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Protective Performance of Thermal Protective Clothing Assemblies Exposed to Different Radiant Heat Fluxes

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Abstract: Three layered clothing assemblies were constructed from commercial heat protective textile clothing materials for outer, middle and inner layers. Thermal liners, used as middle layer, were prepared from Nomex fibres of two different fineness keeping other parameters constant. Different three layered combinations of fabrics were compared for radiant heat protective performance based on the estimate of burn injury time using Stoll’s curve. Analysis of experimental results showed that characteristics of the outer layer fabric and its interaction with applied heat flux are important factors that affect thermal response of the clothing assemblies. Fineness of the constituent fibres of nonwoven thermal liner was found to significantly affect the protective performance. Thermal properties, porosity, optical properties of the clothing layers found to affect heat protection provided by clothing assembly.

Keywords: Radiant heat flux, Multilayered fabric, Protection time

# Introduction

Heat and flame resistant protective clothing is used to protect the person involved from wide variety of occupational hazards. Clothing assemblies providing thermal protection are worn by firefighters and other individuals exposed to heat hazards. Firefighting is a strenuous and hazardous job that exposes the person involved to a variety of extremely challenging conditions including exposure to high heat fluxes, hazardous chemicals and toxic gases. Wool and cotton or rubberized cotton tunics was being used by firefighters since the inception of professional firefighting [1]. Presently a range of heat resistant fibres and clothing made of them is available. Thermal resistance of these fibres arises because of presence of an aromatic or ladder like structures, which make them physically and chemically resistant, having high second order temperatures or absence of melting [2]. Traditional natural fibres, viz., wool and cotton can be given finishing treatment to make them flame resistant and can be used alone or in blends. Synthetic fibres like viscose, polyester, nylon, modacrylic fibres can be made flame retardant using FR finishes or using additives prior to spinning [3,4]. Flame resistant garments are currently used as personal protective equipment for protection from electric arc, general industrial exposure including welding, flame cutting or exposure to temperature sufficient to ignite normal wearing apparel [5].

Characterisation of clothing material those used for

firefighters’ protective clothing in different types of thermal exposures has been done by many people. Krasny *et al*. [6] evaluated many combinations of fabric assemblies at various heat fluxes. Experimental studies showed that loss of integrity, melting and dripping, formation of char and shrinkage are important factors that is affecting safety of the user. Thermal

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inertia, thickness, presence of moisture, cleanliness of reflective surfaces, areal density, ignition resistance and flammability are important criteria affecting performance and safety offered by a particular clothing assembly. Barker *et al*. [7] stressed on thermal diffusivity (*k/ρc* ) of the clothing material affecting heat flow through the fabrics and observed change in this property is dictated by the reaction of individual component fibres and fabric spatial properties. A mixture of radiant heat and flame proved less severe, resulted more protection time and less damage to the fabric than compare to radiant heat or flame alone. Conduction heat transfer dominates in heavily constructed woven, knitted or nonwovens, whereas air volume fraction and air permeability determines heat transfer in intense exposure [8]. Moisture present in clothing assembly has telling effect on thermal protective performance of textiles. Benisek *et al*. [9] found Zipro finished woolen protective clothing to offer best protection against convective heat fluxes whereas aluminized woolen fabric produced best protection against radiant heat. Many researches have done modelling of heat transfer through the clothing assemblies while exposed to different kinds of thermal exposures. Subsequently prediction of burn injury can be done using Stoll’s second degree burn criteria [10,11] or Henrique’s burn integral [12]. Henriques burn integral method is rather involved and require a computer and special software to determine time to cause burn injuries and valid for any heat flux histories. Using Stoll’s second degree burn criteria is comparatively simple and is only valid for rectangular heat fluxes [13].

In some early work Morse *et al*. [14] included flame temperature, radiative properties of fabric, pyrolysis and thermal degradation of constituent polymers, role of moisture, variation in air gap between skin and fabric, conduction and radiation between fabric and skin etc. in their model to predict thermal response of the clothing assembly exposed to high heat, coupled with skin burn model based on

*p*

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Henriques burn integral. Torvi *et al*. [15] developed useful model and studied effects of variation of various fabric properties on thermal response of FR fabric exposed to flash

Table 1. Coding of the clothing component used in multilayered fabrics

Fabric

fire. Fabric thermal properties like thermal conductivity,

Fabric details

code Colour Weave

specific heat and heat transfer coefficient, boundary conditions

found to have large effect on predicted response of protective clothing. Thermal stability, structural and dimensional stability, thermal properties, optical properties of clothing, air gaps between clothing and skin are the most important factor influencing effective insulation of the clothing assemblies. In an earlier work Kothari *et al*. [16] have studied effect of constructional parameters like picks per cm in woven cloth and punch density in nonwoven battings on the radiant heat protective performance of a combination of multilayered fabric assembly. With increasing punch density of a needle punch Conex fibre nonwoven fabric and decreasing picks per cm of Kevlar woven fabric, time to cross Stoll’s second

Conex/Twaron/Beltron (82/15/3) OL1 Greenish 2/1 Twill Nomex IIIA OL2 Yellow 2/1 Twill

\*

Conex OL3 Dark Blue 2/1 Twill

Modacrylic/Cotton (60/40) IL1 Grey Plain

Wool/Viscose (50/50) IL2 Sky Blue 2/1 Twill Nomex Nonwoven -1.7 den×50 mm NW1 White - Nomex Nonwoven -2.2 den×50 mm NW2 White -

OL-outer layer, IL-inner layer, NW-nonwoven thermal insulating layer.

\*

Table 2. Details of the outer layer, thermal liners and inner layer fabrics

degree burn injury curve was found to decrease at any heat

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Fabric codes | Cover | GSM | Thickness (mm) | Bulk  density  3  (kg/m ) | Air permeability  3 -2 -1  (cm cm s )  at 100 Pa |
| OL1 | 0.87 | 160 | 0.40 | 400 | 30.2 |
| OL2 | 0.94 | 220 | 0.44 | 500 | 6.5 |
| OL3 | 0.88 | 280 | 0.62 | 451 | 15.6 |
| IL1 | 0.81 | 196 | 0.41 | 478 | 16.2 |
| IL2 | 0.86 | 297 | 0.49 | 606 | 6.4 |
| NW1 | - | ~150 | 2.70 | 55 | 77.9 |
| NW2 | - | ~150 | 2.85 | 52 | 93.7 |

flux level. In the present study a set of commercial heat protective fabrics including woven outer shell, needle punched thermal liner and inner layer clothes were selected from available set of fabrics and combined together forming three layered fabric assemblies. They were then tested for radiant heat resistance on a laboratory made equipment, where sample combinations were exposed to different levels of radiant heat fluxes. Time taken by the cumulative heat curve to cross the Stoll’s second degree burn injury curve on continuous heating is noted as an estimate of burn injury time. The noted time, has been used to compare performance of different combinations of protective clothing at different heat fluxes.

2 2

Effect of individual fabric layers of the multilayered clothing

combinations, incident heat flux level and their interactions has been studied using statistical techniques. Using the derived regression relationship, prediction of time to cause second degree burn injury for a particular fabric combination can be obtained, within the given range of heat flux. Differences in predicted protection time for different fabric combinations has been analyzed.

# Experimental

Materials

Three woven fabrics were selected from available fabrics which were used as outer layer in the three layered fabric assemblies. All the three outer layer fabrics chosen were made of m-aramid fibres and their blends. Two of them contain Conex fibres and Conex/Twaron/Beltron (82/15/3) and the third one is made of Nomex-IIIA (Nomex/Kevlar/ antistatic fibre, 93/5/2). Some particulars of these fabrics are given in Tables 1 and 2. To observe the effect of fibre fineness on thermal insulation, two varieties of m-aramid fibres were chosen, viz., Nomex fibre of 1.88 dtex (1.7 den) and 2.44 dtex (2.2 den) and of 50 mm in length. Needle punched nonwoven battings were produced from both the fibres, keeping areal

density (~150 g/m ), punch density (150 punches/cm ) and

depth of penetration (10 mm) at constant level. Needle- punched fabrics were produced in a laboratory DILO machine which consist of an opener, roller and clearer card, cross lapper and a needle loom. The mass per unit area of the needle punched fabric of all the samples were measured and pre-adjusted to the target constant value. The layering factor and output of card were adjusted to achieve the required mass per unit area of the final fabric. Two commercially woven fabrics were chosen as inner liner, one is made of a blend of 50/50 Wool and Viscose blended yarns and the other one consisted of 60/40 modacrylic and cotton blended yarns. Coding of the individual clothing components of multilayered assembly was done as it is given in Table 1.

Methods: Measurement of Fabric Parameters

Thickness, cover, areal density, air permeability of the all the fabric samples were measured and noted. Mass per unit area of all inner and outer layer fabric was determined following ASTM D3776. Outer layer and inner layer fabric thickness was determined as per ASTM D1777-2007 96(2011)e1, using SDL thickness tester at a compressional pressure of 2000 Pa. Ends and picks per unit length of the woven fabric samples were determined following ASTM

D3775-12 standard, using the counting glass. Diameter of warp and weft yarn of all the fabrics were determined,

Table 4. Protection time (seconds) of different fabric combinations at different heat fluxes

mounting yarns on glass slides and observing under Leica microscope at 100× magnification. Based on measured warp/ weft yarn diameters and counted ends and picks per unit length cover was calculated (Table 2). Air permeability of all the woven and nonwoven fabric samples were tested on TEXTEST FX 3300 at a pressure of 100 Pa. Mass per unit area and thickness of all the nonwoven fabrics were determined following ASTM D6242 and ASTM D5729. All samples were conditioned in standard atmosphere for 24 hours before the measurements were taken. Some fundamental results of

Three layered

Protection time (s)

the tested individual fabric layers are given in Table 2.

Measurement of Thermal Conductivity, Reflectance and Transmittance

Thermal resistance of all the fabric components of the clothing assemblies was determined on Alambeta, which determines both steady state and transient thermal properties

|  |  |  |  |
| --- | --- | --- | --- |
| combinations | 2  at 10 kW/m | 2 2  at 30 kW/m at 50 kW/m | |
| OL1-NW1-IL1 | 78.8 | 37.8 | 20.3 |
| OL1-NW1-IL2 | 93.5 | 40.2 | 23.0 |
| OL1-NW2-IL1 | 74.6 | 37.0 | 18.5 |
| OL1-NW2-IL2 | 91.8 | 39.2 | 20.3 |
| OL2-NW1-IL1 | 112.0 | 53.5 | 27.8 |
| OL2-NW1-IL2 | 129.7 | 55.7 | 30.5 |
| OL -NW -IL | 107.6 | 47.7 | 24.8 |
| OL2-NW2-IL2 | 124.7 | 49.6 | 25.7 |
| OL3-NW1-IL1 | 75.0 | 31.1 | 15.8 |
| OL3-NW1-IL2 | 91.2 | 30.9 | 15.5 |
| OL3-NW2-IL1 | 73.0 | 29.2 | 14.7 |
| OL3-NW2-IL2 | 89.0 | 33.7 | 16.8 |

2 2 1

-1 -1

of textile materials, while thermal conductivity (W m K ) is

determined at the end of the transient phase [17]. Total obtained which were exposed to three different levels of

2

2

2

reflectance and total transmittance of fabric components were

radiant heat fluxes, viz. 10 kW/m , 30 kW/m

and 50 kW/m .

determined using Perkin Elmer UV-Vis-NIR spectrophoto- meter Lambda 1050 which is capable of operating with in wavelength range 200 nm to 3300 nm and equipped with an integrating sphere. Effective reflectance values for the individual fabrics were determined using the formula provided by Lawson *et al*. [18]. As the operating temperature of the heat source is supposed to be very high, most of the emitted thermal energy falls within 2.5 *μ*m. If the operating temperature of heat source is lower, radiative properties of the fabric surfaces beyond 2.5 *μ*m have to be considered. Effective reflectance of fabric surfaces was calculated assuming heat source temperature to be 2400 K. Values of thermal resistance and reflectance of the studied fabrics are given in Table 3.

Estimation of Protection Time

All the coded fabric layers, as it is shown in Table 1 were combined together as shown in Table 4. OL1, OL2 and OL3 were used as the outer shell fabric in combination with NW1 and NW2 in the middle layers and IL1 and IL2 used as inner layer and thus a total 12 fabric combinations (3×2×2) were

Table 3. Thermal resistance and reflectance of tested fabrics

Radiative heat resistance of all the fabric combinations were carried out on an experimental set up developed at our lab following guidelines given in ASTM F 1939-08 (Standard Test Method for Radiant Heat Resistance of Flame Resistant Clothing Materials with Continuous Heating). In this method fabric samples are heated by an array of vertically arranged quartz infrared heating tubes. Temperature rise on the other side of the fabric is noted using a copper calorimeter. Firstly the desired level of heat fluxes was adjusted by changing variac settings for an exposure of 10 seconds. Heat fluxes produced were frequently checked during testing with bare calorimeter; copper calorimeter blackened face was cleaned after every testing to remove deposited debris, and painted with black paint time to time. An approximate estimate of

Fabric

Thermal resistance

Reflectance

Transmittance

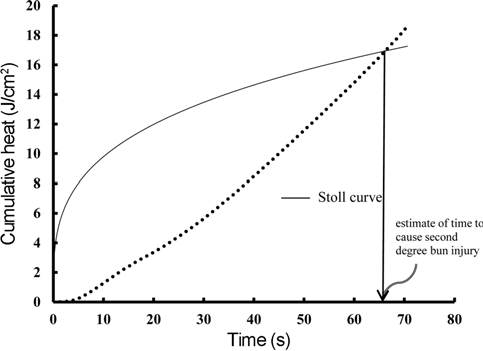
-3 2 -1

code

(10 × m K W )

(%)

(%)

Figure 1. Stoll curve for a combination of fabrics tested at an arbitrary heat intensity.

|  |  |  |  |
| --- | --- | --- | --- |
| OL1 | 19.8 | 15.77 | 2.12 |
| OL2 | 15.0 | 61.38 | 14.52 |
| OL3 | 25.2 | 5.91 | 0.04 |
| IL1 | 24.2 | 62.2 | 17.9 |
| IL2 | 19.0 | 53.56 | 18.44 |
| NW1 | 151.0 | 66.98 | 17.24 |
| NW2 | 145.0 | 66.06 | 18.75 |

second degree burn injury time is noted on continuous heating comparing cumulative heat curve with Stoll’s curve. It is noted as protection time and compared to observe radiant heat resistance performance of the fabric combinations at different heat fluxes. In present study copper calorimeter was kept touching the back side of the opposite face of the exposed fabric. Typical cumulative heat per unit area curve obtained during experiments is shown in Figure 1 with an estimated time to cause 2nd degree burn injury.

# Results and Discussion

Statistical Analysis

Experimental data of estimated protection time on exposure to radiant heat are presented in Table 4. To find significance of heat flux, outer layer fabric and effect of fineness of the fibres used in the Nomex thermal liner, their interaction with applied heat fluxes all the 3×3×2×2 experimental data were

very clear. At the same time interaction effect of outer shell and thermal liner is significant which is physically feasible. Transmitted heat from first layer of clothing meeting the second layer will be partially absorbed and reflected back to the first layer and this will continue until the intensity of heat is diminished to a minimum. Also from one layer to the other, large change in density and thermal resistance has been noticed. To examine the kind of relationship between experimentally found protection time with different factors and their interaction, regression analysis has been carried out. As all the fabrics used in combinations for comparison of protection are qualitatively different, construction of a regression model require indicator variables or dummy variables for the individual fabrics. A second degree polynomial regression equation was chosen in the present study, and is written as

(equation (1)),

*y* = *β*0 + *β*1*d*1 + *β*2*d*2 + *β*3*d*3 + *β*4*d*4 + *β*5*d*1 + *β*6*X*1*d*1

subjected to an n-way analysis of variance, which was carried

+ *β X d* + *β X d* + *β X d* + *β*

*X d* + *β X*2

(1)

out using MATLAB software. ANOVA outputs of the

7 1 2

8 1 3

9 1 3

10 2 3

11 1

experimental data are given Table 5.

2

Where the source of variation, X1 is heat flux, X2 is outer layer fabric of different types, X3 stands for nonwoven fabric from different fineness of fibres, X4 is different inner layer clothes. From anova table it can be observed that main effect of outer shell fabric, heat flux, fibre fineness of nonwoven fabrics and the effect of inner layers are significant. Interaction effect of heat flux and outer layer cloth, outer layer cloth and thermal liner has been found to be significant. Applied heat flux level and outer shell fabric appears to be the most significant factors that explain the variation of data. Calculation of percentage contribution to the total sum of squares shows that for heat flux it is 86.7 %, for outer shell fabric, 8.5 % and contribution of interaction effect of heat flux and properties of outer layer fabric is 2.4 %. Though interaction of heat flux and face cloth (inner layer) has been found statistically significant, physical significance of this is not

Table 5. Analysis of Variance table for estimated protection time

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Source | Sum Sq. | d.o.f. | Mean Sq. | F | P-values |
| *X*1 | 35286.7 | 2 | 17643.3 | 18050.72 | <0.0001 |
| *X*2 | 3449 | 2 | 1724.5 | 1764.33 | <0.0001 |
| *X*3 | 54.8 | 1 | 54.8 | 56.02 | <0.0001 |
| *X*4 | 412.1 | 1 | 412.1 | 421.61 | <0.0001 |
| *X*1\**X*2 | 978.3 | 4 | 244.6 | 250.22 | <0.0001 |
| *X*1\**X*3 | 2.8 | 2 | 1.4 | 1.42 | 0.2699 |
| *X*1\**X*4 | 425.3 | 2 | 212.6 | 217.54 | <0.0001 |
| *X*2\**X*3 | 292 | 1 | 4.5 | 14.84 | 0.0002 |
| *X*2\**X*4 | 0.8 | 2 | 0.4 | 0.39 | 0.6858 |
| *X*3\**X*4 | 0.9 | 1 | 0.9 | 0.89 | 0.3592 |
| Error | 15.6 | 16 | 0.977 |  |  |
| Total | 40655.1 | 35 |  |  |  |

where *y* is the predicted protection time, *d*1, and *d*2 are indicator variables for outer layer fabrics, *d*3 and *d*4 are indicator variables for nonwoven thermal liner layer and inner layers respectively and *X*1 represent different levels of the applied heat flux. Indicator variables take values 0 and 1, for example when *d*1 and *d*2 are both zero then regression equation represent for the third outer layer fabric. Estimate of regression coefficients was done using method of least squares. Test of significance of the individual regression coefficients showed that, outer layers, heat flux and its interaction with outer layers, quadratic term of heat flux, inner layers and thermal liners significantly contributes to the model. Predicted response based on the determined coefficients of the equation has been plotted with experimental results in Figure 2. Average error in prediction, 8.24 % and maximum error, 22.77 %, has been noted with R value 0.9874.

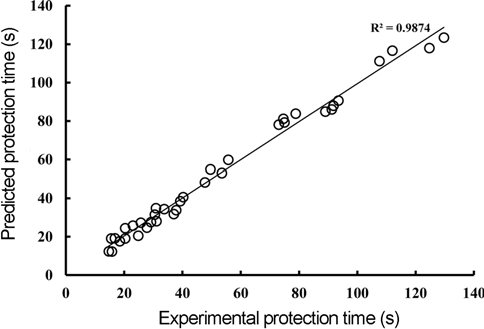
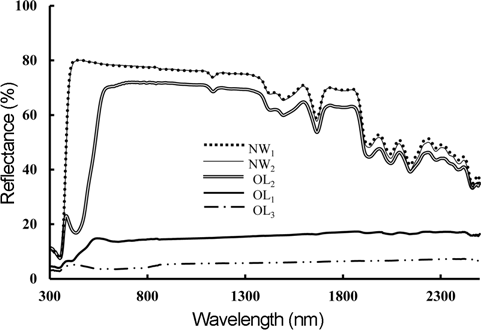
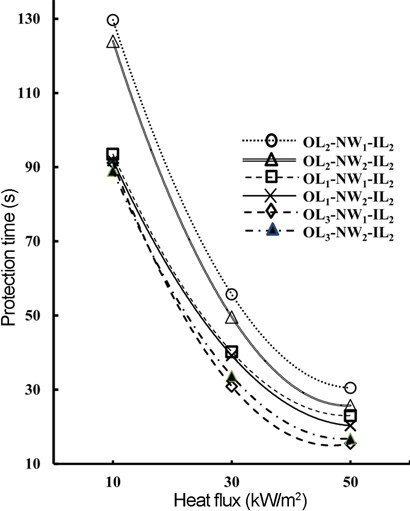


Figure 2. Plot of predicted protection time vs experimental protection time.



Figure 3. Spectral reflectance of the fabrics.

Effect of Outer Shell Fabric

Among the three fabrics chosen as outer layer cloth, OL3 fabric is having maximum areal density (280 g/m ) compare

2

2 2

to the other two OL2 (220 g/m ) and OL1 (160 g/m ).

Thickness and air permeability data shows, OL1 is having lowest thickness and highest air permeability. For all the combinations, where OL2 (Nomex IIIA) was used as outer layer fabric offered maximum protection against at all radiant heat fluxes. While using OL1 or OL3 as the outer layer, fabric combinations with OL3 produced slightly better results compare to the combinations with OL1. Reason for better performance with OL3 can be its lower air permeability, moderate thermal resistance, higher density and greater thickness. Thermal resistance (measured on Alambeta) and reflectivity data of the outer shell fabrics are given Table 3. Spectral reflectance of all the fabric components, except inner layers, is shown in Figure 3. Effective reflectivity of OL1 (15.77) is more than OL3 (5.91) can be the reason that these two, while used in combination, showed similar protection despite OL3 is much thicker and have much higher areal density. Thermal stability of the outer shell fabric and thermal liner material are comparable, as they are either meta-aramids or blends of meta and para-aramids. Though reflectance of Nomex IIIA woven cloth (OL2) is high and is expected to reflect back incident irradiation, same time transmittance of this fabric is also large ~15 % where as other two outer shell fabrics OL1 and OL3 transmits less than 2.5 %. It appears from the observation and analysis that no single observed parameter can solely explain differences in radiant heat protective performance of fabric combinations. Factors like cover, areal density, thickness, reflectivity, air permeability all in combination play important role in prediction of radiant heat resistance of the fabric assemblies.

Effect of Fibre Fineness in Thermal Liner

Effect of fibre fineness of the thermal liner on radiant heat protective performance of the combinations is shown in Figure 4, where effect of using Nomex-IIIA woven fabric as

Figure 4. Comparison of heat protective performance of com- binations of fabrics at different heat fluxes.

outer shell in combination with thermal liner and face clothes can be also observed. Two varieties of Nomex (m- aramid) fibres was used to make nonwoven battings. Effect of fibre fineness on protective performance has been found to be statistically significant from the analysis of variance. However absolute difference of protective performance, between the combinations with NW1 and NW2 is not large. From Figure 3 it can be observed that spectral reflectance of two nonwovens is not different. Thickness and thermal resistance of NW2 fabrics were found be higher than the other. Higher thickness of Nonwoven type 2 is due the larger diameter of the fibres (15 *μ*m). Larger diameter fibres being more rigid offer greater thickness under compression, but at the same time NW1 where finer fibre (13.2 *μ*m) was used has greater density and compactness resulted lower air flow (Table 2). Also longer length, tortuosity and more discontinuities created in case NW1 resulted greater resistance to heat flow. Extinction of thermal irradiation through fibrous insulation is inversely proportional to diameter of fibres and directly to fibre volume fraction [19]. Finer fibres with higher fibre volume fraction is expected to produce best results. Coarser fibres on the other hand produced nonwoven batting of higher bulk, greater thickness and good thermal resistance and lower density.

Effect of Inner Layer

From the ANOVA table, effect of different inner layers (IL1 and IL2) has been found significant. Among wool/ viscose (IL2) and modacrylic/cotton (IL1) fabrics that have

been used for the protective performance assessment of clothing assembly, combinations with the IL2 showed better

2

results. This fabric has comparatively higher GSM (g/m ),

3

density (kg/m ), low air permeability and greater thickness compared to IL1.

Effect of Heat Flux

Radiant heat intensity is the most influencing factor affecting the protection time. Effect of applied heat flux on radiant heat resistance of clothing assembly can be observed from the Figure 4. Protection time can be observed to be decreasing nonlinearly with incident heat fluxes. As the applied heat flux increases from moderately high to higher, protection time decreases rapidly and nonlinearly. Further increase in applied heat flux, protection time decreases but not so fast. This can be related to the nature of the Stoll’s second degree burn curve, based on which estimation of protection time has been done. At increased heat fluxes, degradation of outer layers and thermal liners, was observed to be very rapid. Thermal degradation and charring at high heat fluxes consumes thermal energy and produce charred insulation at outer layers which may cause reduced heat transfer.

# Conclusion

Properties of clothing component, viz. thickness, cover, reflectance and transmittance, density, thermal resistance, fibre fineness of thermal liner are important factors affecting the time taken by temperature sensor to cross the Stoll’s 2nd degree burn criteria. Properties of the outer layer fabric and its interaction with incident heat fluxes appears to be the most important factors. An outer shell fabric with highest reflectivity, excellent cover, higher thickness and greater thermal resistivity is expected to give best protection if other things are kept same. Fineness of the fibres used in thermal insulating nonwoven batting also play an important role. Both finer and coarser fibres have their advantages and disadvantages. For a given bulk density of nonwoven batting with finer fibres creates greater blockage to the thermal radiation. None of the measured characteristics alone dictate the heat flow process while exposed to thermal radiation.

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