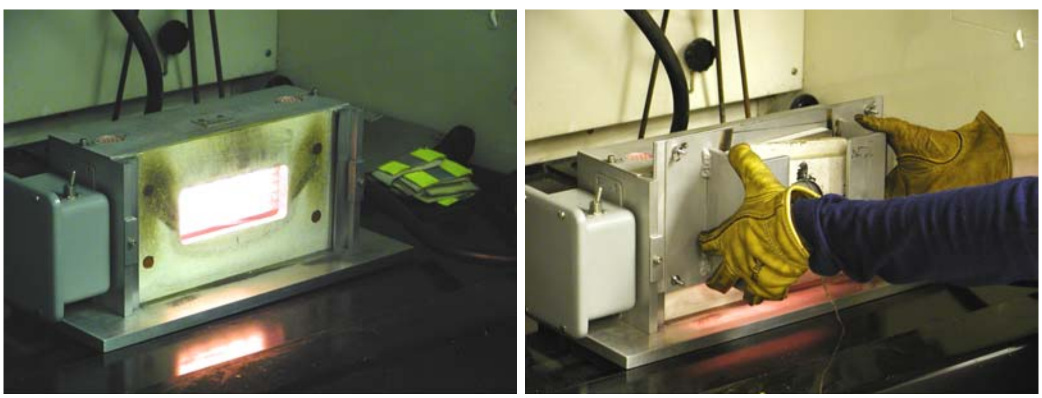
Sample Preconditioning

The simulation in this study was performed in dry and wet turnout systems. Dry systems were measured following sample preconditioning in a standard atmosphere (23°C ± 2°C and 60 % ± 5 % relative humidity) for 24 h. Wet systems were preconditioned using procedures that attempted to simulate the introduction of moisture by sweat produced by an active firefighter. First, the sample was conditioned for one hour in standard condition. Water was sprayed directly onto the face cloth side of the thermal liner component. Spray application was adjusted to introduce 15 % of sample weight water into the thermal liner. Then the thermal liner specimens, wetted in this manner, were laid up with outer shell and moisture barrier fabrics and sealed in a plastic bag and allowed to condition for 24 h in standard atmosphere.

Instrument and Methods

In this study two major thermal hazards were simulated: low level thermal radiation and flashover fire.

Low Level Thermal Radiation Hazard Simulation—The RPP tester was used to simulate the low level thermal radiation. The RPP tester was set up according to ASTM F 1939, (Fig. 2). The heat source was provided by five 500-watt quartz tubes. The temperature rise versus time and heat flux was measured using a copper calorimeter located behind the sample fabrics (ensembles) at a distance of 2.54 cm (1 in.) to the surface of the quartz tubes. The heat source was calibrated according to the procedure called for in ASTM F 1939. Tests were conducted on System B composite in dry and wet conditions with heat exposure levels of 0.5 cal/cm^2·s (21 kW/m^2) and 0.25 cal/cm^2·s (10.5 kW/m^2). Three sample replicates were performed for each condition.



(a) (b)

FIG. 2—*RPP tester: (a) Heat source, (b) Sample mounting and Copper Calorimeter.*

Flash Fire Simulation—A TPP tester was employed to simulate the flash fire thermal hazard. The TPP tester consists of heat source, copper calorimeter, and data acquisition system. The heat source is a combined heat flux provided by two propane fuel-fed Meker burners and a bank of quartz tubes (Fig. 3). The temperature rise and heat flux were measured using the copper calorimeter. A pneumatic shuttering mechanism activated by digital timer was used to control the exposure time. Considering that in a real firefighting situation a firefighter could get wet (sweating) and the fact that an air gap may exist between the garment and human body, this testing was conducted on System A composite with different conditions (dry and wet) and sample configuration (without spacer and with spacer). These tests were performed in accordance with the procedures established in Section 6-10 of NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting. These tests involved exposure of the composites with dry and wet preconditions to a 2.0 cal/cm^2·s (83.7 kW/m^2) heat flux with a measurement of burn threshold times using both the Henriques Burn Integral method and Stoll criterion. Two configurations (with spacer and without spacer) were also involved in this study. The nominal air gap was 6.3 mm with a spacer. Three sample replicates were performed for each condition.

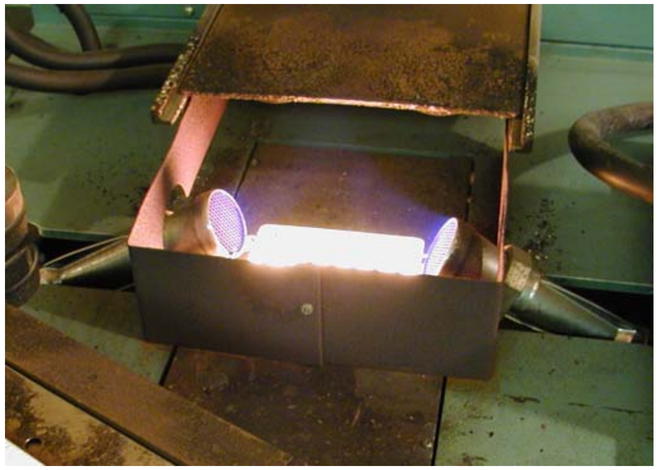


FIG. 3—*TPP tester.*

Results and Discussion

Low Radiation Thermal Conditions

Two low levels of radiant heat exposure were employed in low-level thermal conditions: 0.25 cal/cm^2.s (10.5 kW/m^2) and 0.5 cal/cm^2.s (21 kW/m^2). The typical heat flux profiles behind the protective fabric composite exposed to these low level thermal exposures are illustrated in Fig. 5. The peak heat flux under the protective fabrics was found in the range of 2000–4000 W/m^2 (0.05–0.1 cal/cm^2·s) in about 40–60 s. The overall rate of heat flux rise observed is about 40–80 W/m^2/s. The rate of heat flux rise is relatively rapid in the initial 5–10 s of the test, then slows until equilibrium (steady state) is achieved. The charts suggest that heat transfer in the turnout clothing system reaches the equilibrium within the time of 50–60 s for this low level exposure. A second-degree burn was predicted for both cases.

Table 2 compares burn predictions made using both Stoll and Henriques Burn Integral methods for exposure of 0.5 and 0.25 cal/cm^2·s in dry and wet conditions. For 0.5 cal/cm^2·s level, two exposure times (40 s and 60 s) were used. In the case of the 60-s exposure time, both methods predict second-degree burns in dry and wet conditions. About a 10-s difference in second-degree burn time was identified in both conditions. For the 40-s exposure case, however, the Stoll criterion predicts no second-degree burn while Henriques Burn Integral predicts a second-degree burn at 57.8 s for dry and 50.7 s for wet. It should be noted that for the 40-s exposure, the predicted burn occurred after the exposure (flux-off stage). This predicted burn time in the cooling phase indicates that the thermal stored energy in turnout clothing system contributes to burn injuries. For 0.25 cal/cm^2·s level with exposure time of 180 s, a large difference was found in the time of second-degree burn predictions. Because the heat source level is low, the prediction time as shown in Table 2 occurs in a relatively longer time (90-125 s). The difference for both dry and wet conditions is about the same.

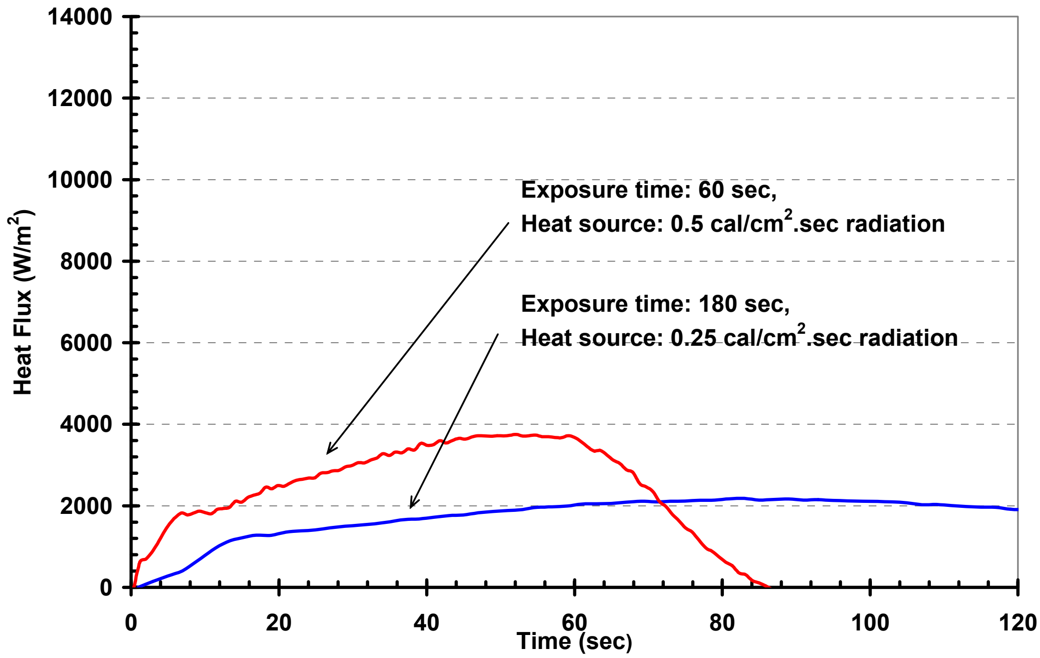


FIG. 5—*Heat flux profiles under firefighter turnout systems exposed to low radiation thermal conditions*.

TABLE 2—*Comparison of Henriques Burn Integral method and Stoll Criteria*.

Heat Source	Exposure Time* (s)	Time to Second-Degree Burn			
		Dry		Wet	
		HBI	Stoll	HBI	Stoll
0.5 cal/cm^2·s	40	57.8	no burn	50.7	no burn
	60	50.3	61.9	48.8	58.2
0.25 cal/cm^2·s	180	92.2**	117.3	98.4	124.9

* Data acquisition time: exposure time + 60 s.
** denotes that 3rd degree burns were also predicted.

Flashover Thermal Conditions

Figure 6 shows the heat flux profiles measured behind a turnout clothing system (dry condition) exposed to 2.0 cal/cm^2·s (83.7 kW/m^2) thermal conditions. A high rate of heat flux rise (380 – 580 W/m^2/s) was observed for both configurations (without and with spacer). The heat flux transmission curve is characterized by high-rise rate and followed by rapid decay. The peak flux for 14-s exposure without spacer is about 6000 W/m^2 and occurs at about 18 s. For 18-s exposure, however, the peak heat flux could reach as high as 13000 W/m^2.

Tables 3 and 4 compare predictions made using Henriques Burn Integral and Stoll criterion for different test conditions and sample configurations. Different fixed exposures were performed in these test conditions and configurations. The preconditions include dry and wet (15 % moisture was added) and configuration covers without spacer and with spacer (6.4-mm air gap). Due to nonlinear nature of the Ω value calculation, larger or smaller difference in times could be observed. In contact configuration (without spacer), the predictions in both dry and wet conditions demonstrate a consistent difference in second-degree burns, except that for 10-s exposure in wet conditions no second-degree burns are predicted using Stoll criterion. The prediction differences for both dry and wet decline as the exposure time increases. This decline also suggests that the larger difference exists whenever the thermal stored energy contributes to the second-degree burn, for configuration with a spacer, as the air gap existing between the clothing system and sensor significantly increases the thermal insulation. No second-degree burns are predicted for 10- and 14-s exposure by the two methods. For 18-s exposure, Henriques Burn Integral predicts a second-degree burn while Stoll predicts no burn in both the dry and wet conditions. More than a 10-s difference in prediction is observed made using the two methods for 22-s exposure.

Figure 7 shows the Stoll curve and temperature rise measured using TPP sensor for a sample exposed to flash fire conditions for 10 s in wet condition without spacer. In this case the Henriques Burn Integral predicts a second-degree burn at 32.5 s, while Stoll criterion predicts no burn. As indicated in Fig. 7, the rise of temperature curve of the copper calorimeter behind composite sample does not reach or pass the Stoll curve, which indicates no second-degree burn predicted by Stoll curve. The Henriques Burn Integral predicts a second-degree burn at 32.5 s, which is about 22 s after exposure stops. During the cooling period (flux-off phase), the thermal stored energy in the fabric composites continue to discharge to skin and keep skin temperature rising. This was indicated in skin layer temperature change along with skin surface heat flux history as shown in Fig. 8. These curves exhibit a sustained temperature rising at the end of 10-s exposure. The difference in times required for skin to generate a second-degree burn made using the methods is attributable to two major factors. The first factor is heat flux curve behind the fabric composite. As shown in Figs. 5 and 6, these heat flux curves deviate significantly from a required "square curve." The second is the different parameters used in Henriques Burn Integral, such as the layer thickness, thermal properties in a skin model, or P and ΔE in the Integral, which can affect burn predictions.

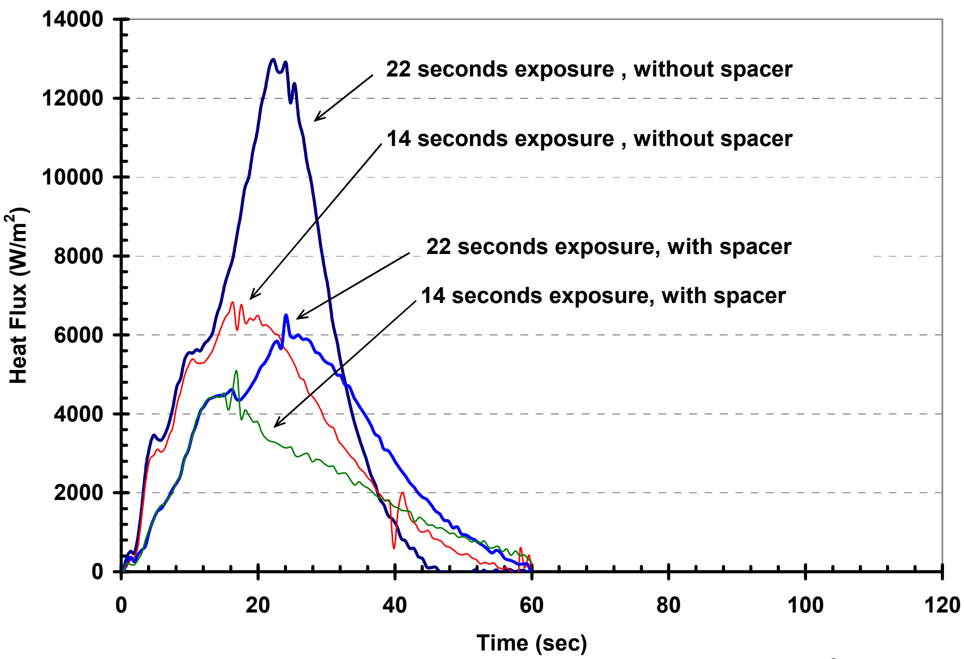


FIG. 6—*Heat flux profiles behind ensembles exposed to 2.0cal/cm^2·s in dry condition.*

TABLE 3—*Prediction comparison of HBI Method and Stoll Criterion without spacer.*

Condition	Exposure Time* (s)	Time to Second-Degree Burn (s)	
		HBI	Stoll
Dry	10	No burn	No burn
	14	23.3	35.9
	18	19.2	23.3
	22	18.9**	22.2
Wet	10	32.5	No burn
	14	17.3	22.6
	18	16.9	20.9
	22	16.7	20.4

*Data acquisition time was set at 60 s.
** Denotes that 3rd degree burn was predicted.

TABLE 4—*Prediction comparison of HBI Method and Stoll Criterion with spacer.*

Condition	Exposure Time* (s)	Time to second-Degree Burn (s)	
		HBI	Stoll
Dry	10	No burn	No burn
	14	No burn	No burn
	18	37.3	No burn
	22	28.8	39
Wet	10	No burn	No burn
	14	No burn	No burn
	18	24.2	No burn
	22	24.2	37.6

*Data acquisition time was set at 60 s.

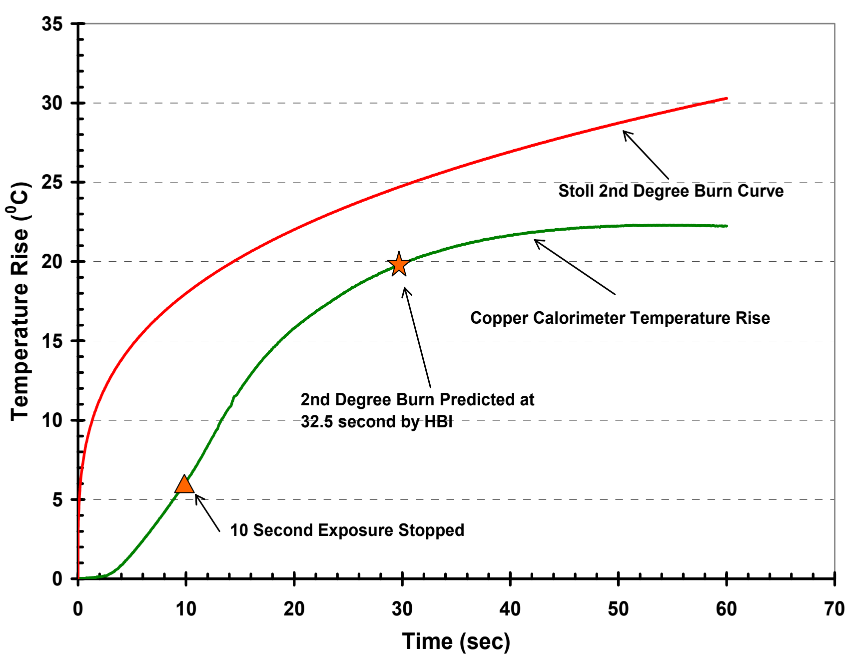


FIG. 7—*Measured temperature rise behind the composite exposed to 2.0 cal/cm^2·s for 10 s in wet condition.*

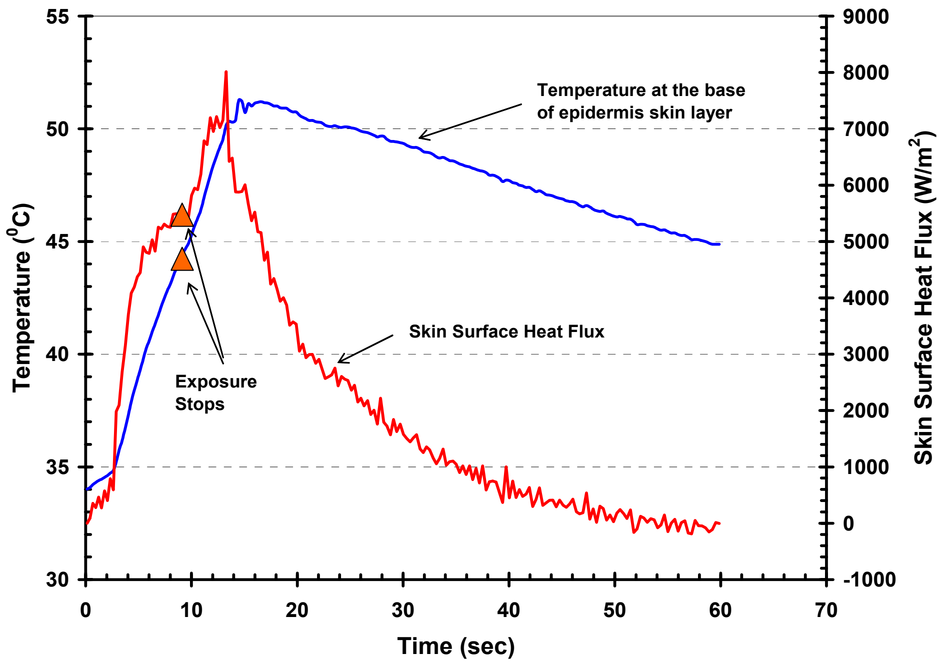


FIG. 8—*Calculated skin surface heat flux and temperature change at the base of epidermis behind the composite exposed to 2.0 cal/cm^2·s (83.7 kW/m^2) for 10 s.*

Conclusions

Heat flux profiles behind the turnout system exposed to different thermal conditions demonstrate different features. These heat flux profiles obtained from these exposures deviate significantly from the shape of "rectangular" or "squared."

Without spacer, the difference in second-degree burn predictions made by the two methods ranges from 3 to 5 s in flash fire conditions for relatively longer exposure time (> 18 s); for lower than this exposure a large difference was found. With spacer, more than 10-s difference was found for a 22-s exposure. In addition, on specific conditions Henriques Burn Integral predicts second-degree burn while Stoll does not. A difference of 10-25 s was predicted in low level radiation.

In flash fire conditions, the differences in second-degree burn predictions made by the two methods are pronounced in wet condition with spacer.

These data demonstrate that the difference in second-degree burn prediction made by the two methods becomes larger in low-level conditions, as well as in conditions when thermal stored energy contributes to second-degree burn. Because of the limitations of Stoll criteria that heat pulse must be rectangular and lack of data for longer exposure, this method is not recommended in burn predictions for low-level thermal hazard. It should be noted that the proper selection of a skin model and its properties, as well as factors in the Henriques integral, are crucial in the correct use of this method.

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Appendix

Heat fluxes measured using a TPP sensor were determined from sensor temperatures using a computer program that is based on a lumped heat capacity analysis of the test sensor

$$q''(t) = \frac{mcc_l}{A}\frac{dT}{dt} + K\big(T(t) - T(0)\big)$$

where
q''= Incident heat flux (cal/cm^2·s)
m = Mass of calorimeter slug (grams)
c = Heat capacity of copper (cal/g °C)
c_l = Thickness factor as experimentally determined
A = Disk area (cm^2)
K = Heat loss coefficient as experimentally determined (cal/cm^2·s· °C)
$T(t)$= Surface temperature of disk at time t
$T(0)$= Initial or ambient temperature

A three-layer skin model was used in this study. The skin layer thermal physical properties are summarized in Table 5.

TABLE 5—*Thermal properties in the skin heat transfer model [8].*

Human Skin		Value
Epidermis	Thermal conductivity (W/m·°C)	0.255
	Density (kg/m^3)	1200
	Specific heat (J/kg.°C)	3598
	Thickness (m)	8.0X10^{-5}
Dermis	Thermal conductivity (W/m·°C)	0.523
	Density (kg/m^3)	1200
	Specific heat (J/kg.°C)	3222
	Thickness (m)	2.0X10^{-3}
Sub-cutaneous	Thermal conductivity (W/m·°C)	0.167
	Density (kg/m^3)	1000
	Specific heat (J/kg.°C)	2760
	Thickness (m)	1.0X10^{-2}

The values of P and ΔE in Eq 2 are from Stoll and Takata [9]:

Epidermis

for $T < 50$ºC $\quad P = 2.185 \times 10^{124}$ s^{-1}

$\Delta E/R = 93{,}534.9$ K

for $T \geq 50$ºC $\quad P = 1.823 \times 10^{51}$ s^{-1}

$\Delta E/R = 39{,}109.8$ K

Dermis

for $T < 50$ºC $\quad P = 4.32 \times 10^{64}$ s^{-1}

$\Delta E/R = 50{,}000$ K

for $T \geq 50$ºC $\quad P = 9.39 \times 10^{104}$ s^{-1}

$\Delta E/R = 80{,}000$ K