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Field tests on human tolerance to (LNG) fire radiant heat exposure, and attenuation effects of clothing and other objects

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Abstract

A series of field tests exposing mannequins clothed with civilian clothing to a 3 m × 3 m square liquefied natural gas (LNG) pool fire was conducted. Both single layer clothing and double layer clothing were used. The radiant heat flux incident outside the clothing and incident on the skin covered by clothing were measured using wide-angle radiometers, for durations of 100–200 s (per test). The levels of heat flux incident on the clothing were close to 5 kW/m^2. The magnitude of the radiant heat attenuation factor (AF) across the thickness was determined. AF varies between 2 and higher for cotton and polyester clothing (thickness 0.286–1.347 mm); AF value of 6 was measured for 1.347 mm thickness. Single sheet newspaper held about 5 cm in front of mannequins and exposed to incident flux of 5 kW/m^2 resulted in AF of 5, and AF of 8 with double sheets. AF decreases linearly with increasing heat flux values and linearly increases with thickness.

The author exposed himself, in normal civilian clothing (of full sleeve cotton/polyester shirt and jean pants), to radiant heat from a LNG fire. The exposure was for several tens of seconds to heat flux levels ranging from 3.5 kW/m^2 to 5$^+$ kW/m^2 (exposure times from 25 s to 97 s at average heat flux values in the 4 kW/m^2 and 5 kW/m^{2}range). Occasionally, he was exposed to (as high as) 7 kW/m^2 for durations of several seconds. He did not suffer any unbearable or even severe pain nor did he experience blisters or burns or any other injury on the unprotected skin of his body. The incident heat fluxes on the author were measured by a hand-held radiometer (with digital display) as well as by strapped on wide-angle radiometers connected to a computer. He could withstand the US regulatory criterion of 5 kW/m^2 (for 30 s) without suffering any damage or burns. Temperature measured on author's skin covered by clothing did not rise above the normal body temperature even after 200 s of exposure to 4 kW/m^2 average heat flux.

Keywords: Radiant heat; Human exposure; Fire; Clothing protection; Radiant heat flux; Attenuation factor

1. Introduction

The hazard to people located outside the immediate vicinity of a fire on a pool of a flammable liquid, and who are not in danger of being impinged by the flames, arises primarily from the radiant heat emanating from the fire. A fire radiates heat to its surroundings from the entire volume within its visible fire plume, and to a lesser extent from the high temperature burnt gases above the visible part of the fire. This radiant heat, which is what one experiences in front of a fire in a fireplace, has very high intensity close to the fire. The radiant heat intensity or the heat flux decreases as one goes away from the surface of the fire plume. The intensity variation with distance is, in general, proportional to the inverse square of the distance. In addition, during the transmission of the radiant heat flux in the atmosphere the intensity is reduced due to absorption by water vapor and carbon dioxide in the atmosphere.

Fig. 1 shows, schematically, the situation of interest to this paper. A large liquid fuel fire caused by the spill of a fuel radiates heat to the surroundings. The figure also illustrates the variation of the emissive power (i.e., the rate of emanation of heat energy from a unit nominal surface of an enveloping smooth volume enclosing the visible fire) with height above the pool surface; as an example, mean values of the emissive power for a large LNG fire at bottom, mid height and at the top of the visible plume are indicated. A person or a group of persons may be exposed involuntarily to the radiant heat effects of this fire at some distance from the fire (without any possibility of flame impingement on the persons). The principal question in this scenario is "how far does the hazard distance extend from the fire" for an involuntary

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Nomenclature

AF	attenuation factor = ratio of transmitted radiant heat flux to incident heat flux

exposure. The key concept here is the word “hazard” which has been defined in different ways in the literature. One of the criteria used to define a “hazard,” in the liquefied natural gas (LNG) fire literature, is that the exposure to the fire for 30 s or less should not cause a 2nd degree burn injury to the skin of the person. This definition does not specify any other parameters that do significantly influence the occurrence of the skin injury.

In many countries regulations and standards applicable to facilities storing flammable liquids require the establishment of zones of safety surrounding such facilities to protect the population from the potentially hazardous effects of accidental releases of the stored liquid. These safety zone distances are determined, using mathematical models that describe the characteristics of the fire, to a specified level of thermal hazard to the outdoor population from specified types of releases, and fires caused by such releases. For the US-based LNG storage facilities the US DOT Regulations, 49 CFR, part 193 and the NFPA 59A Standard, require the calculation of the safety distances from fires in the impoundment(s) from specified “design” spills. The safety distance is defined as that location where the radiant heat flux level is 5 kW/m^2 (or ≈1600 Btu/h ft^2). It is seen that the criteria for “hazard” for human exposure are specified only in terms of limit heat fluxes without specification of either the duration of exposure or the spectral characteristics of the radiant heat incident on the person exposed.

Considerable experimental data and mathematical modeling exist in the literature on fires, characterizing the size, shape and the emission of radiant heat from the visible plume of fires, in general, and from LNG fires in particular; see Welker and Sliepcevich [1], Raj [2], Mudan [3], Beyler [4], Moorhouse [5], Raj [6], Malvos and Raj [7] and Raj [8]. The safety distance depends not only on the size and characteristics of the fire but also (very significantly) on the values and details of the hazard criteria used; yet, there have been no significant research to determine whether the currently used criteria are correct or not when applied to situations of full-scale (large fires in the field). Recently, Raj [8] has reviewed the available literature on skin burn hazards and has evaluated the consequences of considering the detailed characteristics of the radiant heat, the physical characteristics of the exposed skin, the beneficial effects of clothing and other intervening obstructions, and their relationship to the “hazard.” Some interest groups have misrepresented the current criteria as posing extreme injury risks (in some cases even fatalities) to the public simply because of the lack of full-scale test data.

The subject of this paper is the experimental determination of the effectiveness of ordinary civilian clothing and the degree of protection they provide from radiant exposure injury at an intensity level close to 5 kW/m^2. In addition, the test objectives were to determine the ability of a human being, attired in normal everyday clothing (with parts of the skin being bare and susceptible to direct radiant heat exposure), to withstand a 30 s exposure to 5 kW/m^2, and to determine the consequences. It is pointed out that the intent of the tests was not to determine the survivability of clothing to high intensity thermal radiation or the injury caused by the flammable or melting characteristics of clothing.

The principal hazard of concern from a fire, at distances away from the immediate vicinity of the fire, is the exposure of people to the damaging effects of radiant heat. In the 1940s and 1950s several experiments were conducted to determine the effects on the population of radiant heat from conflagrations of city blocks due to fires set by war incendiaries or nuclear blasts (see references in Buttner [9]). Buttner conducted tests to understand the pain threshold when 5 cm × 10 cm area of the forearms of volunteers was exposed to different levels of radiant heat fluxes (over the range 1.28–20 kW/m^2) from a 500 W electric radiator of 600 °C simulating a hydrocarbon fire. This source was essentially a blackbody with peak spectral radiance at a wavelength of 3.32 μm, and an overall radiance of 33 kW/m^2. It is noted from the work of Hardy and Muschenheim [10] and Hardy et al. [11] that over 95% of the incident radiation in Buttner’s experiments was absorbed by the skin of the volunteers, because

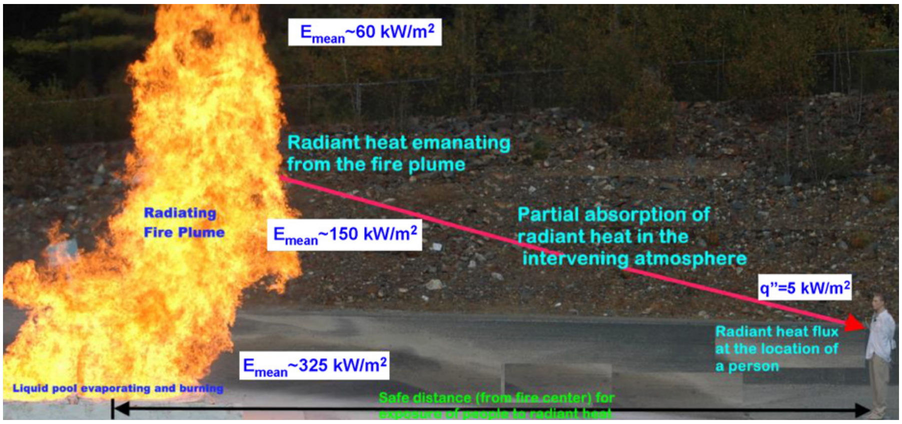

Fig. 1. Schematic representation of radiant heat emanation, and its intensity variation with height, from a turbulent diffusion fire on a flammable liquid pool and exposure of a person to fire radiant heat at a distance from fire center.

of the longer wavelength IR radiation used. His results for the time "t" (in seconds) to experience unbearable pain could be correlated with the incident radiant heat flux "I" (in kW/m^2) by the equation $I^{4/3}t = 114$. Furthermore, Buttner concluded that unbearable pain occurred when the temperature at 0.1 mm below the skin reached $41.8 \pm 0.5\,°\text{C}$. The data from small-scale laboratory tests by Hardy et al. [12] and Stoll and Greene [13], for threshold pain in volunteers, indicate similar results. Stoll and Greene used blackened volar surface of human subject forearms to improve absorption of the radiant heat from a carbon arc source, which was at a much higher temperature than used by Buttner. Their tests also measured the time for blister formation on the forearm skin. Mixter [14] conducted experiments with white pigs and developed data for the times for 2^+ degree burns with different levels of radiant heat fluxes. Mixter's data generally agree, though not exactly (due to differences in both the subject and experimental details), with the data of Stoll and Greene for human skin blistering. Data from fire burn victims admitted to hospitals have been reviewed by Hockey and Rew [15]. They have also analyzed the various probit functions for fatality correlations used in risk analyses. They conclude that these correlations, mainly based on nuclear blast-related skin burns and total fire burns, may over estimate the consequences to the population exposed to direct fire radiant heat. In fact, Daydcock and Rew [16] allude to an unpublished work of another researcher (Lawrence) indicating that only 2% of burn victims suffer from "thermal radiation burns." This implies that most burns are not caused by radiant heat exposure to fires but are, perhaps, caused by direct contact with flames or hot objects.

Two basic types of criteria are used to assess the radiant heat hazard from accidental hydrocarbon fires (pool fires, vapor fires or fireballs) to a population. The first is the specification of a hazard intensity or heat flux (some times combined with a total exposure time). The second approach is to specify a tolerable level of a modified thermal dosage unit (TDU), defined as the product of the incident heat flux raised to 4/3 power and the time of exposure. In addition, the metric used for the hazards varies between a skin burn injury (generally 2nd degree burn) and fatalities from burn injury. The National Fire Protection Association's (NFPA) 59A Standard on Liquefied Natural Gas Facilities [17] stipulates a radiant heat flux level of 5 kW/m^2 for "*the nearest point located outside the owner's property line that, at the time of the plant siting, is used for outdoor assembly by groups of 50 or more persons for fire in an impounding area*." The US Department of Transportation (US DOT) Regulations, 49 CFR Part 193, applicable to LNG facility siting, use the same criteria as in NFPA 59A. Neither the NFPA Standard nor the DOT Regulations specify the duration of exposure of the general public to the hazard heat flux to constitute an injury nor do they specify the basis on which the criteria were developed (2nd degree burns, % of body exposed to radiant heat, effectiveness of clothing, etc.). Recent review (Raj [8]) of the criteria used by different regulatory and standards agencies, both in the U.S. and in Europe, on the criterion used to determine the safety distance to public exposure from LNG fire radiant heat indicates that there is reasonable consensus among the various agencies that an exposure for 30 s to 5 kW/m^2 heat flux represents a threshold limit for causing serious injury. However, this criterion is used both in prescriptive regulations which require the establishment of "separation distances" for prescribed types of releases as well as in assessments where the overall risk to the population is considered (which includes the consideration of a whole spectrum of events and their radiant heat hazard consequences). Also, some agencies in Europe require the use of a specified value of TDU as a metric of safety.

Clothing normally worn by people can partly absorb, partly reflect and scatter incident thermal radiation and thus protect the covered skin from experiencing the full intensity of the incident radiation. Stoll and Chianta [18] conducted simulation studies, both theoretical and experimental, to determine the protection provided by clothing on pilots in aircraft cockpits from direct exposure to fuel fire resulting from aircraft crashes. The experiments show that the time to produce "white" burns in rats, with a 4-mm air gap between a fabric and the skin increased by a factor of 3 compared to the time to produce the same burn without the fabric. For large radiant heat flux levels (30 kW/m^2, which levels would be experienced when the person or an object is very close to a fire) the researchers found that the absolute protection time provided by normal clothing (of 1–1.5 mm thickness) was short and that much thicker (and multi-layered) clothing, such as is worn during winter months, was necessary to provide any burn protection. Theoretical work by Haskestad et al. [19] showed that the thermal protection offered by the apparel depended upon the gap between skin and the clothing, in addition to the thermal properties of the cloth itself. In these calculations high heat flux levels (33.5 kW/m^2) were used. No results have been presented for low thermal flux levels of interest (5 kW/m^2) to this study. If the results are extrapolated to 5 kW/m^2 intensity level, the duration for charring of the cloth is found to be longer than 300 s. The source characteristics used in these assessments were that of a black body. Lotens [20] has discussed the mechanisms of heat exchange through clothing, as a first step in the design of the most effective clothing ensembles for work in extreme temperatures. Lotens concludes that the air gap between a person and the clothing provides the clothing the ability to reduce heat transfer to the skin; in many cases reducing the effective radiant heat flow by a factor of 2. Fukazawa et al. [21] have evaluated both experimentally and theoretically, the temperature distribution in clothing of various thicknesses exposed to radiant heat fluxes close to solar values (1 kW/m^2). It is seen that the radiant heat flux decreases exponentially within the clothing material with the "characteristic penetration depth" dependent upon the type of clothing material. This characteristic depth ranges from 0.11 mm to 0.37 mm for Nomex® clothing material.

The above summary review of past experiments on skin burns or effect of clothing clearly indicates that controlled, full-scale, fire exposure experiments have not been conducted with human beings clothed in normal civilian clothing. Most criteria used currently in safety assessments for fire radiant heat exposure hazards are based on either indirect data or extrapolation from laboratory scale tests involving the exposure of small areas of skin to radiant heat from electric heaters, which have substantially different spectral emission characteristics (than that of a fire). In addition, the heat sources in the laboratory tests were

Table 1
Summary of conditions prevailing during the field tests

Test dates in 2006	# of tests	Atmospheric air temperature (°C)	Relative humidity (%)	Mean wind speed (kph)	Weather condition and other remarks
09/28	3	21.1	55	1–6	Cumulus clouds, otherwise bright sun
10/05	3	21.7	31	3.0	
10/19	3	16.1	61	1–2	
10/21	3	9.5	49	2, 6, 13, 24	Blue sky. Very gusty winds. Highly variable wind directions
11/02	4	8.3	75	1–6	Rained prior to the tests. Tests conducted only when the sky was clear; however, gusty and variable direction wind occurred during the tests

physically very close the test subjects resulting in essentially no absorption of the radiant energy in the intervening atmosphere, a situation contrary to that which occurs in the atmosphere for radiant heat from a large fire.

2. Field experiments

This paper describes a series of tests conducted to evaluate the ability of a person in civilian clothing to withstand the "regulatory" level of radiant heat exposure and also to evaluate the effect of ordinary clothing in attenuating the fire radiant heat flux to the skin. The tests were conducted in late 2006 at the field test facility of the Commonwealth of Massachusetts, Department of Fire Services at Stow, MA. Liquefied natural gas pool fires were created in a pre-cooled, 3 m × 3 m × 0.6 m depth dike (with wet sand walls and concrete floor). The test objectives included the determination of (i) the magnitude of attenuation of the incident radiant heat flux by clothing worn by a person, (ii) reduction in transmitted radiant energy when one and two sheet thick newspapers were held in the radiation path, and (iii) durations of tolerance to different levels of radiant heat flux by a person in civilian clothes, without sustaining severe pain or burn injury when exposed to a LNG fire. All of the tests were conducted with the test subjects located at a distance from the fire where the un-attenuated mean radiant heat flux was about 5 kW/m^2. However, in all tests there were temporal variations in the incident heat flux due to flame tilting caused primarily by wind velocity and wind direction variability. A summary of the field tests and the atmospheric conditions prevailing during the tests are indicated in Table 1.

2.1. Tests with mannequins

The tests to determine the clothing attenuation factors (AFs)[1] were conducted using two mannequins, one male and the other female. The difference between the two was in how tight the clothing was on the skin of the mannequins. Fig. 2 shows general view of the clothed and instrumented fiberglass mannequins (two) used in the tests. The clothing on the mannequins consisted of both cotton apparel (outside shirt and undershirt), as well as polyester and cotton mix (65% and 35%, respectively) outer garment. The details of the type, number and thickness of clothing on the mannequins are indicated in Table 2. Each mannequin was instrumented with two wide-angle radiometers mounted on a vertical aluminum bracket affixed to the mannequins below the neck. Each radiometer was the MedTherm Heat Flux Transducer, model # 21037, with heat flux measurement range of 0–12 kW/m^2 and fitted with a 1-mm thick Zn–Se window. One radiometer was mounted just outside the clothing, the sensor element being about 5 cm in front of the skin and the other mounted such that the front surface of the radiometer was flush with the inner garment over it. Fig. 3 shows the details of the mounting and the location of the radiometers on the mannequins. In addition, each mannequin was also instrumented with two type J, Iron-Constantan, thermocouples (with temperature measurement range 32–1000 °F), one just affixed outside and barely touching the outside of the outer garment at chest level and the other inside the inner garment touching the mannequin skin. The data from the thermocouples and the radiometers were fed to a National Instrument Data Acquisition and Control Module (Model # NI-SCXI-1600). The inputs

Fig. 2. General view of the fiberglass mannequins used in the tests.

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[1] Attenuation factor = radiant heat flux incident on the clothing/radiant heat flux behind the clothing.

Table 2
Details of the clothing used on the mannequins and the human subject

Exposed subject	Garment color	Garment fabric	Garment location	Thickness of garment (mm)
Male mannequin	White undershirt	Cotton	Inner	0.320 and 0.292, mean = 0.306
	"US Polo" white, full sleeve shirt	Cotton	Outer	Mean thickness over button flap = 1.041 Mean thickness in other areas = 0.313
	Black, full sleeve shirt	65% polyester and 35% cotton	Outer	0.635 and 0.660 on the button fold, 0.198 and 0.196 on rest of the shirt
Female mannequin	Dark green	60% cotton and 40% modal	Inner	0.259, 0.30, and 0.30, mean = 0.286
	Red, full sleeve shirt	60% cotton and 40% modal	Outer	0.302, 0.363, 0.279, 0.320, mean = 0.316 Collar border thickness = 2.433 mm, width of border = 1 cm
Human (the author)	White undershirt	Cotton	Inner	0.254 mm (mean)
	"Arrow" gray full sleeve shirt	60% cotton and 40% polyester	Outer	Mean thickness over button flap = 0.702, mean thickness in other areas = 0.290
	Light green full sleeve shirt	60% cotton and 40% polyester	Outer	Mean thickness over button flap = 0.676, mean thickness in other areas = 0.272
	Washed light blue jeans	–	Outer	Mean thickness at thigh position = 0.787 mm
	Light brown pants	65% polyester and 35% rayon	Outer	Mean thickness at thigh position = 0.309

into the module were through 32-channel, millivolt signal amplifier (Model # NI-SCXI-1102), which mated with the Channel Isothermal Terminal Block (Model # NI-SCXI-1303). The data acquisition module converted the input millivolt dc signals to digital pulses. The digitized data together with internal clock generated time data were fed to a laptop computer through a USB port and recorded every 0.1 s interval. The digital data were stored and displayed on the computer using the LabVIEW$^{\text{TM}}$ software.

The mannequins were deployed side by side at a distance where the outer radiometer measured about 5 kW/m^2 incident radiation. Fig. 4 shows a snapshot of the location and orientation of the mannequins in front of the LNG fire. Both mannequins were located, side by side, at the same distance from the dike. In general, the mannequins were placed between 8.4 m and 12.2 m from the fire center. The mannequin placement position, relative to the dike was always in the upwind direction from the fire, the optimal location determined in each test by walking towards the fire with a hand-held wide-angle radiometer and finding the position at which the "average" heat flux measured 5 kW/m^2. This placement position varied from test to test because of the wind conditions and flame tilt.

The experimental procedure consisted of filling the dike with LNG up to about 0.5 m depth and letting it evaporate for a while until very low evaporation was noticed. This generally took about 15 min. Then the pool was ignited with a propane

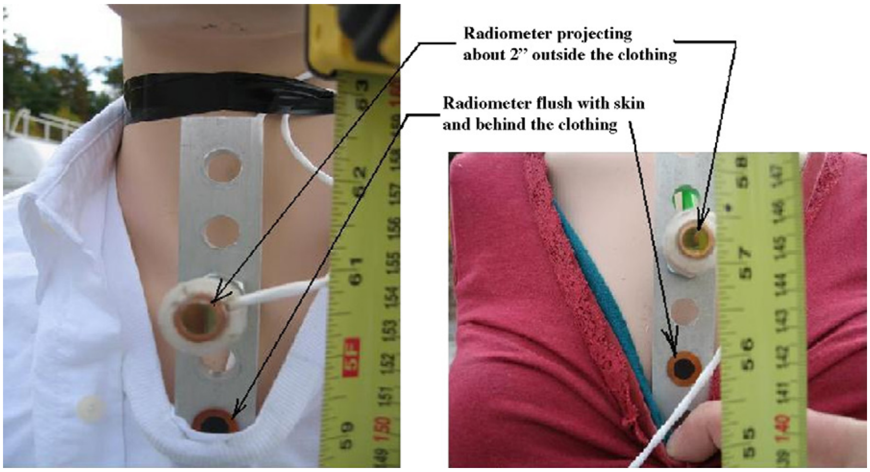

Fig. 3. Details showing the placement of the radiometers on the mannequins behind clothing and outside clothing.

Fig. 4. Mannequins facing the 3 m × 3 m LNG pool fire in an earthen dike.

torch. A fireman in bunker gear carried the held radiometer and approached the fire from the upwind direction and determined the location where the heat flux was in the 4–5 kW/m^2 range. The mannequins were moved to this location and data gathering on the computer was initiated[2].

2.2. *Newspaper masking tests*

The effectiveness of newspaper sheets in providing temporary reduction in the radiant heat flux impinging on an object was also determined experimentally. Single sheet (or double sheets) of size 0.3 m × 0.3 m cut out from a local newspaper was attached by edge-gluing to a wire frame made from coat hanger wire. The newsprint was generally white in color. The newssheet stretched over the frame was placed about 5 cm in front of the outside radiometer on a mannequin, ensuring at the same time that the outside radiometer on the neighboring mannequin was not in the shadow of the newspaper. The thicknesses of newsprint used in the tests and the exposure radiant heat flux levels are indicated in Table 3. Tests were repeated with and without the newspaper to ensure that both outside radiometers were measuring the same heat flux when there was no obstruction in front of them.

2.3. *Tests involving exposure of a person to radiant heat from fire*

During some of the tests the author, wearing ordinary civilian clothing, conducted tests exposing him to the fire[3,4] radiant

Table 3
Thickness of newspaper sheets used and attenuation factors

Test date in 2006	Test #	Overall newssheet thickness (mm)[a]	Averaging time interval for heat flux and attenuation factor statistics (s)	Radiant heat flux (kW/m^2)	Attenuation factor from inner and outer radiometer data		Remarks
					Mean	Standard deviation	
10/19	2A	0.076	22–35	6.22 ± 0.67	3.58	1.74	1 sheet of newspaper
	2B	0.147	48–57	6.54 ± 0.33	4.29	2.04	2 sheets of newspaper
10/21	3A	0.076	66–186	4.1 ± 0.5	5.40	1.00	1 sheet of newspaper
	3B		245–359	4.2 ± 0.4	8.10	1.60	
11/02	2	0.076	0–28.1	4.13 ± 0.45	4.72	0.37	1 sheet of newspaper
	3	0.147	0–41.5	4.3 ± 0.63	11.75	1.43	2 layer newspaper sheets
	4A	0.147	0–189	3.96 ± 0.7	9.10	1.69	2 sheets of newspaper
	4B	0.076	240.3–270	6.37 ± 1.07	5.40	1.00	1 sheet of newspaper

[a] All distances are from the center of the dike. These distances represent the mean values during a test in which the author moved closer to or away from the fire depending upon whether he received less than or higher than 5 kW/m^2 heat flux.

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[2] A table containing laptop and other instruments was generally set up at about 15 m in the upwind direction. The personnel that manned this table wore the firemen bunker gear as a matter of safety and to comply with the rules of the facility. The heat flux measured at the instrument location never exceeded 2 kW/m^2. In later tests, these personnel removed their head gear without any adverse effects.

[3] This was approved by the site authorities after stipulating that in each test the author would be accompanied, very next to him, by a fireman in full bunker gear.

[4] In none of the tests did the author suffer any injury of even severe “burn” pain. In addition, he was always accompanied on the side by a fireman in full bunker gear to provide assistance in case of need, which never occurred.

Fig. 5. Hand-held radiometer and illustration of its use in the tests.

heat flux at levels close to 5 kW/m^2. In the first few tests only a hand-held radiometer was used. This wide-angle radiometer was capable of displaying on a LCD screen the current level of incident radiant heat flux (in W/m^2 units), but had limited capability to record, digitally, the data history once every 10 s. The use of this hand-held radiometer is illustrated in Fig. 5. In subsequent tests, the author strapped upon the mounting bar with the two radiometers from one of the mannequins, which were connected to a computer to record the heat flux values in intervals of 0.1 s. The recording radiometer arrangement on the author is shown in Fig. 6. In addition, the author had thermocouples affixed to him with duct tape at chest level; one on to the outside of his shirt almost touching the cloth surface, one affixed to his skin and a third thermometer dangling in the air 1 cm above the shirt surface.

The test procedure consisted of the author walking towards the fire from the upwind direction with the hand-held radiometer in hand and monitoring its reading. He would go up to the location where the hand-held radiometer read a value close to 5 kW/m^2. An illustration of this condition is provided in Fig. 7. Because the wind conditions changed continuously (both in direction and magnitude), and consequently the flame tilted in different directions, the heat flux to the author was never constant. Therefore, he had to move closer or away from the fire, as fast as the reading on the hand-held radiometer was changing, to maintain as closely as possible the 5 kW/m^2 level. This was not easy and the author could not keep pace with the rapid changes of heat flux. Many times the author was exposed to levels higher than 5 kW/m^2 and other times to less than this value. The “test” ended when any one of the following conditions occurred; (i) the wind shifted towards the author and increased the heat flux to levels he could not bear (>7 kW/m^2) for durations greater than 10 s, or (ii) he started feeling very hot, or (iii) he was able to withstand the heat flux for times significantly longer than 30 s.

Fig. 6. Illustration of the placement of recording radiometers on the author.

Tests were conducted with full sleeve shirt (both white and green colored), half sleeve shirt (white), denim pants (blue and brown) and white undershirt (in all tests). No eye glasses were worn and tennis shoes were used. The details of the clothing worn by the author are also indicated in Table 2.

The parameters varied in the mannequin exposure tests included, single layer clothing, double layer clothing, and the use of newspaper sheets to mask the radiometer in front of one of the mannequins. The view of the inner radiometer, behind the under shirt was also varied; in some cases this was through the two thin cloth layers of the inner and outer garment, and in other cases it was through the thin inner garment and through

Fig. 7. Author located at about 10 m from fire center holding the hand-held radiometer: fireman’s raised arms indicate the reading by the radiometer to be 5 kW/m^2.

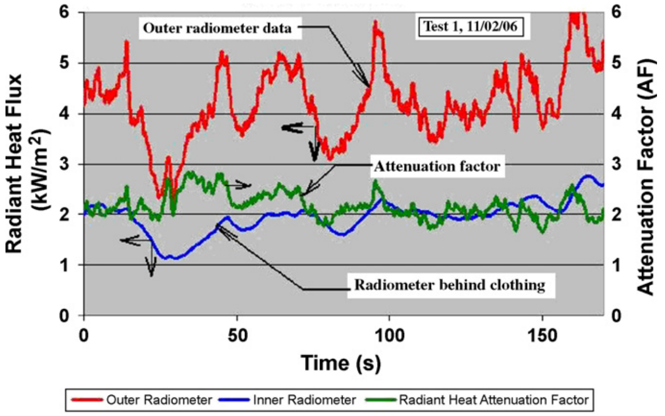

Fig. 8. Radiant heat flux behind and in front of two-layer clothing in series (on the male mannequin) and attenuation factor variation with time.

the thick, button flap part of the outer garment. The author's exposure tests were conducted simultaneously with mannequin exposures. Complete details of the test conditions, the parameter varied in each test, the time of the day when the test was conducted, the duration of the test, etc. information is available in a technical report to the sponsors (Raj [22]).

3. Test results

3.1. Attenuation by clothing

Table 4 provides the details of the types of clothing used, number of layers, mean exposure radiant heat flux level, mean and standard deviation of the calculated AF and other results related to the tests with clothing on mannequins exposed to the radiant heat flux from LNG fires. A typical time trace of the readings of the outer and inner radiometers for double layer clothing when the view of the inner radiometer was through "thin sections of the clothing" is shown in Fig. 8. The results from the same test, when the inner radiometer is viewing through the thicker button flap of the outer garment, are shown in Fig. 9. It is seen that the average AF is 2.17 when viewed through two thin layers of clothing and 3.74 when a thicker section of the clothing is obstructing the inner radiometer view. A complete set of time trace data from the inner and outer radiometers for each of the tests conducted are available in Ref. [22]. Also indicated in Ref. [22] are the least square fit correlations for the AF with clothing thickness. The results in Table 4 for the AF indicate that it can vary from about 2–4 depending upon the total thickness of clothing and the air gap between the clothing. Unfortunately, the air gap was not controlled in these experiments nor was it measured.

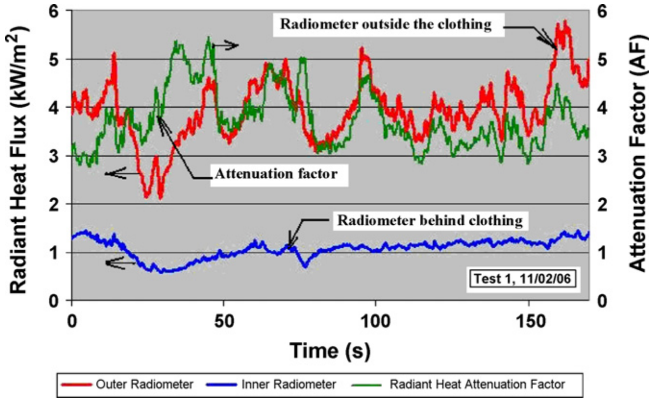

Fig. 9. Radiant heat flux measured by the radiometer behind the inner clothing (of female mannequin) viewing through the thick button flap section of the outer clothing.

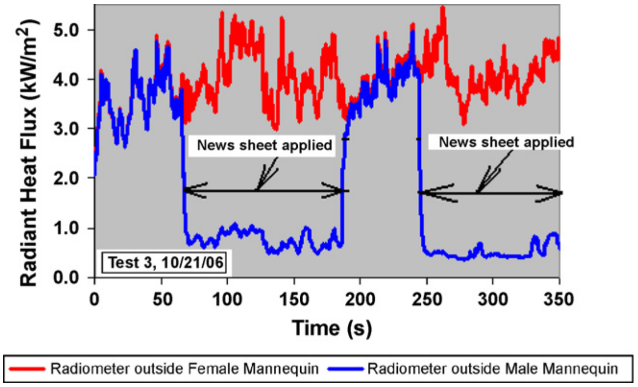

Fig. 10. Attenuation of radiant heat flux by a single sheet of newspaper (0.076 mm thick) held 5 cm in front of radiometer. Both radiometers at the same distance from fire.

3.2. Newspaper masking results

The results for attenuation of radiant heat flux by single and double sheets of a newspaper are indicated in Table 3. A typical time trace of the two radiometer data (one masked by a newssheet and the other not masked) are shown in Fig. 10. It is seen that the AF value for single sheet has an average 5.4 ± 1.7 and 8.4 ± 3.8 for double sheets. The AF is correlated with newssheet thickness and the magnitude of the incident radiation by (plot of data is presented in Ref. [22])

$$\mathrm{AF(newspaper)} = 6.528 + 30.423t - 0.68q \qquad (1)$$

where AF = attenuation factor by newspaper sheet, t = newssheet thickness in millimeters, q = radiant heat flux in kW/m^2 incident on the sheet.

It is clear from the data that even a single sheet of newspaper held in front of a person provides significant reduction in the radiant heat impinging on the subject. During the tests the highest intensity of heat flux to which the newspaper sheets were exposed was 6.5 kW/m^2. The exposure for a long duration (>300 s) at an average heat flux of about 4.5 kW/m^2 did not result in the newspaper sheet catching on fire or showing any discoloration; however, the sheet felt "hot" to touch after the long exposure.

3.3. Human exposure results

3.3.1. Qualitative information

In all of the tests the author did not experience severe pain or any type of burn on the exposed parts of the skin when he

Table 4
Attenuation factors for clothing of different (combined) thicknesses at different exposure levels

Test date in 2006	Test #	Mannequin type	Inner radiometer view through	Overall clothing thickness (mm)[a]	Averaging time interval for heat flux and attenuation factor statistics (s)	Mean outside radiant heat flux (kW/m^2)	Attenuation factor (AF) from inner and outer radiometer data		Remarks
							Mean	Standard deviation	
9/28	1	Male	Inner and outer clothing over the belly. View through outer button flap	1.347	0–100	2.0	5.73	0.76	Normal air gap between inner and outer clothing
	2			1.347	0–20	1.0	7.11	0.68	
	1	Female	Inner and outer clothing over the belly. View through thinner parts of both clothing	0.602	0–100	2.0	2.33	0.20	Inner & outer clothing layers very close and tight. Inner radiometer bulging on the two clothing.
	2			0.602	0–20	1.0	1.97	0.64	
10/5	1	Male	Double layer clothing. Inner radiometer view through the outer shirt button flap	1.347	15–300	3.92 ± 1.1	2.86	0.50	Radiometers at chest level
	2			1.347	0–40	3.75 ± 0.31	3.23	0.29	
	3		Only outer shirt. View through button flap.	1.041	0–120	2.97 ± 1.41	2.71	0.65	
10/19	2	Male	Only inner white undershirt used. View through thin part of clothing	0.306	0–70	6.81 ± 0.94	1.71	0.46	Radiometers at chest level
	2	Female	Only inner green undershirt used. View through thin part of clothing	0.286	0–70	6.81 ± 0.94	1.76	0.13	
10/21	1	Male	Black outer + white under shirt. Two thin parts of the clothing in series	0.503	0–290	3.9 ± 0.7	2.60	0.30	Radiometers at chest level
	2		White undershirt only	0.306	0–250	3.8 ± 0.6	2.20	0.30	
	3			0.306	0–66	3.6 ± 0.5	2.60	0.50	
	1	Female	Black outer + green under shirt. View through button flap of outer black shirt.	0.931	0–290	4.2 ± 0.7	5.40	1.50	Radiometers at chest level
	2		Green undershirt only	0.286	0–250	3.9 ± 0.6	3.60	1.00	
	3			0.286	0–350	4.0 ± 0.6	2.90	0.80	
11/2	1	Male	Double layers. View through thin parts of the clothing	0.619	0–170	4.21 ± 0.73	2.17	0.25	Radiometers at chest level
	2			0.619	0–50	4.49 ± 0.3	2.05	0.14	
	3			0.619	0–55	4.68 ± 0.87	2.34	0.22	
	4		Single outer shirt only. View through the thin part of the shirt	0.306	0–300	4.16 ± 1.14	1.91	0.14	
	1	Female	Double layers. View through collar border thickness on outer and thin part of the inner clothing	2.719	0–170	3.93 ± 0.64	3.74	0.61	Radiometers at chest level
	2			2.719	28–50	4.13 ± 0.45	4.31	0.62	
	3		Double layer clothing. View through thin parts of the clothing	0.619	41.5–55	5.36 ± 0.21	5.35	0.44	
	4		Single layer outer red shirt only. View possibly changed during test, initially through the collar flap and later through the thin part of the clothing	0.316	0–15.5	3.7 ± 0.46	2.57	0.58	

[a] All distances are from the center of the dike. These distances represent the mean values during a test in which the author moved closer to or away from the fire depending upon whether he received less than or higher than 5 kW/m^2 heat flux.

was exposed to the radiant heat from the fire. Each test was conducted with the author wearing a full sleeve shirt (and in two tests with a half sleeve shirt), undershirt and a full length pant. It was very difficult to maintain the incident heat flux level at or near 5 kW/m^2 because of shifts in wind velocity and direction, and the consequent (fast response) fire plume tilt both in direction and magnitude. Also, in some cases the natural turbulence created by the fire itself resulted in burst of energy in different directions. The human response action considerably lagged behind the variations in the heat flux at any given point, even though the author made an effort to maintain the reading on the hand-held radiometer as close to 5 kW/m^2 as possible. In some cases, he was exposed to short bursts of heat flux (for 3–5 s) as high as 7 kW/m^2 and in other cases to as low as 3.5 kW/m^2.

When exposed to relatively prolonged durations (of the order of 20 s) to heat flux levels close to 5 kW/m^2 the sensation of heat was close to what one experiences when standing close to (say, 1 m) and in front of a well established fire in a home fireplace. Heat flux levels of 6.5 kW/m^2 and higher resulted in a sensation of pain on the unprotected skin within duration of the order of 10 s. Even when exposed to long durations (of the order of 50 s) at levels equal to or less than 4 kW/m^2 or for durations slightly less than 30 s at 5–7 kW/m^2 no feeling of heat was felt on the skin protected by clothing. However, the body began to sweat resulting in the maintenance of the body temperature at the normal human temperature (37 °C).

Exposure for short intervals (of the order of tens of seconds) of time followed by very short time (less than a minute) away from the radiant heat flux levels of 3–5 kW/m^2, followed by another session of exposure to the fire, resulted in less tolerance to the radiant heat flux (both magnitude as well as duration). What the author noticed was repeated exposure without insufficient "cooling" time after each exposure resulted in the outer clothing getting 'hot' and the ability to withstand heat flux levels of 4–5 kW/m^2, lower. These observations are supported by documented data from the radiometers and thermocouples indicated below.

The author's skin on the gullet became red in the final test by repeated exposure to the fire and the irritation due to this "redness" persisted for about 30 min after the completion of the test. There were no other temporary or permanent damage or skin injuries to the author, even though the exposures were repeated several times in one fire test (without, as noted above, any prolonged cool down period) to levels as high as 4 kW/m^2 and with bursts of 5 kW/m^2 or 6 kW/m^2 and exposure times measured in 30–50 s.

3.3.2. Hand-held radiometer data

The hand-held radiometer data manually recorded after each test, based on the memory of the author of the number he saw on the display screen on the radiometer, are shown in Table 5. Location of the author relative to the fire, flame heights and the exposure time were obtained from the video records of the tests. The range of heat fluxes indicated show the minimum and maximum displayed on the screen and do not necessarily indicate how long such levels were experienced. In some tests the digital output of the hand-held radiometer was recorded on a computer; however, these proved to be not useful since the recording software could only record once in 10 s the value averaged over the 10-s interval. The hand-held radiometer was however, very useful in the author locating himself, in real time, to those distances where the flux level was as close to 5 kW/m^2 as he was able to achieve.

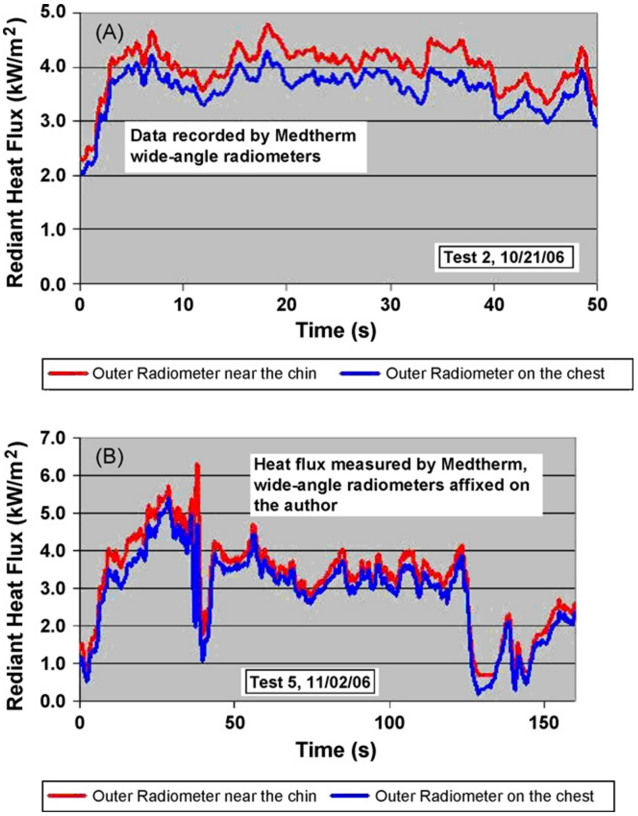

Fig. 11. (A) Author's exposure to radiant heat flux from a LNG fire, Test 2, 21 October 2006. (B) Author's exposure to radiant heat flux from a LNG fire, Test 5, 02 November 2006.

3.3.3. Data from fast response radiometers strapped on to the author

Two sample records of real time data on heat flux incident on the author, recorded by the Medtherm wide-angle radiometers strapped on to the author (see Fig. 6) when exposed to the radiant heat flux from the LNG fire, are shown in Fig. 11A and B. Each figure refers to a different test. It is seen that in each of these tests the radiant heat flux is well above 3.5 kW/m^2, and in spurts above 5 kW/m^2 and the durations are significantly longer than 30 s. No unbearable pain, injuries, skin burns or skin blisters were experienced by the author, anywhere on his exposed skin surfaces.

3.3.4. Thermocouple data

Fig. 12 shows a comparison of the skin temperature recorded on the author's skin and on one of the mannequin's skin (both behind two layers of clothing) when both the author and the mannequin were located at the same distance from the fire and exposed to the same radiant heat flux. It is seen clearly that in the case of the author, the temperature of his skin was always below

Table 5
Hand-held radiometer data on human exposure to radiant heat

Test date in 2006	Exposure session #	Mean flame height (m)	Location of human subject[a] (m)	Mean radiant heat flux and range (kW/m^2)	Exposure duration[b] (s)
09/28	1	5.1	12	2.2 [2.1–2.9]	53
	2	4.2	8	4.4 [3.8–5.8]	17
	3	5.1	10.5	2.2 [2.7–5.8]	60
	4	5.9	11.0	2.2 [2.0–3.0]	103
	5	5.5	7.9	4.4 [3.8–6.0]	22
	6	4.3	7	4.4 [3.8–5.8]	21
	7	5.5	7.9	2.2 [2.0–3.2]	120
10/05	1A	7.2	9.3	5.0 [4.9–6.2]	26
	1B	7.1	12.2	5.03 [4.0–8.0][c]	93
	2	6.6	11.1	5.0 [4.5–6.0]	42
	3	5.5	8.7	5.0 [4.9–6.2]	24
11/02	1	6.7	9.7	5.0 [4.9–6.2]	57
	2	5.0	9.3	5.0 [4.9–6.2]	16
	3	5.1	8.4	5.0 [4.9–6.2]	32
	4	5.0	8.8	5.0 [4.9–6.2]	20
	5	4.7	9.1	5.0 [4.9–6.2]	31

[a] All distances are from the center of the dike. These distances represent the mean values during a test in which the author moved closer to or away from the fire depending upon whether he received less than or higher than 5 kW/m^2 heat flux.

[b] No injury of any kind was sustained by the author exposed over the duration indicated in the table.

[c] Based on measurements on the mannequin radiometer next to the author.

38 °C whereas the temperature of the mannequin "skin" climbed up to 60 °C. It should be noted that the exposure times were quite long (350 s). The mean heat flux over this duration of exposure was about 4 kW/m^2. This difference in the ultimate temperature rise is clearly due to the active cooling mechanism in a human being (such as increased blood circulation and sweating) which are absent in the mannequin.

4. Discussions

This paper has discussed the results from several tests conducted in the fall of 2006 to study the effectiveness of normal civilian clothing in providing protection against radiant heat flux from a fire as well as determining the human tolerability of the heat flux values used in safety analysis, namely, 5 kW/m^2. Also, indicated are the results from tests on the effectiveness of shadow of ordinary objects in providing relief, albeit temporarily, from the harmful effects of radiant heat from a fire. Most of the tests with clothing discussed in the literature dealt with the protection against very high heat fluxes and temperatures, essentially for designing the protective clothing for firemen. No systematic study of the civilian clothing's effectiveness to provide safety to the ordinary population from relatively low level heat radiation was available.

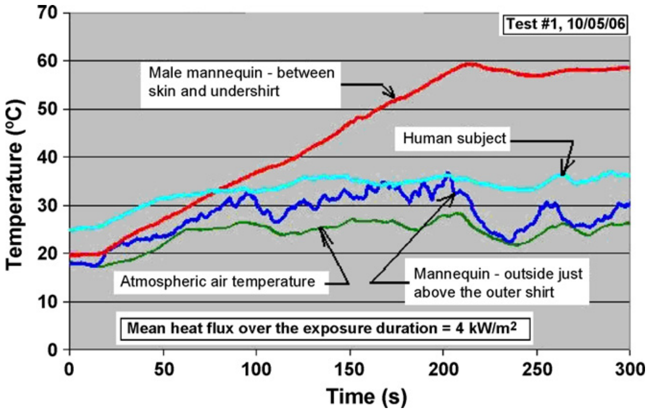

Fig. 12. Skin temperature increase in a person and a mannequin during exposure to radiant heat from a LNG fire.

All other experiments on the effect of radiant heat on human beings were conducted either in a laboratory setting with artificial heat sources and small skin exposure areas, or with skin simulants and anesthetized animals. No direct exposure of a person to the heat from fire had been conducted under controlled and instrumented conditions. The tests indicated in this paper have over come both limitations that were prevalent in the scientific knowledge. All radiant heat conditions simulated in these tests are similar to those that the general population may be exposed to, at a plant boundary, due to a large accidental fire in a LNG facility. Further more one of the objectives of the test was to experimentally determine the veracity of concern that exists in the minds of many citizens that 5 kW/m^2 heat flux level for safety represents too high a level and at this level people exposed even for a short duration would experience severe burns and other injuries. There have been suggestions in regulatory hearings that this safety level should be reduced to as low as 1.5 kW/m^2. It is hoped that the results from the series of tests discussed in this paper should put to rest these concerns, once and for all.

Good data have been obtained for the conditions investigated in the tests. However, not all combinations or ranges of parameters that could be varied were investigated, due to obvious time and resource constraints. For example, the extent of clothing coverage on a person's body, the number of layers and the type of clothing depend to a great extent on the local climactic and weather conditions; beach goers in summer are scantily clad whereas in mid winter many more layers of clothing can be seen on a person than were used in these tests. In these tests only one set of civilian clothing purchased, at random, from a department store, were used. The clothes used probably represent the normal attire of a significant percent of the population under "average" weather conditions. Similarly, the effect of variable temperature of the atmosphere could not be studied because of the relatively short duration of the test period. Last, but not the least, the ability of different persons (by age, sex, health and other people distinguishing characteristics) could not be studied.

In the tests reported in this paper the tolerance to radiant heat from a fire by persons of different skin pigmentation was not studied. However, Hardy et al. [11] indicate, based on laboratory tests with skins of different pigmentation, that in the spectral range of wavelengths 1–2.4 μm, white and dark skins have essentially the same optical characteristics in the infra red region. Therefore, the effect on both the white skin and the dark skin is the same in the response to radiant heat from a LNG or similar fire. It is noted that the peak spectral radiance of a large LNG fire occurs at about 1.8 μm (Malvos and Raj [7]). This wavelength of the peak spectral emission from a LNG fire is almost mid way between the IR limits studied by Hardy et al. [11]. The fraction of the total energy output from the fire between 1 μm and 2.4 μm is significant. Also in this spectral wavelength region there is very little absorption in the atmosphere, whereas a substantial fraction of the energy in the wavelengths beyond 2.6 μm gets absorbed (depending upon the path length) in the atmosphere. That is, the human tolerance to radiant heat from a fire is largely dependent upon the energy content in the 1–2.4 μm wavelength band, in which range, there is no difference in IR absorption characteristics between skins of different color. Therefore, without loss of generality, it can be surmised that if a person is able to withstand a given level of radiant heat flux from a fire, all other persons, irrespective of their skin color (which represents reflectivity in the visible light) can tolerate the same level of IR heat flux.

Based on the tests conducted and the results there from, the following findings can be made.

(1) Ordinary civilian clothing, even a single layer clothing, provides a factor of, at least, 2 reduction in the magnitude of radiant heat flux reaching a person's skin for relatively long term exposures (of the order of minutes) at an exposure level of 5 kW/m^2 or close to it. The radiant heat AF increases with increase in overall thickness (and probably with the intermediate air gap) but decreases with increased heat flux impinging on the clothing. These results are valid for incident heat flux values near 5 kW/m^2.
(2) Any object that intervenes between the heat flux source and a person or an element receiving the heat flux results in a substantial decrease in the heat flux to the person or the element. The intervening object could be as thin as a single sheet of newspaper. A single sheet of newspaper held in front of and close to a person results in a factor of 4 decrease in the radiant heat felt by the person.
(3) A person with ordinary civilian clothing can, relatively easily, withstand incident heat flux levels up to 5 kW/m^2 for at least 25–30 s without experiencing unbearable pain, permanent injury/skin burns or skin blisters.
(4) At 4 kW/m^2 radiant heat flux level a person can be exposed for as long as 60–120 s without feeling either severe pain or suffering any skin burns.
(5) Repeated exposure to the radiant heat exposure–time combination without any appreciable time interval to cool the person's clothing or skin between exposures will result in reduced tolerance time. However, at the 4–6 kW/m^2 levels the ability to withstand the heat, initially, does not decrease.
(6) The temperature measured on the skin of a fiberglass mannequin exposed to radiant heat does not provide a representation of the temperature attained by the skin of living human being. The human temperature remains relatively constant at the normal body temperature due to intervention of the human body temperature regulation system (which is absent in a mannequin).

The above findings are very conservative in that the durations of tolerance of a given magnitude heat flux without any pain or injury are in many tests longer than indicated above. Similarly, the AFs of clothing and of intervening objects have also been observed at higher levels than has been indicated in the findings.

5. Conclusions

(1) The author has demonstrated with the test data that a normal adult can easily withstand, without severe pain or injury, a radiant heat flux level of 5 kW/m^2 for much longer than current literature numbers (for unbearable pain) and up to almost 30 s without skin burns/blisters. At lower heat flux values these "tolerance" times are significantly longer. Therefore, the current criterion for public safety in the US regulations and standards for public exposure to radiant heat from LNG fires (5 kW/m^2 for 30 s exposure) is very conservative and represents a value with a reasonable level of factor of safety.
(2) The current regulatory criterion is, perhaps, based on exposure of bare skin. All human beings in a civilized society are clothed, and serious injury to skin depends not only on the level of heat flux and time of exposure but also on the percent of a person's skin area that is exposed to the heat. As seen from the results of this investigation, even thin clothing on the skin provides a reduction of heat flux (to the skin) by a factor of 2–3. Hence, when the heat flux level outside the clothing is, say, 5 kW/m^2, the skin will feel only about 1.67–2.5 kW/m^2, a level that can be easily withstood over a duration of hundreds of seconds.
(3) Very simple and even single layer clothing and other simple objects provide significant reduction in radiant heat flux to the skin of a person. The reduction in the heat flux levels by single layer of clothing can amount to a factor of 2 or 3. Newspaper sheets in front of the face or hands can reduce the heat flux levels by factors of 5 or more. Opaque objects, such as buildings and solid objects provide even more protection.

(4) The temperature increase of skin protected by clothing on a person when exposed to an external radiant heat flux of about 5 kW/m^2 is small. In the tests conducted the author's skin temperature behind the inner clothing never was higher than 38 °C. Generally, mannequins can be used as a substitute for live human tests to determine the effectiveness of clothing to reduce radiant heat flux to the skin. However, mannequins cannot act as a substitute when determining the skin temperature rise in a person from to exposure to radiant heat flux, because the human physiology of skin cooling is completely and drastically different from that in a mannequin. A mannequin skin, generally part of the fiberglass body, does not conduct heat. Also in a mannequin there is no mechanism of heat removal by internal cooling or sweating as in the case of a human being.

(5) In a clothed person the area of skin exposed to the elements is generally less than about 15%. Because of this small "bare" fraction, in a situation of exposure to radiant heat from a fire the human physiological systems may work to reduce the effect of the heat flux on the exposed part of the skin by carrying away heat and initiating other protective mechanisms, such as sweating. That is, a partially clothed human body may withstand a higher overall heat flux exposure than a completely naked body.

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