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Fire Fighter's Protective Clothing and Thermal Environments of Structural Fire Fighting

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FIRE FIGHTER'S PROTECTIVE CLOTHING AND THERMAL ENVIRONMENTS OF STRUCTURAL FIRE FIGHTING

by

J. Randall Lawson

Abstract

Fire fighter's protective clothing is designed to perform several functions. Of these, protection from heat and flame is one of the most important. Today's fire fighter protective clothing designs are based on years of field experience and research studies which addressed structural fires. Much of this work has concentrated on the fire environment where a fire fighter suddenly becomes enveloped in flames. This exposure generally results in serious life threatening injuries and sometimes death. Little appears to have been done to address the conditions where most burn injuries occur, outside of the flaming envelope. This paper attempts to define the general thermal environment at locations where fire fighters stage and begin their attack on a fire.

A great deal of research has been done to evaluate structural fires as they relate to building design, materials and contents. Only small elements of these data have been used in evaluating the thermal environment around fire fighters during normal attack situations. Results from early and recent studies clearly demonstrate the severity of thermal environments at fire attack staging areas. The flow of hot gases from a doorway or through a window may be well above 400 °C (752 °F) and may extend tens of meters down a corridor or across a adjoining room ceiling. Thermal radiation from a room's open doorway or window may reach levels which will cause burn injuries to exposed skin and cause charring or ignition of protective clothing fabrics which result in burn injuries to protected skin. Surface temperatures of solids within this staging zone may easily exceed 100 °C (212 °F) , and touching these surfaces without protection could result in a sudden burn injury. A brief scenario is presented which serves as an example of how a fire fighter could receive second degree burns while attacking a fire from outside of the flaming envelope.

KEY WORDS: Environments, fires, fire fighters, heat transfer, burns (injuries), protective clothing, structures, thermal insulation

1.0 INTRODUCTION

Structural fire fighter's protective clothing, as currently used by the fire servic designed to give the fire fighter "limited" protection from heat, flame, and mois It also serves to protect against minor cuts and abrasion. In addition, this clo is expected to provide a small degree of protection from chemical and biolc contact. The clothing's design is based primarily on experience in the fielc research studies on structural fires. Additionally, there is a small body of fiel laboratory research associated with fire fighter/protective clothing interactior performance. These fire research studies have generally concentrated o: performance of equipment exposed directly to flames from fully developed fire where fire fighters experience life threatening situations. Although life safety this flaming environment is paramount and deserves detailed evaluatior understanding, many burn injuries affecting fire fighters occur while outside flaming envelope. This envelope refers to the region bounded by the flame's edge. It is not known how many fire fighters receive non-flame contact burn year since injury statistics don't provide these details. Fire fighters don't ge fight fires from inside of the flaming envelope produced by a structural fi initiate their attack from outside of the flaming environment. As a result, this imply that non-flame contact injuries are relatively frequent.

Data from a survey conducted by the International Association of Fire F (IAFF), of its members for the year 1994, shows that about 2,418 fire fighter the 96,431 surveyed received serious burn injuries [1]. This amounts to 6.4 of the total 37,775 injuries reported, which includes all types of fire service [2]. It also represents 2.5 percent of the number of fire fighters surveyec reported by the National Fire Protection Association (NFPA) in its mucl survey for 1994 showed similar results, with 6,485 reported burn injuries repr 6.8 percent of the total number of injuries reported. Communications with L NFPA regarding these statistics show that both of these studies are based on definition of the word injury, and each organization indicated that all burn are not necessarily reported in their surveys. In addition, the NFPA fire fight survey does not include injuries sustained by private fire brigades, such as industrial or government operated installations. In order to better compre causes of these burn injuries it is important to understand: 1) the environment around fire fighters when the injuries occur; 2) the perfor thermal protective clothing used by fire fighters in these fire fighting envir and 3) the activities of fire fighters which contribute to the burn injuries.

2.0 THE FIRE FIGHTER VS. MODERN FIRE LOADS, MATERI BUILDING TECHNOLOGY

The United States has seen some significant changes in fire growth cha over the last few decades as a result of increased fuel loads from the use c building materials, interior finishes, and furnishings [5-8]. From a survey by Ingberg in 1942, the residential fire loads ranged from a low of 9.8 kg/m^2 (2.0 lbs/ft^2) in bathrooms to a high of 64.4 kg/m^2 (13.2 lbs/ft^2) in bedrooms with closets [3]. In comparison, the survey by Issen in 1980 showed a residential fire load range of 29.3 to 125.5 kg/m^2 (6.0 to 25.7 lbs/ft^2) [7]. In addition to the much larger fire loads, many of the new materials have greater burning rates than those used years ago. Figures 1 and 2 illustrate the burning behavior of two easy chairs [7]. Figure 1 shows a 15.7 kg (34.6 lbs) chair of mostly wood construction with a minimum amount of foam padding. This chair resembles a construction predominant many years ago when little padding was used. Also, furniture produced during the nineteenth and early twentieth centuries was usually stuffed with horse hair or cotton which had relatively low heat release rates as compared to the synthetic foam cushions used today. The second chair, shown in figure 2, with a mass of 28.3 kg (62.4 lbs) is a typical modern stuffed easy chair with an abundant quantity of fire retardant foam cushioning. Figures 1 and 2 clearly show the difference in burning behavior. The older style chair's peak heat release rate was 225 kW, and its burning was spread over a relatively long period of time. The modern stuffed easy chair exhibits a significantly different burning behavior even though the peak heat release rate occurred at approximately the same time as the older style chair. The major difference is that the modern chair released a large quantity of heat over a very short period of time. The peak heat release rate for the modern chair was greater than 2,100 kW. Heat released from this single chair would likely cause flashover [8] in an average size family room, while heat released from the older style chair would not cause flashover in the same room. Flashover is defined as a very rapid change from localized burning to full room involvement [9]. Flashover of an average size family room will usually occur with a heat release rate of about 1,000 kW [10][11]. Flashover is controlled by room size, fuel load, heat release rate, and ventilation. The occurrence of flashover will vary as these controlling factors change.

As modern comfort furnishings and other new materials were introduced into the home and work place during and after the 1950's, there appeared to be an increasing trend in fire severity [7][9]. The introduction of these new types of combustibles in North America brought about new challenges for the fire fighter in that they were seeing more fully developed fires upon arriving at the scene. In addition, buildings are being built to conserve energy. Highly insulated buildings that are being built or retro-fitted for energy conservation appear to promote rapid fire growth [8]. Fire growth in well insulated buildings is more likely to lead to rapid flashover conditions and/or oxygen starved fires which may produce a backdraft if a building is not properly ventilated [8]. With the introduction of properly maintained and operating smoke detectors, residential alarm systems, and modern fire services communications systems it is being reported that fire fighters are again presented with the opportunity to arrive on the fire scene before a structure is fully involved [8].

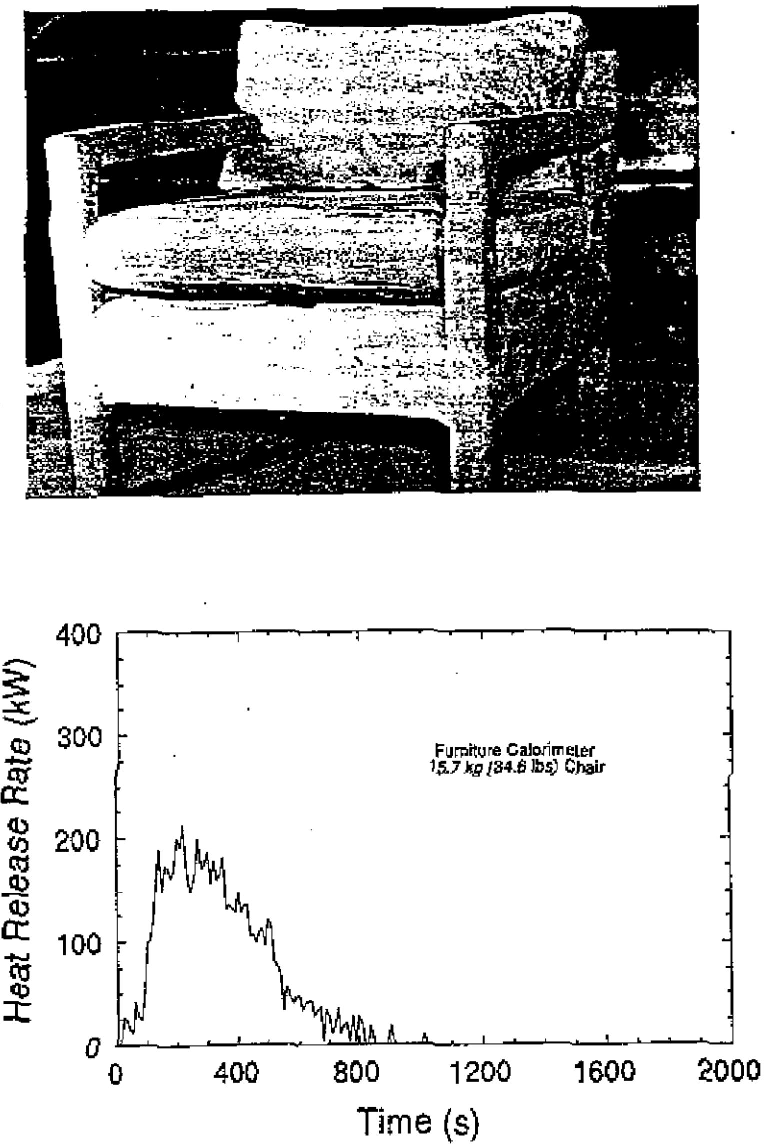

FIG. 1 Photograph and rate of heat release for older chair construction.

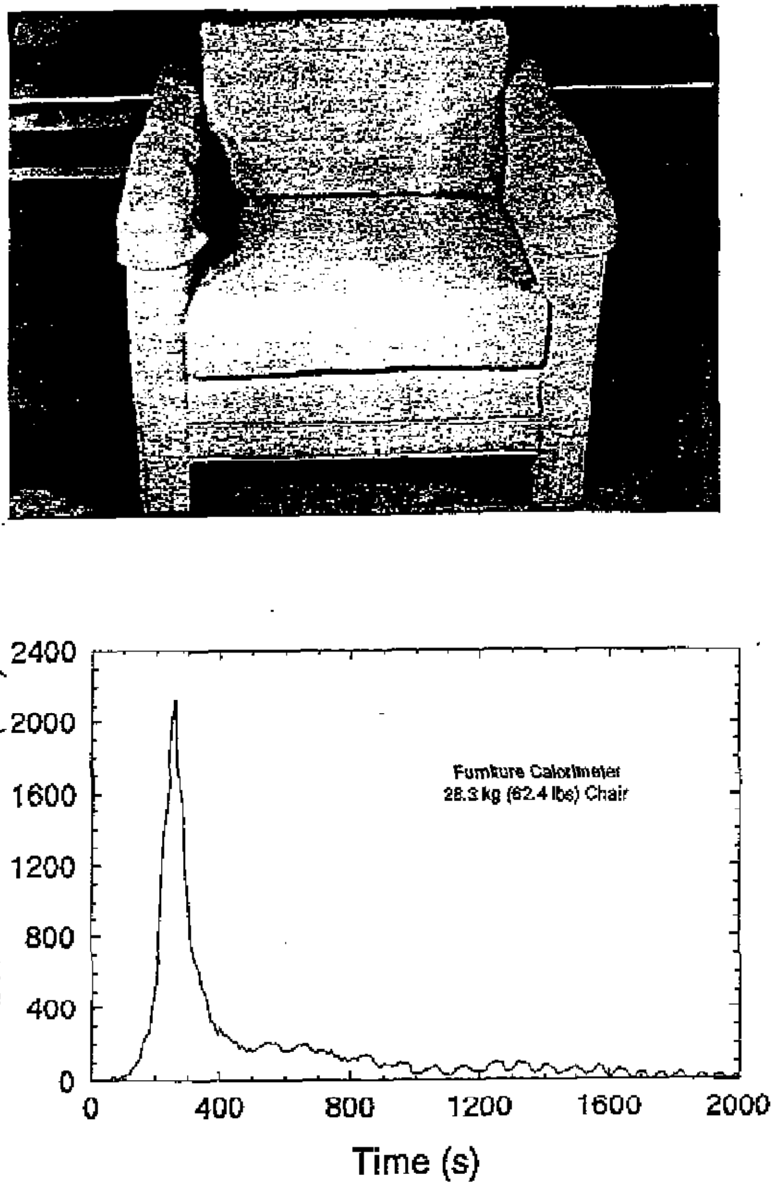

FIG. 2 Photograph and rate of heat release for modern chair construction.

As would be expected, fire fighters may arrive on the fire scene during any of th various stages of fire development, from incipient burning to post flashover deca Upon arriving at the fire scene fire fighters are immediately faced with the need correctly evaluate the fire's behavior and develop a safe and productive means attack. If fire fighters arrive on the scene just before flashover and attempt to ente the building at flashover, they run the risk of facing a rapidly changing fire situatio that could quickly expose them to severe conditions. In an oxygen starved pos flashover fire, entry could lead to an oxygen induced explosion (backdraft) whi would potentially expose the fire fighter to a violent out-rush of hot gases, flame and thermal radiation from the structure [12][13]. A fire fighter must be able safely deal with the wide range of fire behavior. To do this, one must have understanding of fire growth, must use safe and productive fire fighting procedur and must have a general understanding of the limitations of their protective clothi and equipment.

3.0 *FIRE FIGHTER PROTECTIVE CLOTHING AND BURN INJURIES*

Fire fighter's protective clothing is primarily designed to give an individual a deg of protection from the thermal environment produced by a fire. It affords a limi degree of protection from thermal radiation, hot gas convection from a fire, a direct contact with hot surfaces [15][16]. Burn injuries while wearing this protect clothing are directly related to the fire fighter's thermal exposure, the actions of fire fighter within the thermal environment, the physiological functions which regul heat buildup within the human body, and the performance of components wh make up their protective clothing ensemble.

Today's protective clothing ensembles typically consist of a flame resistant outer s and an inner liner. The outer shell resists ignition upon being exposed to ther radiation or very short periods of direct flame contact. The inner liner is gener composed of a moisture barrier and a thermal barrier. Moisture barriers may tot prevent the passage of moisture, whether liquid or vapor. Other types of mois barriers prevent liquid water from penetrating but permit the passage of mois vapor. The thermal barrier is a layer of insulating material which retards heat through the garment. The insulating quality of this barrier primarily depends the amount air space within the material and to a lesser degree on the heat tra properties of the materials used to make the barrier. Although protective clo is designed to reduce the flow of heat and moisture from the fire fig environment to the fire fighter, it also reduces the flow of heat and moisture from the fire fighter to the environment. Because of this, the wearer can not lose body heat which may result in a rise in body core temperature. The body become heat stressed which activates the sweating process in an attempt rest normal body temperature. Since the protective clothing is resistant to liquid sweat can not easily evaporate from the skin's surface and evaporative cool limited. The protective clothing insulation may absorb this sweat which pote could reduce its insulating properties. It has been shown for garments with moisture barriers that permit the transmission of moisture vapors, the body core temperature is approximately 1.0 °C (1.8 °F) less than with a moisture barrier which doesn't allow for vapor loss [17]. This small difference in body core temperature can be critical. Experimental data shows that its not uncommon for body core temperatures of fire fighters to be as high as 38 °C (101 °F) [17]. Data from Huck shows that a body core temperature of 39 °C (102 °F) is commonly considered to be the limit where the body begins to loose efficiency and medical problems may begin to occur [18]. A core temperature of about 43 °C (109 °F) may be fatal [18].

Research by Veghte [19] shows that humans have the ability to produce substantial quantities of sweat. Sweating rates for humans carrying out heavy exercise activities, as would be expected with fire fighters, range from 1200 to 1800 g/hr (2.64 to 3.96 lbs/hr) [19]. Once sweating has begun, fire fighters become susceptible to injuries referred to as steam or scald burns [20]. These burns are believed to be produced when protective clothing temperatures are well below 100 °C (212 °F). Moisture produced by sweating and from water that leaks through garment closures becomes trapped inside of the fire fighter's protective clothing by the moisture barrier. Some moisture barrier materials will allow water vapor to escape; although, liquid water will not pass through the membrane. Moisture located on the outside of the moisture barrier or on the outer shell can produce cooling through evaporation or run-off which carries heat away from the clothing. Moisture trapped inside of a protective garment, absorbed by the protective garment's liner and fire fighter's clothing, would not be expected to produce the same rate of evaporative cooling. This trapped moisture may result in a decrease in thermal protective performance (TPP) of the fire fighter's garments, especially during fabric compression [15][19]. It should be noted that the TPP test values quoted for fire fighters protective clothing are developed from tests performed on dry garment assemblies. Garments that are wet exhibit significantly different heat transfer rates. Water transfers heat about 21 times faster than air at a temperature of 93 °C (200 °F) [22]. Wet garments result in higher heat transfer rates through the garment; however, this increased heat transfer rate may be offset, to some degree, by an increase in moisture evaporation rate. Burn injuries that result from the heating and evaporation of moisture trapped within one's protective clothing often comes as a sudden surprise to the fire fighter. In many cases the fire fighter has not even come into direct contact with a flame or hot surface. Frequently, it has been observed that when these burn injuries occur there is no apparent damage to the fire fighter's protective clothing.

Research done by Veghte, Stoll and others gives an indication of typical skin temperatures which result in pain and various degrees of burn injury [20][23]. A human will experience discomfort or pain when the skin temperature reaches 44 °C (111 °F). A first degree burn occurs at a temperature of about 48 °C (118 °F), and a second degree burn occurs at a skin temperature of about 55 °C (131 °F) [23]. This does not mean that a burn immediately occurs when the skin comes into contact

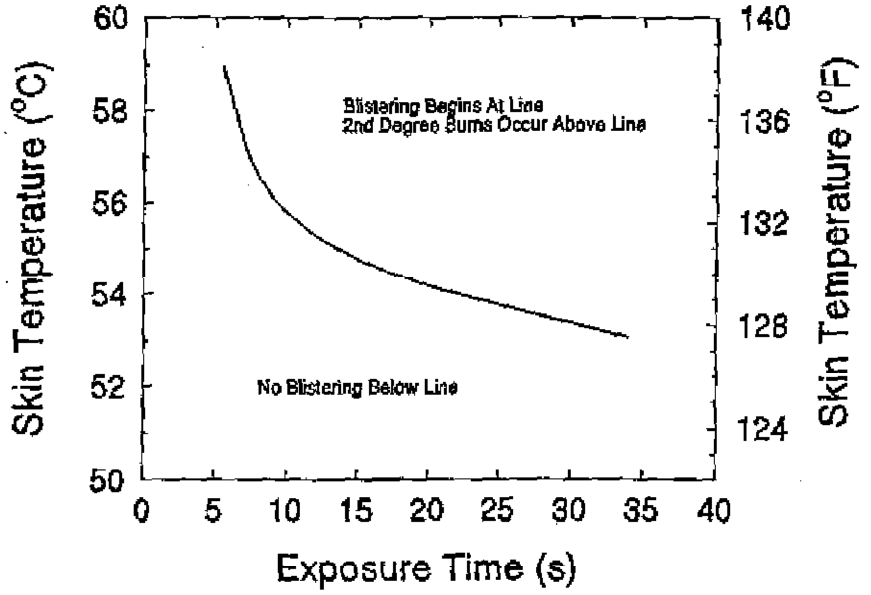

FIG. 3 Exposure threshold conditions for skin blistering.

with a gas, liquid or hot surface which is 55 °C (131 °F). Prolonged exposure to this thermal environment and higher temperatures will ultimately cause the skin temperature to rise to a critical point where heat losses which protect the skin can no longer be maintained, and a burn occurs. Heat losses from the skin are controlled by blood flow to and from the exposed area, thermal radiation from the skin's surface and heat losses resulting from sweating. Exposure to 55 °C (131 °F) tap water can be very uncomfortable and yet no burn occurs if the hand is quickly removed from the water. Leaving the hand in the hot water over a period of time will cause a burn, and the higher the temperature, the quicker the burn injury will occur. This is shown by data on temperatures for skin blistering from the "Project Fires" study, figure 3 [24]. Instantaneous skin destruction occurs at a temperature of 72 °C (162 °F) [23]. Table 1 gives a listing of heat flux exposures with time which result in second degree burns. These values are drawn from Stoll's [23] work and are presented in the TPP test standard [21]. The above data shows that relatively small changes in skin temperature can lead to serious burn injuries.

It should be noted that once a fire fighter's protective clothing has been heated and the skin temperature has risen to the dangerous levels mentioned above, it is unlikely that a fire fighter can immediately remove the protective clothing to start the cooling processes and prevent additional injury.

3.1 BURN INJURIES SCENARIO

The following scenario addresses the phenomenon described above where a burn injury occurs, and there is no damage to the protective clothing: An alarm comes into the station, and fire fighters don their turn-out gear (protective clothing including helmet, hood, turn-out coat and pants, and boots). As soon as they don their gear, normal heat loss from the body is slowed. This may feel good to the fire fighter on a cold winter's day, but after arriving at the scene, putting on SCBAs (Self-Contained Breathing Apparatus) and gloves, pulling hose lines and carrying out other duties required before attacking the fire, sweat may already be soaking clothing next to the skin. The fire fighters enter the building and climb a flight of stairs. As the fire fighters move down a corridor looking for the fire, their protective clothing and bodies become heated from the outside by thermal radiation and hot convective flows from the fire. This heating not only affects an individual's fire fighting performance, but alters the protective performance of the individual's turn-out gear. Liquid sweat is absorbed by the fire fighter's clothing. Sweat vapors which fill the protective clothing air spaces may be absorbed by fabric fibers. The heat capacity and thermal conductivity of the protective clothing starts to change. As increased quantities of sweat are absorbed into the fabric more and more heat can be stored in the fire fighter's clothing, and the thermal conductivity of the turn-out gear increases. Upon heating the garments, moisture evaporation rates tend to increase. This increased evaporation rate helps to keep the fire fighter comfortable but hot as work continues. The fire fighter with the nozzle begins the attack and water spray splashes back from the wall and ceiling. If the protective clothing becomes saturated with sweat and water spray from the hose line, the protective clothing's thermal conductivity may approach that of water, and decrease the insulating properties. The fire fighter feels heat increasing on the body and senses that the attack is working, but the temperature is still increasing within the protective clothing. As the attack proceeds the fire fighter with the nozzle suddenly feels pain. The fire fighter receives second degree burns on the left hand, the left shoulder next to the SCBA strap, on the right biceps and to the right knee. The fire fighters retreat to find a cooler environment. After the fire is extinguished and the fire fighters return to the firehouse, an investigation begins which documents the burn injuries. A safety report is filed detailing the actions of the fire fighter and fire conditions. The report states that standard fire fighting practices were followed, the fire fighter never came into contact with flames, and the turn-out gear showed no thermal or other physical damage. The fire fighter did not require hospital treatment for the first and second degree burns. In addition, the report states that the fire fighter on the hose behind the fire fighter with the nozzle received no burns or equipment damage.

3.2 THE SCENARIO BURN INJURIES - WHAT CAUSED THEM ?

In the scenario presented above, the fire fighter with the nozzle received burn injuries at four different body locations. Based on injury pattern data produced at NFPA by

Karter [25] and conversations with a number of fire fighters, these burns represent common injuries which occur in the fire services. But, these injuries may not all happen at once to a single fire fighter as illustrated in this scenario. Over the years, the author has studied a number of fire fighter burn cases which are similar to the scenario presented here. From this knowledge, it is suggested that each of the burn injuries in this case have common contributing factors. Also, each of the burn injuries resulted from factors specifically associated with the particular burn.

TABLE 1 Human tissue tolerance to second degree burn [21][23]

Exposure Time	Heat Flux	
(s)	(W/cm^2)	(cal/cm^2 · s)
1	5.0	1.2
2	3.1	0.73
3	2.3	0.55
4	1.9	0.45
5	1.6	0.38
6	1.4	0.34
7	1.3	0.30
8	1.15	0.274
9	1.06	0.252
10	0.98	0.233
11	0.92	0.219
12	0.86	0.205
13	0.81	0.194
14	0.77	0.184
15	0.74	0.177
16	0.70	0.168
17	0.67	0.160
18	0.64	0.154
19	0.62	0.148
20	0.60	0.143
25	0.51	0.122
30	0.45	0.107

Common factors:

- The fire fighter was preheated before attacking the fire.
- The fire fighter was sweating.

- The fire fighter's clothing, inside of the turn-out gear's moisture barrier, absorbed sweat and water spray changing the thermal protective performance of the clothing.
- The fire fighter was located several meters (yards) away from any flames, and the thermal environment didn't appear to be a problem.
- The fire fighter's protective clothing provided enough delay in heat transfer through the clothing to allow the individual to enter a thermal zone which was hazardous.

In addition to the above, each of the burns are related to moisture within the fire fighter's clothing and the compression of protective clothing components against the skin. Specific issues related to each type of burn are:

Burns On The Hand: Burns to a fire fighter's hands and wrists are common injuries sustained by many members of the fire service. NFPA data shows that arm and hand burn injuries are second only to burns injuries of the head [25]. These injuries often result from a combination of fire fighter actions while attacking a fire, human physiological functions, and the design of fire fighter's gloves [20]. Actions by fire fighters that contribute to hand burn injuries are: Hands are generally extended toward a fire during the attack where they may receive a high heat flux. A fire fighter may touch a hot object and compress the protective glove. Hot objects that fire fighters may contact are gases, vapors, liquids and solids. Steam produced by applying water to the fire and hot surfaces during fire fighting is a common source of injury [20].

Burns On The Shoulder: Data provided by Karter does not clearly separate these shoulder injuries from the head area or trunk area statistics. However, the combined statistics for these two areas account for about 56 percent of all burn injuries [25]. As with the head, the shoulders are generally exposed to thermal radiation emitted from the hot gas cloud above the fire fighter. Also, sweat from the head and neck tends to collect in fabrics at a fire fighter's shoulders. In addition, SCBA straps extend across the shoulders and back compressing protective clothing layers increasing the thermal conductivity in areas under and adjacent to the straps.

Burns On The Biceps: Burn injuries to the arm and hand account for about 29 percent of all fire fighter burn injuries [25]. In this scenario the fire fighter's arms were extended toward the fire and sweat was being produced, it is suggested that one or a combination of things may have happened. The fabric and moisture within the clothing was heated from thermal radiation to a temperature high enough to cause a burn, and/or the hot turn-out coat fabric was compressed against the skin by the fire fighter.

Burns On The Knee: Burn injuries to the legs and feet account for about 9.0 percent of all fire fighter burn injuries and are the fourth most common type of burn injury

[25]. In the scenario presented, the fire fighter's knee was pressed against a hot surface in the corridor. Again the turn-out gear's thermal protection was degraded by moisture and compression. Although the fire fighter's knee was well away from the fire and was exposed to very little thermal radiation, it was pressed against a surface preheated by the fire. This hot surface then transmitted its heat to the protective clothing and fire fighter as soon as it was touched.

3.3 BURN INJURIES AND DRY PROTECTIVE CLOTHING

In the above scenario, the fire fighter was burned primarily as a result of being exposed to temperatures high enough to cause injury while the fire fighter's protective clothing was wet on the inside and outside. This moisture when combined with garment compression accelerated heat transfer through the protective clothing, producing the burns.

Burn injuries can also occur when moisture is not a contributing factor inside of protective clothing and without any apparent damage to the protective clothing. As related earlier, second degree burns will occur when the skin temperature reaches 55 °C (131 °F) and instantaneous skin destruction occurs at a temperature of 72 °C (162 °F). These temperatures are very low when compared to the decomposition or charring temperatures of protective clothing and common clothing fabrics. For example, ordinary cotton fabrics that have not been treated with fire retardants will not show any apparent signs of thermal degradation at temperatures below 250 °C (482 °F) [27]. Although, temperatures in this region will cause serious burn injuries. Instantaneous skin destruction occurs at a temperature of about 178 °C (352 °F) below the charring temperature of cotton. Therefore, a fire fighter could receive a serious burn injury even though no thermal damage to the clothing is evident.

4.0 STRUCTURAL FIRE THERMAL ENVIRONMENTS

The discussions above demonstrate several of the human and equipment factors which contribute to fire fighter burn injuries. Another factor that must be addressed is the thermal environment where these injuries occur. Data produced by decades of fire research on structural fires shows that the thermal environments outside of the flaming envelope are easily capable of causing serious burn injuries.

4.1 PRE-FLASHOVER FIRES

Pre-flashover fires, although relatively small, develop thermal environments that can cause serious burn injuries to fully equipped fire fighters. Flame temperatures measured by Gross and Fang within low intensity fires were in excess of 700 °C (1292 °F) [28]. In addition, they reported that the total heat flux measured at the edge of a burning common wastebasket was generally in excess of 1 W/cm^2 (0.24 cal/cm^2 · s), and in some cases it was more than 4 W/cm^2 (0.96 cal/cm^2 · s). Air

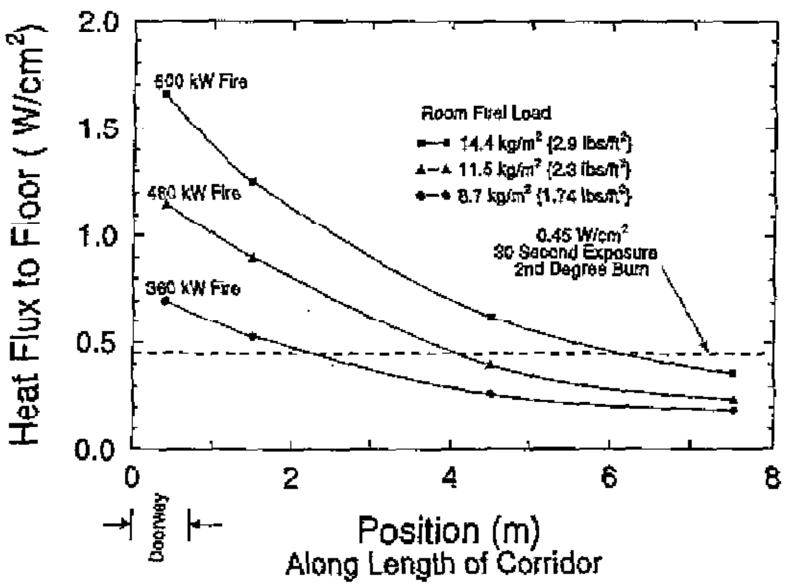

FIG. 4 Heat flux to corridor floors from low intensity room fires.

temperatures at the ceilings of test rooms with wastebasket fires ranged from 100 to 400 °C (212 to 752 °F). Quintiere's work on pre-flashover room fires and their relationship to flame spread in corridors also provides information useful to fire fighters [29]. He found that relatively high incident radiant heat flux values can be experienced several meters away from the open door of a fire room. In his experiments, none of the room fires resulted in flashover, and all flaming was contained within the burn room. Radiant heat flux plots for the corridor floors are shown in figure 4 and can be compared with Stoll's burn data in table 1. For example, figure 4 displays a dashed line across the plots which represents a 0.45 W/cm^2 (0.11 cal/cm$^2 \cdot$ s) radiant heat exposure. The Stoll data indicates that human skin will receive a second degree burn after a 30 second exposure at 0.45 W/cm^2 (0.11 cal/cm$^2 \cdot$ s). A 30 second exposure to the environment created by a 600 kW room fire could cause burn injuries to a fire fighter on the corridor floor 6 m (20 ft) away from the fire room door. From the three different radiant flux data sets which represent the three different fires (360, 480 and 600 kW), it can be seen that a fire fighter can easily receive second degree burns to exposed skin from all three fires. And, these burns would occur without a fire fighter coming into direct contact with a flame or hot surface. These fire data also indicate that the fire fighters will be receiving substantial amounts heat energy that will be stored within their protective clothing and equipment. As a result of this heating, thermal performance of protective clothing will be affected and the fire fighter's performance is likely to be altered. This heat energy exposure could lead to serious injuries from sweat related burns or burns by heat transfer from the protective garments if they become compressed against the skin. When comparing these data to the environmental data related to burn injuries, it is easy to see how a fire fighter may be burned during these small fires even though there is no flashover, direct flame contact or contact with a hot surface.

4.2 FLASHOVER AND POST-FLASHOVER FIRES

Many of the serious burn injuries reported each year involve fires where flashover has already occurred, and in some cases the fires have been growing over a long period of time. Thermal radiation, hot gases and hot surfaces are found at relatively great distances from the fire's source. Fire fighters often locate a fire's source by crawling through and under the hot gas clouds and/or using hose streams to extinguish and to push the flames back. In areas where these tactics are used, fire fighters have often been preheated for several minutes before attacking the fire. Thermal radiation levels are high in these areas as a result of the hot gas clouds and the heated structural surfaces. The structural surfaces and building contents that have been heated will quickly change cool water from the hose line to steam and hot water. Examples of floor temperatures and thermal radiation resulting from a room undergoing flashover are shown in figures 5 and 6 [30]. These plots provide information about thermal environments along a corridor at various distances from the burn room's open door. Note in figure 5 that the carpet flooring surface temperature remains higher than the air temperature 25.4 mm (1 in) above its surface. This demonstrates how thermal radiation emitted from hot gases and smoke flowing along the corridor's ceiling heats solid objects well away from the fire. Fire fighters are heated by this thermal radiation as well. Figure 6 shows thermal radiation to the floor from the same fire depicted in figure 5. Comparing this radiant heat flux data with table 1, it is again evident that a fire fighter, after a 30 second exposure, can receive a second degree burn to exposed skin at a distance of 6 m (20 ft) away from the burn room door. In both figures, 5 and 6, the air temperature and thermal radiation increases a meter or so just outside of the room's doorway and then decreases. This increase indicates that flashover is occurring in the room and that flames are extending through the doorway into the corridor. Figure 4 does not show this energy rise which indicates that these fires did not result in flashover or have flames extending beyond the fire test room's doorway.

4.2.1 FIRE DATA PRODUCED BY RECENT NIST EXPERIMENTS

Data obtained from fire tests at the National Institute of Standards and Technology, NIST, on post-flashover fires shows that the total incident heat flux measured at the floor of a burning room can be as high as 17 W/cm^2 (4 $cal/cm^2 \cdot s$) with gas temperatures in the room averaging as high as 1000 °C (1832 °F) [31]. In this post-flashover fire environment, floor temperatures at the room's open doorway may be greater than 600 °C (1112 °F). This temperature is significantly higher than that shown for the room undergoing flashover, in figure 5. In more recent NIST fire studies involving rooms with smaller fuel loads, floor temperatures were measured at a distance of 2 m (6.6 ft) away from the fire room door. Metal plates, measuring 6 mm (0.25 in) thick, with thermocouples attached were positioned on the floor in one test, and thermocouples were attached directly to the surface of the 102 mm (4 in) thick concrete floor in another. Temperatures from these measurements easily exceed 300 °C (572 °F) during post-flashover burning. Again these surface temperatures remained well above those needed to cause serious burn injuries. As room flashover continues and the corridor undergoes flaming, second degree burn injuries can be obtained much further away from the room of fire origin.

Two other recent fire studies carried out by NIST, in cooperation with two fire departments, shed additional light on structural fire fighting environments. One study sponsored by the U.S. Fire Administration, related to arson induced fires, was conducted in cooperation with the Florence Fire Department, Florence, Alabama [32]. The second NIST study, related to fires in overcrowded housing, was conducted in cooperation with the Santa Ana City Fire Department, Santa Ana, California [33]. These fire studies using different single family structures and fuel loads were initiated using various techniques. As a result, the fires behaved differently. One fire where a liquid accelerant was poured on the bedroom floor, near the open bedroom door, produced peak heat flux values of 3 W/cm^2 (0.72 cal/cm$^2 \cdot$ s) on the corridor floor just outside of the room. At the same time, temperatures measured 25.4 mm (1 in) above the floor at the doorway were about 175 °C (347 °F). In another experiment where a fire was allowed to grow for several minutes, in a bedroom and living room with a high fuel load, temperatures measured 25.4 mm (1 in) above the floor in the building's living room exceeded 700 °C (1292 °F). Fire fighters trying to bring this fire under control experienced some difficulty when their hoseline, which was in good condition prior to the fire, was damaged. This provides an example of how fire fighters exposure time to a fire may be increased without warning. Just after entering the structure, the hose line just behind the fire fighters with the nozzle was damaged causing a leak and a reduction in water flow to the nozzle. This reduced the effectiveness of the fire fighting attack and left the fire fighters exposed for a longer period of time to the fire environment. Fire extinguishment was successfully and safely completed with no injuries using a backup line.

4.2.2 THERMAL ENVIRONMENTS ON THE OUTSIDE OF BURNING BUILDINGS

The discussions of pre-flashover and flashover fires illustrate that radiant heat and hot gases can extend significant distances away from the fire's source. With large post-flashover fires, it is common to have hot fuel-rich gases burning well away from the room of origin as fresh air provides oxygen for combustion. Thermal radiation

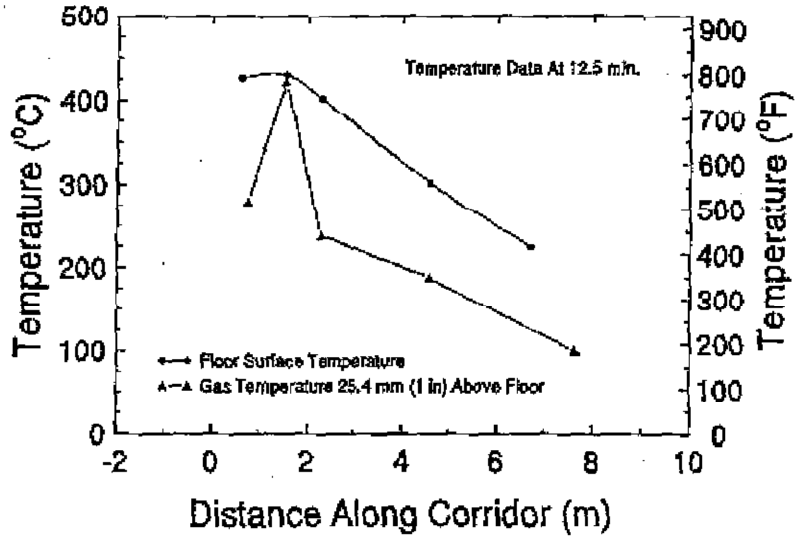

FIG. 5 Floor surface and gas temperature 25.4 mm (1 in) above a corridor floor.

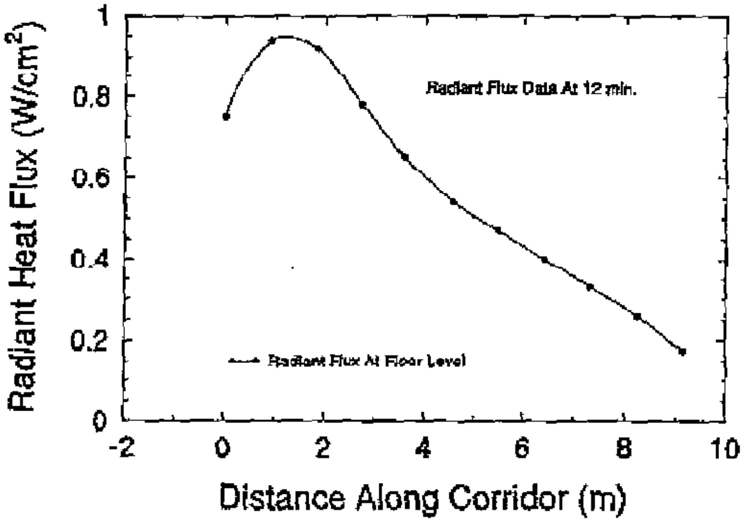

FIG. 6 Heat flux on a corridor floor just prior to flameover.

from windows and doorways can be high enough to cause sudden ignitions of grass, other buildings and fire fighters. The ignition of adjacent buildings by thermal radiation was investigated by numerous researchers during the 1960's. Research teams lead by Margaret Law [34] and J.H. McGuire [35] produced some of the most significant results from these studies. Their findings can be used to understand fire fighting environments on the outside of buildings or within large open spaced structures. Their data shows that radiant heat flux from a window or door can be more than .5 W/cm^2 (1.2 cal/cm$^2 \cdot$ s) at a location 6 m (20 ft) from the building opening. Data from the St. Lawrence structural burns showed that a fully involved single family house with flames in the interior and covering portions of the exterior can produce radiant heat flux levels in excess of 50 W/cm^2 (12.0 cal/cm$^2 \cdot$ s), up to 12 m (40 ft) from the structure [36]. As fire size gets larger, the effects of radiant heat energy will be experienced at greater distances from the fire's source. With exterior structural fires, a fire fighter must use protective clothing performance to help select staging areas and tactics for attacking the fire. When fighting large structural fires from the outside, as with all other fires, safety from burn injury is based on the performance limits of the fire fighter's protective clothing and equipment ensemble, and the fire fighting tactics which control a fire fighter's distance from a fire and thermal exposure time.

5.0 SUMMARY AND CONCLUSIONS

This paper addresses the broad spectrum of fire conditions and events which lead to some common types of first and second degree burn injuries experienced by fire fighters when using today's protective clothing and fire fighting tactics. Even though thousands of fire fighters receive serious burn injuries every year, injury statistics show that fire fighters frequently attack fires without being burned. These fire attacks are generally made from locations outside of the flaming envelope, but they are typically from locations where dangerous thermal environments exist. The reasons why many fire fighters don't receive burn injuries in these areas may be attributed to the following:

- a sufficient amount of protection is provided by protective clothing,
- fire fighters avoid direct contact with hot surfaces,
- successful fire fighting tactics keep the fire fighter's exposure times to high thermal radiation and temperature environments short.

Currently, there is a basic understanding of fire environments, human response to thermal exposure, and burn injuries. But, there is a need to develop a better understanding of the relationships between thermal environments, human response to the thermal exposures, and fire fighting tactics that result in burn injuries. Fire service statistics don't provide information on the relationships between burn injuries and fire fighting tactics. As a result, no evaluations can be made to determine if certain fire fighting tactics, such as positive pressure ventilation (PPV), produce fewer burn injuries. A better understanding of the relationships discussed above should lead to advancements in fire fighter safety. Based on present knowledge, it is suggested that fire fighter burn injuries may be reduced by improvements in protective clothing and fire fighter training.

Fire fighter protective clothing improvements:

- reduction and control of moisture inside of protective clothing,
- decreasing materials and clothing thermal conductivity,
- reducing a garment system's heat capacity or the ability of a garment to store heat energy.

In addition to the above, the emerging sensor technology may have a positive impact on warning the fire fighter of impending untenable conditions. The protective clothing manufacturing industry has been steadily working on improvements to their products to deal with the above issues. Progress in the development of protective clothing is in part controlled by advancements in materials technology, and it often takes years to bring new products to the market.

Improvements in protective clothing are of little use if fire fighters don't understand the performance limits of their clothing. Although it may take years to develop new protective clothing technology, fire fighter training may have an immediate impact on safety.

Fire fighter training improvements:

- It is critical that every fire fighter has a thorough understanding of their protective equipment's performance and limitations.
- Fire fighters must also have a thorough understanding of how burn injuries occur.
- The fire fighter must be trained to avoid preheating and how to deal the issues of sweating and wet protective clothing. Fire fighters need to understand that the thermal protection provided by their protective clothing is generally altered by moisture inside these garments, which includes wet uniforms and underwear. Preheating increases heat energy levels in a fire fighter's protective clothing, and sweating may increase heat flow and heat storage in protective clothing.
- Fire fighters must also be aware of what happens when their protective clothing becomes compressed by body movement, external fire fighting equipment (i.e. SCBA), and against hot surfaces. Compression of protective clothing will accelerate heat transfer through the clothing and may cause heat stored in garments to be immediately transferred to the skin resulting in a burn.

The above discussion related to the limits of protective clothing and the severity of fire environments should be considered in the development of fire fighting tactics. It is critical that, where possible, the fire fighter not be placed into environments where the limits of their protective clothing and equipment are challenged. Pressing protective clothing and equipment to their critical limits can lead to serious burn injuries.

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