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Components, characteristics and some evaluation methods for the firefighters' protective clothing

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Abstract

Multilayered heat protective clothing assemblies used for firefighters' protective clothing and similar other applications need to satisfy complicated and contradictory need of the users. Along with primary need to protect the person involved from heat and fire, it must light enough and must not hinder the easy working. All the fibres used for construction of such clothing assembly and the clothing layers as a whole must fulfil some minimum performance criterion in terms of heat protection, integrity and other required mechanical performance needs. Time to cause the burn injury is often regarded as a criterion to assess the performance of protective clothing assemblies. Process of estimation of burn injury time is complicated and requires thorough study and working of various types of sensors are in use in these studies need to be understood. An overview of the performance requirement of the firefighters' protective clothing has been discussed along with some standard methods those are followed to evaluate them.

Keywords: Burn injury, multilayered protective clothing, sensors, thermal protective performance.

I. Introduction

Firefighting is an intense, strenuous and hazardous occupation that exposes the person involved to a great variety of extremely challenging situations involving exposure to high heat fluxes, flames, hazardous substances, and toxic gasses. The person is subjected to work in an oxygen deficient smoky atmosphere. There is additional risk from falling objects and in extreme cases there may be a structural collapse. Firefighters may be exposed to high heat fluxes or may come in contact with surfaces of high temperature for different duration of time from which they need protection. Apart from thermal and chemical hazards there is also heat stress and exertion related problems, biological hazards, and long term consequences from firefighting.

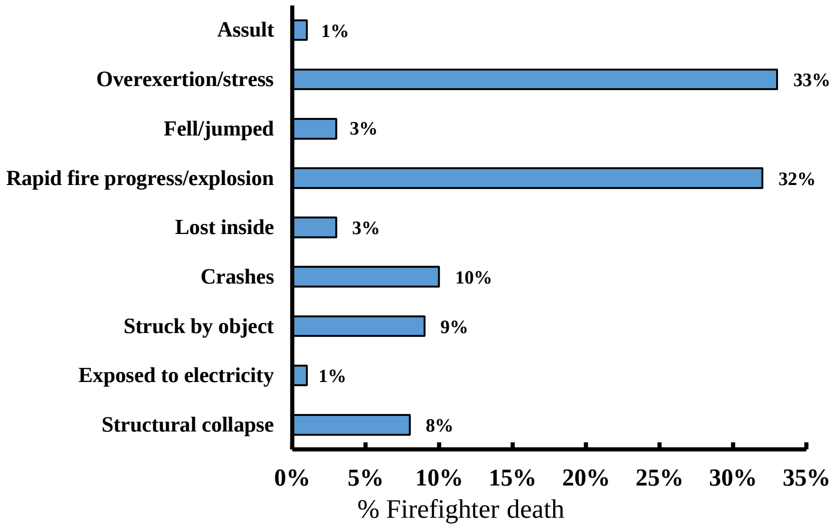

Fig. 1 Firefighter deaths by cause of injury [2]

Primary purpose of the protective clothing used in firefighting is to protect the person involved from convective heat, flames, contact and radiant heat. It must also fulfil some secondary requirement such as being cut resistant, waterproof, and chemically resistant and should not accumulate static electricity. Apart from fulfilling these requirements the garment or suit must provide convenience during intervention and should be comfortable under normal climatic condition. Researches have been concentrated on evaluation of heat protective performance of clothing assemblies, evaluation methodologies and development of test standards, modeling heat and moisture transport in protective clothing, heat stress and breathability related issues, protection against moisture and other hazardous chemicals, ways to enhance protection and estimating useful lifetime of turnout gear [1]. From Figure 1 it can be seen that overexertion and rapid fire progress are the two major causes of firefighter fatalities [2]. Increased rate of fatigue, reduced flexibility and mobility, and changes in a firefighter's center of gravity due to wearing firefighting personal protective equipment (PPE) and carrying firefighter tools can be assigned as reason to slip, trip and fall injuries as well as overexertion/strain injuries. As per NFPA estimates 65,880 firefighter injuries have occurred in US in 2013, of which approximately 45% occurred during fire ground operations. The leading type of injury received during fire ground operations was strain, sprain or muscular pain (55%), followed by wound, cut, bleeding, and bruise (14%) [3]. Overexertion & strain (27%) and fall & trip (23%) are the two main causes of firefighter injuries. Inspite of advent of new fibres, materials and improvement in clothing design firefighters receive fatal injuries. Multiple layer clothing used for firefighters' protective ensembles have many stringent and contradictory requirements, such as providing protection from heat and fire and being light weight and comfortable at the same time. This chapter presents a review of the firefighters' protective clothing performance requirements, evaluation methodologies and researches on firefighters' protective clothing.

II. Thermal Hazards and Burn Injuries

The human skin is very sensitive to high temperature and high incident heat flux. A total thermal energy of value 26.8 kJ/m^2 effects a pain sensation, and an aggregate heat of 50.2 kJ/m^2 results a second degree burns on the exposed tissues in just one second. In terms of temperature sensation of pain is experienced at 45°C and at 72°C, and the skin is completely burnt [4]. The anticipated time to cause a second degree burns on human skin at a heat flux of 330 kW/m^2 is only 0.07s, whereas for an incident heat flux of 200 kW/m^2 and 100 kW/m^2 it has been found to be 0.15s and 0.39s respectively. With the introduction of an insulation material of thickness only 0.5 mm, the protection time increases to 2.5s for at a heat flux of 100 kW/m^2 [5]. The intensity of the thermal energy at the fire grounds is a function of many elements viz. the area and the height of the fire or heated surfaces, its temperature and smolder present. The environmental situation in a fire situation has been classified as the routine, hazardous, and emergency conditions [6]. The Figure 2 presents a typical firefighting exposure conditions. The air temperature and the radiation heat flux in kW/m^2 are shown along the two axes that shows the routine, hazardous and the extreme circumstances. The routine condition can be compared with what a person experience in a hot summer day and applied to the firefighters operating hoses or involved in some other activities at some distance from the source of fire. Hazardous conditions can be experienced when a firefighter approaches to the close vicinity to the fire. Period during which the firefighter can safely work in such state is mostly restricted by the beginning of pain in the hands, face which are often covered by the gloves, and the mask etc. and thermal shielding capacity provided by the protective clothing assemblages. The emergency category can be defined as the region extending from the hazardous levels to a heat flux level of 100-200 kW/m^2 [7]. In a study done earlier by Morse et al. [8] on JP-4 pool fire, it had been found that the fire had an equilibrium temperature approximately of 1000°C and considered radiating from a black body. In diverse accidental circumstances, the measured heat fluxes lie in the range of 42-126 kW/m^2, while 84 kW/m^2 has been the estimate of a flash fire [9]. The heat fluxes in fire conditions can be estimated by using some steady state devices namely a Schmidt–Boelter heat flux meter or a Gardon type heat flux meter [10, 11].

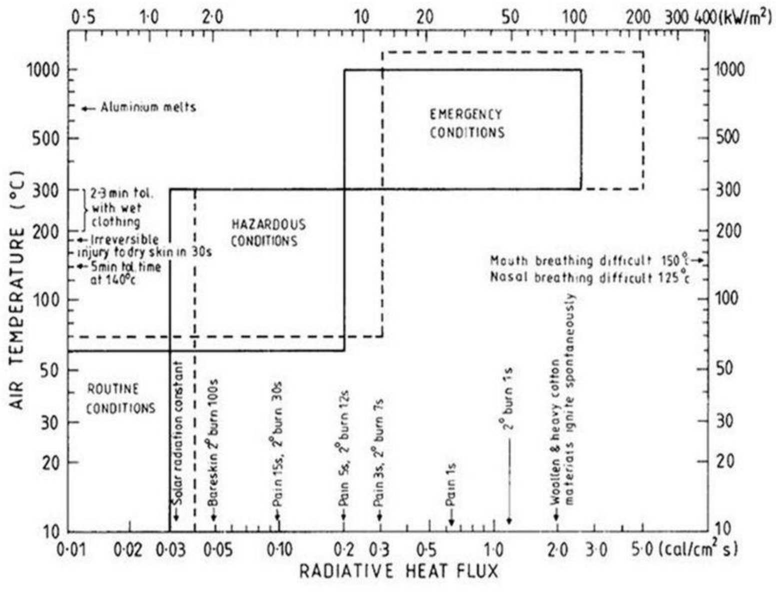

Fig. 2 Firefighters' exposure conditions [7]

III. Components of the Firefighters' Protective Clothing

The structural and proximity firefighter's protective clothing components comprises of the turnout coat, that is composed of an outer shell, moisture barrier, a thermal liner, helmet, a protective hood, specific gloves & boots, and other accessories [12]. The outside layer is a strong and hard-wearing woven cloth which is made of the heat resistant fibres. Moisture barriers and thermal linings are typically quilted as the multilayered fabric assemblies. For the wild land firefighting, the protective clothing have an outer casing, providing scratch, wear and perforation resistance that can be made of the heat resistant fibres like the aramids or FR finished fibres (Proban® and Pyrovatex®, for cotton). The thermal liner and a moisture barrier are included optionally only, for wearing in the winter seasons. The station uniform is a comfortable outfit over which the turnout gear is put on, when required by the firefighter. The flame resistant wool or the cotton fibres are advised in a station wear and it has also been instructed that fibres should be avoided those are known to stick, melt and drip. The firefighting pants are composed of an inner thermal lining or wadding layer and a protective outer case layer, protected at the knees and having big and small pockets. A steel toed rubber or leather boots are used, which may have handles at their tops to pull them on upto just below the knees. A positive pressure mask, goggles for eye safety, the respirator, communication devices and the self-contained breathing apparatus (SCBA) are the other features.

IV. Requirements of Firefighters' Protective Clothing

All the firefighting turnout clothing is usually consisted of three components: the outer shell, the moisture barrier, and a thermal barrier [13]. The primary requirements of the thermal protective clothing is a flame and heat resistance (that it must not catch fire easily or carry on burning), the integrity (that the garment should remain undamaged, i.e. should not shrink, melt or form some brittle chars, which may break open and expose the wearer to flame), should have adequate protection (clothing combination must resist conductive, convective and radiation heat in order to provide a time for the wearer to function in such an environment; and during combustion clothing should not deposit tar etc.) and should have liquid repellency (to avoid infusion of oils, solvents, water and other fluids) [14]. Protective garments should have an adequate tear resistance and seam breaking strength. Threads used for the purpose must be of sufficient thermal stability and laminations must not disintegrate on wet flexing. Additional concerns are garment life, abrasion resistance, resistance to UV degradation, resistance to burning deposits, cleanability, water absorption on the fire ground, weight and suppleness, mobility, visibility, breathability to water vapour. Polymeric membranes with high waterproof characteristics are frequently used, to provide operational protection against soaking, while simultaneously shows a high permeability for water vapor enabling physiological heat loss and cooling. The outer shell materials are the first layer, exposed to thermal hazards. Most of the outer layer fabrics have a content of meta-aramids and para-aramids, PBI, PBO and blended spun yarns, with twill or ripstop woven construction and can have an areal density of 200–250 g/m^2. This layer provides flame resistance, heat resistance, and mechanical resistance to cut, punctures, tear, abrasion, and other related hazards. During firefighting operations persons involved are often exposed to water and steam hazards. Direct suppression of fire using large hose liner with huge amount of water creates steam, mist and splash back and accumulation of water, which many firefighters may come in contact with. Dripping of water from ceiling or water on floor, can make the person involved wet during actions. Internally coated fabric layers known as "vapour barriers" are often being used to protect firefighters from both the steam and the hazardous gasses during a firefighting activity.

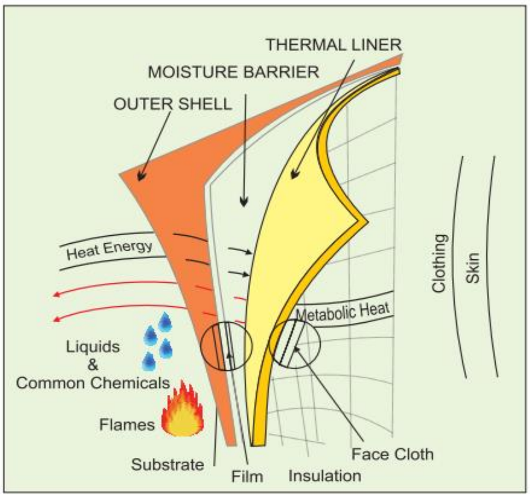

Fig. 3 General multilayered arrangement of a firefighters' protective clothing [16]

The breathable barriers constructed to protect the clothing and the person from outside water and steam, allows some amount of moisture vapour from the body to go out and offer some physiological comfort. Breathable membranes can be either microporous, hydrophilic or combination of both. The thermal liner blocks transfer of heat from the firefighting environment to the body of the wearer. It usually consists of a hydro-entangled or needle punched nonwoven felt or batting quilted or laminated to a woven face fabric. The fabric areal density may be in the range of 200-300 g/m^2. The felt or insulation is made from Polybenzimidazole, Nomex or Kevlar (meta or para aramids) or a mixture of these two or others like flame retardant cotton or thermoset fibres such as Basofils. The woven face fabric has usually been made from spun meta-aramids. Continuous Kevlar filament yarns can be used in face cloth to increase mobility and make it easier to use the garments [15]. It may also help in wicking perspiration away from the body and provide better moisture management. The firefighters' pants can be reinforced at the knees providing additional protection against heat, abrasion, compression, and absorbing shock. Reinforcement materials, for example, can be both side or single side coated woven twill fabric made using spun aramid yarns, napped leather, closed cell silicone foam padding [16]. A general multilayered arrangement of a firefighters' protective clothing is shown in Figure 3.

V. Evaluation Methodologies of Firefighters' Protective Clothing

Firefighters' protective gear and all of its components are tested, evaluated and judged on how well the clothing and its components meet performance and design requirements of established standards. Standards are developed on international, continental or national level following principles specified by the World Trade Organisation Technical Barrier to Trade (WTO/TBT). There are available standards that has been developed by standardisation bodies such as ISO, International Organisation for Standardisation; ASTM, American Society for Testing and Materials; NFPA: National Fire Protection Association, European Committee for Standardisation. List of such standards for protective clothing, flame resistant textiles and clothing used in industries, and for firefighters' protective clothing are documented in published literatures [17]. NFPA 1971, (Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting), BS EN 469:2014 (Performance requirements for protective clothing for firefighting), ISO 11613 (Protective clothing for firefighters - Laboratory test methods and performance requirements) are examples of some standards for firefighters' clothing. These standards comprises of a series of design and performance requirements which specify minimum criteria for clothing, materials and components. Performance criteria are based on measurements using standardized test methods. Test methods are made to relate to the environments the firefighters face during routine and emergency conditions. Among many of the performance requirements specified in NFPA 1971, Thermal Protective Performance (TPP), Conductive Compressive Heat Resistance (CCHR), Radiant Protective Performance (RPP), Total Heat Loss (THL), liquid/water penetration for barrier and seams, flame resistance, heat and thermal shrinkage, thermal stability of threads, cut resistance, tensile strength and tear resistance, seam strength, viral penetration performance are few methods that have been developed.

VI. Thermal Protective Performance test (TPP)

NFPA 1971 outlines TPP test method which is a modified version of the arrangement used and described in ASTM D 4108-82 [18]. Instead of a single Meker burner a pair of burners are used along with a horizontally arranged set of quartz heating lamps. The heating arrangement is capable of creating 50/50 mixture of radiant and convective heat. The fabric samples are laid on the mounting frame in a proper order and a weight of 4.0 Kg is used to put as an additional load on the sample. Testing arrangements with two Meker burner and radiating heating lamps arrangement for evaluating TPP as per NFPA 1971, has been shown in Figure 4. Time required to cause a second degree burn is estimated from blackened copper disk sensor temperature rise, using Stoll's criterion [19]. As per NFPA1971:2013 standard test for protection against heat and flame can be performed in accordance with ISO 17492 where the sample is exposed to a heat flux of 84 kW/m^2 (2.0 $cals/cm^2/s$) and shall have an average TPP (Thermal Protective Performance) rating 35 (17.5s protection against a heat flux of 2.0 $cals/cm^2/s$). ISO 6942 can be used when evaluating heat-transfer through materials due to radiant heat and ISO 9151 can be followed when evaluating heat transfer through materials due to flame contact only. Firefighters can receive burn injuries from heat exposures, which are less severe than flashover situations. This is associated to the stored thermal energy in firefighter protective clothing in addition to the transmitted radiation [6]. ASTM F 2702−08 and ASTM F2703−08 standards can be followed to estimate 2^{nd} degree burn injury time for clothing assembly exposed to radiant heat and combined convective and radiant heat source, where the test methods accounts for the thermal energy stored in the clothing after the exposure is ceased. As an additional requirement, the garment outer shell for proximity firefighting is tested for radiative heat protective performance. As per NFPA standards, radiation heat protective performance test is done for garment and glove outer shell material, helmet faceshields, footwear, helmet outer covers with some modifications. Radiation heat protective performance (ASTM F1939) is determined by exposing fabric to a definite radiant heat flux of 84 kW/m^2 (for Proximity firefighting, NFPA 1971) or 21 kW/m^2 (for Wildland firefighting, NFPA 1977) using Stoll's criteria.

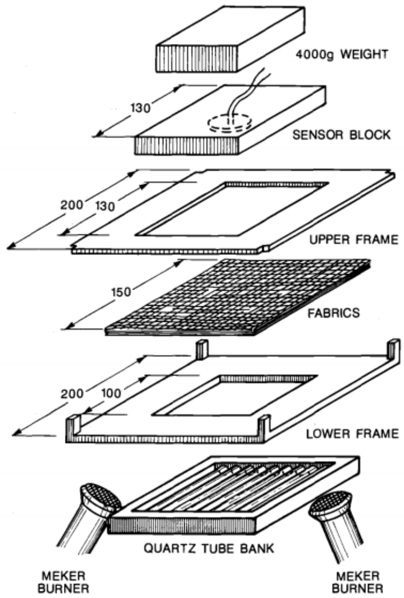

Fig. 4 Schematic of the NFPA 1971 testing apparatus (all dimensions in mm) [18]

VII. Total Heat Loss test (THL)

The total heat loss (THL) test was introduced in the 2000 edition of NFPA 1971, which was a new requirement for evaporative heat transfer through structural firefighting clothing. Garment composite consisting of all the three layers are to be tested for total heat loss test using a sweating guarded hot plate (SGHP) instrument. This test established a minimum requirement for total heat loss of 130 W/m^2. In revised version of NFPA 1971 2007, the minimum requirement was raised up to 205 W/m^2, which was retained in the 2013 revision. It is an additional requirement for structural firefighting only; aluminized fabric for proximity firefighting is impermeable and exempted. It has been observed that at mild working environment (21°C, 65%RH) THL values correlate well with indexes that describe turnout comfort performance while in warm environment (39°C, 35%RH) correlation of physiological heat stress response of fabric composites with different THL (range,146-251 W/m^2) were not significant [20].

VIII. Stored Energy Test (SET)

Depending upon the nature and intensity of the thermal exposure and the properties of the protective clothing, a large amount of thermal energy is stored. This may be discharged by conduction, natural convection and radiation or may be released on application of compressive forces, resulting an early burn injury. In practice this type injury can take place to knees/legs and arms of the firefighter when he has to crawl on hot surfaces, to the elbows due to repetitive flexing, to the shoulders where the SCBA strap squeeze around the surrounding fabric assemblies or where ever fabric layers get compressed by some external surfaces. A test apparatus has been developed to study the energy stored in firefighter clothing during heat exposure and the contribution of stored heat energy to burn injury under compression. These studies on stored thermal energy can be carried out following test standard ASTM F 2731.

IX. Instrumented Manikin test

Full scale and most realistic laboratory evaluation of thermal protective performance of protective clothing assemblies is assessed by instrumented manikin fire tests as defined in standard ASTM F 1930. The system consists of an adult size manikin with more than 100 sensors over its body exposed to a flash fire with an average heat flux 84 kW/m^2 and data is processed for 20 seconds, analyzed and tissue burn injury is calculated by a software, using Henrique's damage integral model. High degree of technical expertise is required to conduct such tests, for data acquisition and using software used for data analysis. Some other related standardized evaluation methodologies developed are test procedure for evaluating thermal protective performance of materials for protective clothing for hot surface contact (ASTM F1060), evaluating heat transfer through materials for protective clothing upon contact with a hot liquid splash (ASTM F2701), convective-thermal protective performance (C-TPP, ASTM WK29697) etc.

X. Thermal Sensors and Thermal Protective Performance

Many types of thermal sensors commonly used for heat protective evaluation of clothing assemblies are available, for example, TPP sensor, embedded sensors, skin simulant sensors, Pyrocal sensors and water cooled sensors [21]. These sensors differ in constructional features and working principles. Usually TPP, embedded, skin simulant, and PyroCal sensors are applicable for measuring the heat protective performance of firefighters'/industrial-workers' clothing under a fire exposure. Skin simulant and embedded sensors uses a material that simulates nature of skin heat transfer, hence these sensors are supposed to estimate burn injuries in more realistic way. Most of these available sensors except the water cooled sensor have limitations in operating for long time and/or higher intensity heat fluxes. Sensitivity of copper disk calorimeters which is commonly equipped with four thermocouples (ASTM D 4108) used for measurement of average temperature rise has been proved to be of no difference compared to copper calorimeter with single copper – constantan calorimeter. Curved plate copper calorimeter is used in radiant heat test, defined in standards ISO 6942:2002, to maintain proper specimen – sensor contact and avoiding variability due to fabric distortion. This method resulted efficient heat transfer and shorter predicted burn injury times. Methods adopted for mounting fabric samples, for example restrained and unrestrained, compressed or relaxed, in contact to each other or separated, air gap between fabric and sensor remarkably affect evaluation of heat protective performance [22].

XI. Conclusion

The firefighters' protective clothing usually composed of multiple components where each and every components play their own role to ensure the firefighters' safety, as the person is exposed to different levels of thermal and other hazards. Evaluation of firefighters' protective clothing is often done in terms of time to cause burn injuries, exposing fabric and sensor combination to high intensity heat flux. Various thermal sensors and test methods has been developed to evaluate their performance for the different levels of heat fluxes. The other factor that is considered extremely important is the comfort characteristics of the clothing combinations, i.e., it must offer a minimum level of comfort to the wearer. Dexterity and suppleness, and light weight are the other desired characteristics of the protective gears.

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