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ScienceDirect

Journal of Hazardous Materials 159 (2008) 61–71

Journal of Hazardous Materials

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# A review of the criteria for people exposure to radiant heat flux from fires

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Received 29 July 2007; accepted 16 September 2007
Available online 7 October 2007

**Abstract**

The NFPA 59A Standard and the Federal Regulation, 49 CFR Part 193, stipulate a level of 5 kW/m$^2$ as the criterion for determining the hazard distance to people exposure from a LNG fire. Another regulation (24CFR, Section 51.204) while stipulating a lower exposure limit of 1.42 kW/m$^2$ provides administrative relief from the regulation if mitigation measures are provided. Several countries in Europe and the Far East have adopted both a specified heat flux value (generally, 5 kW/m$^2$) as well as modified dose criteria for human exposure hazard calculation in risk assessments. In some cases, the regulations in Europe require the use of lower values for children and physically challenged persons.

This paper reviews the available literature on the phenomenon of skin burn caused by radiant heat exposure. The associated thermal and spectral properties of human skin are reviewed. The basis for regulatory setting, of 5 kW/m$^2$ and other exposure criteria (as a part of hazard and risk calculations) for evaluating distances to hazards from the exposure of people to radiant heat effects of large fires, is evaluated. An example calculation is provided to show the extent of reduction in the hazard distance to specified radiant heat flux from a fire when the spectral reflection and absorption properties of skin are considered with and without the inclusion of the mitigating effects of clothing. The results indicate that hazard distances calculated including the reflective and band absorptive properties (in IR wavelength) of skin results in a reduction of between 30 and 50% in the hazard distances obtained with current methodology, which ignores these effects. Unfortunately, there are no test results, from full-scale human-exposure-to-IR radiation, with which these predictions can be compared.

*Keywords:* Radiant heat flux; Skin burn; People exposure; Thermal exposure hazards; Regulatory fire exposure criteria

## 1. Introduction

In the U.S. several applications for the development and construction of a number of on-shore and off-shore LNG import terminals have been submitted, respectively, to the Federal Energy Regulatory Commission (FERC) and the US Maritime Administration (MARAD), which are the principal regulatory agencies in the US for permitting LNG storage terminals. These applications have triggered renewed attention of potential hazards from accidental or intentional (by terrorist actions) LNG releases. One of the principal concerns, in the minds of the public as well as the regulatory agencies, is the potential exposure of people to the radiant heat effects of a large LNG fire arising from LNG releases. A number of hazard assessment studies have used very conservative theoretical models for LNG release and subsequent fire behavior (Hightower et al. [1], FEIS/EIR on Cabrillo Port [2], DFEIS on Long Beach [3]). These studies have concluded that damaging "heat effect" on people may occur as far as 1600 m from the fire center. In many highly populated areas of the US this extent of hazard area will encompass several thousands of people. Unfortunately, these models and calculations have not used realistic conditions, either for the characteristics of very large pool fires or for the conditions of people exposure to evaluate potential thermal injury to human beings from radiant heat from such fires. These assessments are based on a single criterion of human exposure, namely, 5 kW/m$^2$ heat flux level. The distance at which this level of heat flux occurs is considered to be the distance at which human beings will suffer serious skin burn injury. In these distance assessments there have been no consideration of other parameters such as the "quality of the heat flux," exposure time, the effects of obstructions in the path of the radiant heat, effects of clothing on a person, the radiant

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doi:10.1016/j.jhazmat.2007.09.120

heat reflecting and absorbing properties of a living, “average” skin, the effects of actions of persons exposed to radiant heat in seeking shelter, etc.

The purpose of this paper is to review (i) the different standards and regulations that are currently in effect for determining radiant heat exposure hazards to people from fires, (ii) the hazard heat flux or heat dosage criteria and the bases for their values, (iii) the literature on human skin and its physical and thermal properties as they apply to the determination of radiant heat injury, (iv) the “spectral quality” of the heat flux from a LNG fire, especially, at considerable distances from the fire and (iv) the effects of other objects and clothing intervening between the fire and the human receptor of heat. In addition, an approach is indicated in a model to estimate, more realistically, the potential hazard distances by using the parameters that mitigate the effect of incident heat flux on people.

Most of the discussion is related to LNG fires simply because of the availability of accurate data on spectral emission and other carefully measured characteristics of these fires. However, the methodology of determination of the hazard distance at which serious skin burns may occur due to radiant heat exposure is equally applicable to other types of fires provided sufficient data are available to estimate the spectral emission characteristics from such fires.

## 2. Thermal exposure criteria in standards and regulations

### 2.1. NFPA 59A

The National Fire Protection Association’s LNG Standard, NFPA 59A [4], applicable to siting on-shore LNG facilities, includes requirements for calculating the extent of “thermal radiation flux limit” areas around the facilities, arising from LNG fires caused by “design spill” or impoundment fire conditions. Table 1 shows these requirements. 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. For outdoor exposure of people the limiting heat flux is 5 kW/m$^2$. A review of the history of this standard indicates that this “human exposure thermal hazard heat flux” was incorporated for the first time into the NFPA standard in its 1979 edition. The justification provided for introducing the 5 kW/m$^2$ criterion was that (it) “*. . . limits the allowable radiation at the property line from such spills to a level below that considered hazardous to life . . .. It is recognized that persons in outdoor open area would intercept a greater level of fire radiation than would be the case for persons inside buildings . . .. Therefore, a limit is set for outdoor exposure at places of moderately large group or assembly below the level considered hazardous to life*.” Unfortunately, no additional information is provided as to what constitutes “hazard to life” when exposure to thermal radiative heat flux is involved.

Table 1
Thermal radiation flux limits to property lines and occupancies in NFPA 59A

| Thermal radiation flux (kW/m$^2$) | Exposure |
|---|---|
| 5 | A property line that can be built upon for ignition of a design spill |
| 5 | The nearest point located outside the owner’s property line that, at the time of plant siting, is used for outdoor assembly by groups of 50 or more persons for a fire in an impounding area |
| 9 | The nearest point of the building or structure outside the owner’s property line that is in existence at the time of plant siting and used for assembly, educational, health care, detention and correction or residential occupancies for a fire in an impounding area |
| 30 | A property line that can be built upon for a fire over an impounding area |

*Source*: NFPA [4].

### 2.2. API 521

American Petroleum Institute standard-API 521 [5], which references many other standards in its specifications (including those published by the NFPA), specifies the permissible thermal radiation levels applicable to the design, installation and operation of pressure relieving and depressurizing systems, such as flares. Flares are continuously run operations at facilities that utilize them for safe disposal of flammable waste gases. Table 2 indicates the API 521 specified, safe heat flux levels for different conditions of exposure. API 521 specification for tolerable heat flux level (indicated in Table 2) for emergency actions lasting several minutes (approximately 5 kW/m$^2$) will mean that the time to reach the pain threshold is on the order of 16 s. API 521 suggests that in emergency releases, a reaction time of 3–5 s followed by the lapse of an additional 5 s before an average

Table 2
Recommended values for permissible radiant heat flux levels in API 521

| Permissible design level (kW/m$^2$) | Conditions |
|---|---|
| 15.97 | Heat intensity on structures and in areas where operators are not likely to be performing duties and where shelters from radiant heat is available (for example, behind equipment) |
| 9.46 | At any location to which people have access (for example, at grade below the flare or a service platform of a nearby tower) in the event of a design flare release. Exposure should be limited to few seconds, sufficient for escape only. |
| 6.31 | Heat intensity in areas where emergency actions lasting up to 1 min may be required by personnel without shielding but with appropriate clothing |
| 4.73 | Heat intensity in areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing |
| 1.58 | - At any location where personnel with appropriate clothing may be continuously exposed in a design flare release condition |

*Source*: API [5].

individual could seek cover or depart from the area. Hence, an average individual would react to an emergency release before feeling pain at the heat flux levels prescribed in API 521 or by NFPA 59A. API 521 suggests a tolerable level of 6.3 kW/m$^2$ for situations in which emergency actions lasting up to 1 min may be required by personnel without shielding but wearing "appropriate" clothing. This level may be the tolerable exposure heat flux level for the public in an emergency involving LNG fire radiant heat. This is because, the public will not continue to congregate in an emergency situation; they will evacuate and seek shelter. The above API 521 criterion for radiant heat flux is higher than the 5 kW/m$^2$ level for public protection specified in NFPA 59A.

### *2.3. 49 CFR Section 193.2057 (US DOT regulations [6])*

The thermal radiation protection requirements in the US DOT regulations in 49 CFR, part 193 are applicable to on-shore LNG terminals. These regulations specify, to a great extent, the same requirements as in NFPA 59A, by reference. That is, the people exposure heat flux criteria are the same as in NFPA 59A, 2001 edition. These regulations do not provide any relief in the calculation of the hazard distance from a potential fire due to mitigating circumstances or specific emergency response action.

### *2.4. 24 CFR, Section 51.203 et seq. ("HUD" regulations [7])*

The Housing and Urban Development (HUD) regulations are applicable to siting HUD-assisted residential projects. The project is required to be located at a distance greater than the separation distance (based on tolerable heat flux) or be provided with mitigation measures to minimize the potential blast or thermal radiation effects on the project from fuel or other hazardous substance storage tanks or systems either within the property boundary or outside the project area. These regulations may not be applicable to LNG terminals or LNG ships that may be next to the HUD projects since the locations of such terminals are regulated by 49 CFR, part 193 regulations. However, since LNG is listed as one of the "storage" fuels for HUD projects, its requirements (for storage within the project boundary) are discussed below. In these regulations, the allowable thermal radiation flux level for outdoor, unprotected facilities or areas of congregation is required not to exceed 1.42 kW/m$^2$ (450 Btu/h ft$^2$), which is slightly lower than 1.5 times the peak solar heat flux on earth's surface. It is interesting to note, however, that the HUD regulations recognize the protective value of obstacles and structures. Section 51.205 of these regulations lists a number of mitigating circumstances, which if present, could be utilized in "eliminating or modifying" the application of the requirements in these regulations. The scientific foundation for the 1.42 kW/m$^2$ (450 Btu/ft$^2$/h) as the safe radiant heat flux level for exposing people specified in HUD regulations is not known. One document in the literature (SFPE [8]) indicates that even for long duration of exposure at1.7 kW/m$^2$ (540 Btu/ft$^2$/h) pain will not be experienced. This pain "threshold" value is approximately 0.3 kW/m$^2$ (90 Btu/ft$^2$/h) more than specified in the HUD regulations for safe exposure.

Table 3
Allowable thermal radiation flux (excluding solar radiation) outside the boundary, EN 1473, Table A.2, European regulations

| Outside boundary | Description of the area | Maximum thermal radiation flux (kW/m$^2$) |
|---|---|---|
| Remote area | An area only infrequently occupied by small numbers of persons, e.g. moor land, farmland, desert | 8 |
| Critical area | This is an unshielded area of critical importance where people without protective clothing can be required at all times including during emergencies, or an urban area (defined as an area with more than 20 persons per square kilometre) or a place difficult or dangerous to evacuate at short notice (e.g. hospital, retirement house, sports stadium, school, outdoor theatre) | 1.5 |
| Other areas | Other areas typically include industrial areas not under control of the operator/occupier of the LNG facilities | 5 |

*Source*: EN 1473 [9].

### *2.5. EN 1473, European Standard [9]*

This is primarily a risk-based standard in which both the probabilities of occurrence of events and the respective consequences are considered. The limiting criteria indicated in this standard for safe exposure of people to radiant heat are the parameters of interest to this paper. The specifications for safe heat flux levels for different types of exposure are indicated in Table 3. It is seen that a level of 8 kW/m$^2$ is specified for areas infrequently occupied by few persons, 5 kW/m$^2$ for industrial areas and 1.5 kW/m$^2$ for unshielded area of critical importance where people without protective clothing could be exposed. The standard allows consideration of the ability of the person exposed to take evasive action or is capable of initiating some protective/mitigative measures. It is noted that the above thermal radiation exposure threshold criteria are used for the purposes of risk assessment. Acceptability of the plant is not based solely on how many persons of a given group are exposed to specified levels of heat flux. Decisions are made on the basis of the *overall risk*.

Clearly, the thermal heat flux level of 1.5 kW/m$^2$ specified in the EN 1473 is among many other threshold levels specified in the Standard to be used in conjunction with risk assessment taking into consideration exposure to different types of populations. The 1.5 kW/m$^2$ is an injury criterion for a specific type of population and not a fatality criterion. Considerations of number of potential injuries and fatalities and their probabilities also form part of the decision-making; the acceptability or rejection of a proposed plant does not depend solely upon the potential

Table 4
Acceptable thermal radiation hazard levels for public exposure set by various agencies

| Agency | Reference | Acceptable heat radiation flux for public exposure | | Duration of acceptable exposure (s) |
|---|---|---|---|---|
| | | kW/m$^2$ | Btu/h ft$^2$ | |
| National Fire Protection Association | Section 2.2.3.2, NFPA/ANSI 59A Standard (2001 edition) | 5.0 | 1,600 | Not specified |
| U.S. Department of Transportation | 49 CFR 193.2057 | 5.0 | 1,600 | Not specified |
| UK Health and Safety Executive | http://www.HSE.gov.uk/offshore/strategy/effect.htm ("Fire Effects") | 5.0 | 1,600 | Not specified |
| Austrian Government | http://www.env.cz/www/Phare-CZ02-06-01.nsf/0/c0ec8e357154c5bbc1256df80052498d/$FILE/RecommendationLUP_ENGLISH.doc (Recommendation of the Austrian Permanent Seveso Working Group for the calculation of appropriate distances for the purposes of Land Use Planning, Emergency Planning and Domino Effects, November 2002) | 4.5 | 1,425 | 20 s exposure for blistering to begin |
| State of New South Wales, Australia | http://www.aidgc.com/AIDGC%202003%20Sylvester.pdf (SEEP Regulation #33) | 4.7 | 1,490 | Not specified |

exposure of a person to a level of thermal radiation specified in the Standard but on the overall risk presented by the plant.

None of the standards or regulations reviewed above indicates the scientific basis on which the specified threshold exposure heat flux levels are specified. A sample of human exposure threshold heat flux values, specified in various standards and regulations worldwide, is indicated in Table 4.

In the following section some of the known data and results from scientific experiments on human skin and the physical basis of pain or skin injury are provided. However, to put the above values of the heat intensity in perspective, a compilation is provided in Table 5 of the different "heat exposures" to which human beings may be subject in the normal course of daily life, and the quantitative values of such exposures. Society, in general, is tolerant to these types of potential "hazardous heat" exposures.

## 3. Skin burn injury phenomenon

A person's skin exposed to heat radiation reacts by perspiring and increasing blood flow to the "hot" area. Pain is felt when the initial normal temperature (at 37 °C or 98.4 °F) of the skin rises to just above 44 °C (111 °F) over a depth of 0.1 mm (Buettner [12], Stoll and Greene [13]). Pain and injury continue whilst the temperature remains above 44 °C.[1] The rate of injury increases by about a factor of 2.3 for every degree Celsius above 44 °C, such that at 50 °C the injury rate is ∼100 times that at 44 °C. Burn injuries are reversible or permanent depending upon the degree of burn (based on the exposure heat flux, heat dose or duration of exposure).

The burn injury to a human skin can range from heat pain to first, second and third degree burns (see Table 6 for definitions of the degrees of burn). Burn injury to a skin is the result of coagulation of the protein "collagen." The degree of necrosis (death) of skin and coagulation of protein depends upon the total amount of energy absorbed after the epidermis (the outer skin) reaches 44 °C. In fact, the degree of burn is related to a modified dose quantity given by the product of $I^{4/3}$ and $t$, where '$I$' is the intensity (in kW/m$^2$) and '$t$' is the time of exposure (in seconds). The publications of Raj [14], Lees [15] and TNO Green Book [16] provide detailed discussions on experimental results. Fig. 1 shows the results of laboratory-scale experimental data on human subjects and animal studies as well as data from (accidental) skin burns from direct contact with flames. These data are also correlated in Table 7 in terms of burn injuries versus modified dosage values. Also indicated in this table are the exposure times to cause an injury at an intensity level of 5 kW/m$^2$.

It is noted from the results indicated in Fig. 1 that second degree burns can be expected when a bare, unprotected (by clothing), skin is exposed to a thermal intensity of 5 kW/m$^2$ for 30 s or more. It is estimated that a person can ambulate at a speed of 2–4 m/s in an emergency (TNO Green Book [16]). However,

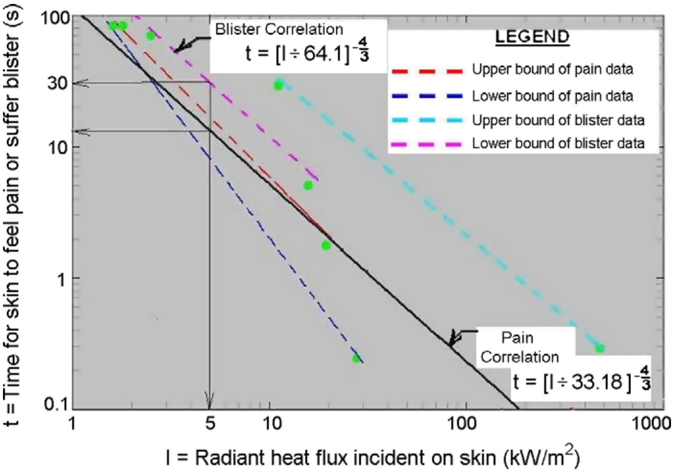

Fig. 1. Range of experimental data on skin pain and skin burns and correlations of time for injury vs. incident radiant flux.

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[1] It is noted that the water temperature of "normal" shower bath ranges between 38 °C (100 °F) and 40.5 °C (105 °F). In the U.S. Consumer Product Safety Commission recommends the setting of maximum water heater temperature to less than or equal to 48.9 °C (120 °F).

Table 5
Heat flux values from different experiences

| Number | Condition | Heat flux (kW/m$^2$) | Remarks | Reference |
|---|---|---|---|---|
| 1 | Heat outflow through a house wall in winter | 0.009 | Heat leak from a 70 °F room through a R19 wall insulation when outside temperature is 14 °F (10 °C) | www.sensorsmag.com/articles/1003/37/main.shtml |
| 2 | Heat loss from a person on a cold winter day | 0.085 | Assumes bare human skin exposed to the elements on wintry day, unprotected by clothing and radiating to air at 32 °F | www.sensorsmag.com/articles/1003/37/main.shtml |
| 3 | Sun bathing | 1.135 | Heat flux from the sun in the tropics on a cloudless day when the sun is at its zenith (absorption in the atmosphere is taken into account) | Mitchell [10] |
| 4 | Solar constant | 1.37 | Annual average heat flux from the sun impinging on the earth above the atmosphere | Publication on the internet from the Department of Oceanography, Texas A&M University, December 2002 |
| 5 | Fireplace exposure, 2 ft from the fireplace edge | 3.2 | From a typical household fireplace burning dry wood. Thermal radiant heat is from roaring fire in the fireplace and brick walls heated by fire for at least 4 h | Raj [11] |
| 6 | Exposure to thermal radiation from a large fire—safe limit | 5.0 | Flux level for exclusion zone distance to places of public assembly, which could be exposed to a fire from a burning LNG pool. Exposure to this level longer than 30 s causes second degree burns over the exposed skin | 49 CFR, Part 193 and Health and Safety Executive (www.hse.gov.uk/oofshore/strategy/effects.htm) |
| 7 | Heat from an incandescent light bulb | 6.4 | Exposure to a 100 W incandescent light bulb at 10 cm distance | www.sensorsmag.com/articles/1003/37/main.shtml |
| 8 | Ignition of wood | 12.0 | Unpiloted ignition of dry (oak) wood exposed for a long time to thermal radiation (several minutes) | Lees [15] |
| 9 | FAA criterion for aircraft escape chute exposure to fuel fire | 17.0 | The chute material must withstand for at least 90 s, without degradation when exposed to the specified level of radiant heat flux from an aircraft fuel fire | www.sensorsmag.com/articles/1003/37/main.shtml |
| 10 | Human fatality | 37.5 | Instantaneous death from exposure to this level of thermal radiation over a very short duration | Health and Safety Executive, UK (www.hse.bov.uk/oofshore/strategy/effects.htm) |

*Note*: Clothing on people provides additional protection by increasing the time to feel the pain from exposure to thermal radiation at 5 kW/m$^2$. According to the Phoenix, AZ fire department, second degree burns are considered minor if less than 15% of the body surface in adults is burned. When treated with reasonable care, second degree burns are reported to heal themselves and produce very little scarring. Healing is complete in 3 weeks.

Table 6
Symptoms and quantitative descriptions of various degrees of skin burn

| Degree of burn | Description of effects[a] | Skin temperature °C (°F) | Total energy absorbed (cal/cm$^2$) |
|---|---|---|---|
| Pain | Tingling sensation involving notice of hotness | 44 (111) | N/A |
| First degree | Superficial injuries that involve only the epidermis or outer layer of skin. They are the most common and the most minor of all burns. The skin is reddened and extremely painful. The burn will heal on its own without scarring within 2–5 days. There may be peeling of the skin and some temporary discoloration | 44–55 | N/A |
| Second degree | First layer of skin is burned through and the second layer, the dermal layer, is damaged but the burn does not pass through to underlying tissues. The skin appears moist and there will be deep intense pain, reddening, blisters and a mottled appearance to the skin. Second degree burns are considered minor if they involve less than 15% of the body surface in adults and less than 10% in children. When treated with reasonable care, second degree burns will heal themselves and produce very little scarring. Healing is usually complete within 3 weeks | 55 (131) | 1.09–2.0 |
| Third degree | Involve all the layers of the skin. They are referred to as full thickness burns and are the most serious of all burns. These are usually charred black and include areas that are dry and white. While a third degree burn may be very painful, some patients feel little or no pain because the nerve endings have been destroyed. This type of burn may require skin grafting. As third degree burns heal, dense scars form | – | – |

*Reference notes*: [a]http://www.ci.phoenix.az.us/FIRE/burns.html. [b]http://www.hse.gov.uk/offshore/strategy/effects.htm.

Table 7
Burn injury vs. modified heat dose

| Effect | Modified dosage in TDU ((kW/m$^2$)$^{(4/3)}$ s) | Injury time at 5 kW/m$^2$ intensity (s) |
|---|---|---|
| Threshold of blistering[a] | 300–500 | 35–60 |
| Second degree burn[b] | 1,200 | 140 |
| Third degree burn threshold | 1,060 | 125 |
| Third degree burn, 50% mortality[c] | 2,300 | 270 |

TDU: Thermal dosage unit. *Source*: Part of information in the table from Lees [15].

[a] There is evidence for a region of constant injury between these limits.

[b] Second degree burns with a burn depth of 0.1 mm.

[c] Third degree burns with a burn depth of 2 mm. This value is approximately the same as that for 50% mortality. This value is approximately the same as that for 1% mortality. Burn depth increases linearly up to a thermal load value of 2600.

it is also known that when human beings are exposed to a heat episode they tend to take evasive action within 5–10 s of exposure. Therefore, in a 30 s exposure, with the first 10 s becoming the set up time for evasive action, a person may be able to move a distance of 40–80 m in the remainder 20 s. It can be argued that in an urban or an industrial area, within a 20 m distance from any location it is highly likely that a person, ambulating at the above speeds, would be able to find protection or shelter behind a building (shadow), a large tree, a tall object or a building to enter into. If the person is able to run away from the fire at the top speed of 4 m/s for say 25 s and cover 100 m distance away from the fire the radiant intensity felt will be less than that would cause a second degree burn. Also, a person is normally clothed over 50% of the skin in warmer climactic areas and almost 85% in colder climates. The clothing on a person provides substantial additional protection (by reducing the heat intensity by a factor to 2–3) not considered in the above assessment.

It should be noted that data discussed above have been obtained from very small-scale, laboratory type, experiments in which relatively small area of the subject's skin was exposed[2] to the radiant heat flux. Also, the sources of heat in laboratory tests were close to the skin (only a few centimeters from the skin surface). No tests have been performed with exposure of the skin to a fire as the heat source. In a fire the continuum emission from luminous soot and the band emission from $H_2O$ and $CO_2$ vapors dominate the emission spectrum (Raj [17]). Because of the closeness of the source to the skin the energy incident on the skin surface would have had the same spectral characteristics as that of the source. That is, there was no absorption and consequent distortion of and reduction in the spectral energy due to the intervening atmospheric constituents. The effects of atmospheric absorption, which are noticed in field-scale tests, can be considerable. Skin properties of interest to predicting the skin temperature increase and the effect of atmospheric absorption on the skin temperature increase are discussed in the subsequent sections.

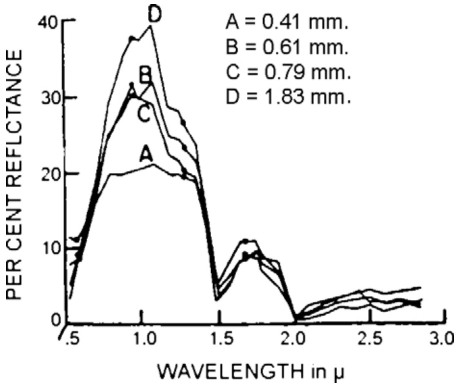

Fig. 2. Surface reflectance of dark (in visible light) human skin at NIR wavelengths. Reprinted with permission from the Journal of Applied Physiology.

## 4. Radiant heat absorption properties of human skin

A number of experimental and theoretical studies are reported in medical journals related to understanding the effect of thermal radiation on human skin (Buettner [12], Stoll and Greene [13], Hardy and Muschenheim [18]; Hardy and Muschenheim [19]; Hardy et al. [20]; Dai et al. [21]). The principal results of interest from these research studies to the subject of this paper are:

1. Normal human skin reflects over 20% of the incident energy in the near infrared (NIR),[3] in the wavelength range 0.7 μm to about 1.7 μm, with peak reflection of almost 40% at 1.2 μm. (Hardy and Muschenheim [18] and Hardy et al. [20]). The percentage reflection is relatively independent of the color of the skin in visible light. The average reflection is about 20–25%. Skin spectral reflectivity data published by Hardy et al. [20], are shown in Fig. 2 (Reprinted with permission from the Journal of Applied Physiology).
2. In the NIR, skin reflectivity varies with "skin moisture" content, which itself varies with the ambient relative humidity (Martin [22]).
3. Human skin contains water in absorbed as well as adsorbed form. The percent absorption of the total radiant heat flux by the skin varies with the wavelength of radiation and skin thickness. Fig. 3, a modified plot of a figure published by Hardy et al. [20], shows the fractional energy absorbed by the skin at various wavelengths of the spectral energy that propagates into the skin (the results in Fig. 3 are not based on the energy that is incident on the skin but on the energy that actually penetrates the skin surface after reflection—see Eq. (1) below). It is noticed that the fraction of spectral energy entering the skin surface ($e_0$) that is absorbed increases with

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[2] In the experiments reported by Buettner [12], the radiant heat source was a 500 W electric radiator at 600 °C with a cylindrical parabolic aluminum reflector. The area of skin on the forearm of volunteers exposed was 5 cm × 10 cm size. Stoll and Greene [13] used a filament type projector lamp of 1000 W rating whose radiance was varied by changing the current through the lamp. The radiances of these sources were (reported to be) calibrated against standard blackbody sources. Emissions from projector lamps and electric heaters have very different spectral radiance characteristics compared to that from a fire.

[3] The near infrared (NIR) is defined as the region of the electromagnetic spectrum in the wavelength range 0.7–10 μm.

Table 8
Principal absorption bands in the IR for water vapor and carbon dioxide

| Absorbing specie | Strength of emission or absorption | Center of wavelength (μm) of the principal band emission or absorption |
|---|---|---|
| Water vapor ($H_2O$) | Strong | 1.87, 2.66, 2.73 and 6.27 |
| | Weak | 0.94, 1.1, 1.38, 2.74 and 3.2 |
| Carbon dioxide ($CO_2$) | Strong | 2.7, 4.3 and region between 11.4 and 20 |
| | Weak | 1.4, 1.6, 2.0, 4.8, 5.2, 9.4 and 10.4 |

*Source of data*: Wolfe [23].

increased skin thickness. The skin absorbs the (NIR) radiation, the absorption fraction varying with wavelength. Strong absorption occurs in the bands centered at 1.4 and 1.88 μm, which are primarily the absorption bands for water. Table 8 shows the principal wavelengths of the water vapor (and $CO_2$) absorption bands.

The energy balance of radiant heat flux incident on a skin surface can be represented by the following equations:

$$e_0(\lambda)\,d\lambda = e_{in}(\lambda)[1 - r(\lambda)]\,d\lambda \tag{1}$$

$$e(\lambda, x)\,d\lambda = e_0(\lambda)\{1 - \alpha(\lambda, x)\}\,d\lambda = e_0 e^{-k_\lambda x}\,d\lambda \tag{2}$$

where $e_{in}(\lambda)\,d\lambda$ is the monochromatic spectral intensity, on the skin surface, of incident radiant heat over a wavelength interval $d\lambda$ centered at $\lambda$. $e_0(\lambda)\,d\lambda$ is the monochromatic spectral intensity of radiant heat at the skin surface propagating into the skin. $e(\lambda,x)\,d\lambda$ is the monochromatic spectral intensity of radiant heat at any depth '$x$' from the skin surface. $r(\lambda)$ is the total reflectivity (due to both specular reflection at the surface and back scattering) at skin surface (see Fig. 2). This is the fraction of $e_{in}$ that is reflected back to the ambient space. $x$ is the distance through the skin along a direction normal to the surface. $\alpha(\lambda,x)$ is the monochromatic absorptivity over distance '$x$' through the skin. $k_\lambda$ is the monochromatic extinction coefficient.

The value of "monochromatic extinction coefficient, $k_\lambda$" obtained by Hardy et al. [20], is dependent on the wavelength of NIR and is indicated in Table 9. It is also found by these researchers that in the region of 1 μm wavelength the skin has the lowest absorption coefficient and that energy in this range will be largely reflected or penetrate so deeply as to be carried away from the skin by the flow of blood beneath the surface and not contribute to the rise in the skin temperature.

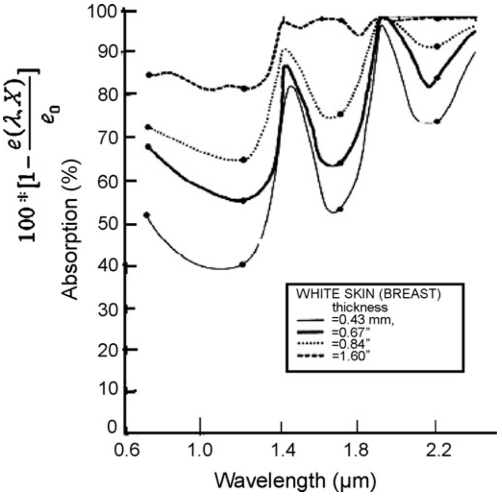

Fig. 3. Absorption coefficient in NIR wavelengths over the thickness of a human skin.

Table 9
Spectral extinction coefficient for absorption in NIR wavelengths by human skin

| NIR wavelength (μm) | Extinction coefficient ($k$) ($cm^{-1}$) for skin pigment | |
|---|---|---|
| | White | Dark |
| 0.95 | 10.1 ± 3.1 | 11.2 ± 3.4 |
| 1.23 | | 9.2 ± 1.9 |
| 1.68 | | 13.4 ± 2.8 |
| 2.20 | 26.9 ± 8.6 | 32.6 ± 4.7 |

*Source of data*: Hardy et al. [20].

A mean value of the extinction coefficient "$k$", independent of the wavelength over NIR region, can be defined by the following equations;

$$I_0 = \int e_0(\lambda)\,d\lambda \tag{3}$$

and

$$e^{-kx_S} = \int_{Over\ all\ IR\ values\ of\ \lambda} \frac{e_0(\lambda)}{I_0} e^{-k_\lambda x_S}\,d\lambda \tag{4}$$

$I_0$ represents the total radiant heat intensity penetrating the skin surface and $x_S$ is the thickness of the skin. The integration is (assumed to be) carried out over the NIR range of wavelengths. The wavelength independent intensity variation within the skin is then represented by the equation (Bouguer–Lambert law),

$$I(x) = I_0 e^{-kx} \tag{5}$$

Hardy et al. [20] indicate that in the 1–2.4 μm NIR region Bouguer–Lambert law appears to give a reasonably good description of the absorption of NIR radiation as a function of thickness with a single, wavelength independent extinction coefficient. That is, the absorptance due to scattering and that due to pigments, water, etc., can be combined into a single absorption coefficient.

## 5. Spectral properties of radiant heat intensity from a LNG fire

Raj [17] and Malvos and Raj [24] have discussed the spectral characteristics of radiant heat emission from a LNG fire. The

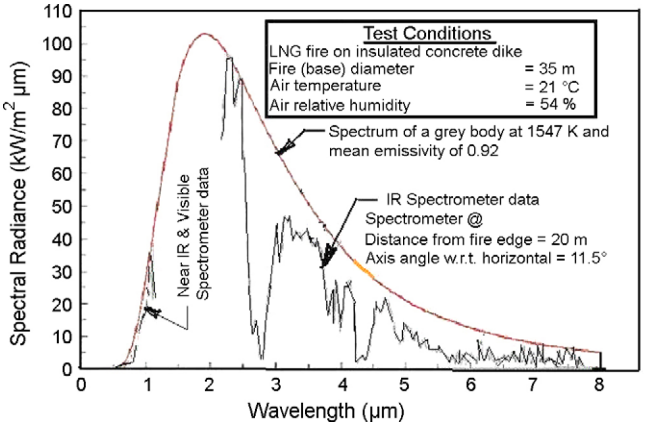

Fig. 4. Radiant heat spectrum measured at close proximity to a 35 m diameter LNG fire.

attenuation of radiant heat intensity due to water vapor and carbon dioxide in the atmosphere has been discussed by Raj [14], Raj [17] and also in Malvos and Raj [24]. Fig. 4, reproduced from Malvos and Raj [24] paper, shows the LNG fire spectrum measured at about 20 m from the edge of the base of a 35 m diameter LNG fire, in a 21 °C and 54% relative humidity atmosphere.. As can be seen from the figure, the spectrum shows significant absorption in the water vapor bands, even at a 20 m distance.

The spectral data from LNG fires indicate that a significant fraction of the energy emitted by the fire is absorbed by water vapor in the atmosphere. The intensity of the radiant heat diminishes with distance not only due to “beam dispersion” (obeying the inverse square law) but also due to absorption of energy in the atmosphere. Therefore, the overall intensity of thermal radiation incident on an object at a distance will be different both in magnitude and spectral energy (intensity) characteristics.

Unfortunately such detailed spectral data, as in Fig. 4, are not available for other hydrocarbon fuel fires. However, it can be argued that the characteristics of energy emitted by a fire in different wavelengths and the extent of absorption of energy as function of the wavelength by the intervening atmosphere changes the spectrum of energy incident on a human skin. Because of the dependence of the skin heat absorption properties on the wavelength of energy incident on it, the heating response of skin will vary with the type of fire emission spectrum and atmospheric absorption. This has profound implications for calculating the effects on human beings of radiant heat emitted by LNG fire or another fire. This will be discussed in the next section.

## 6. Human exposure hazard distance calculation procedure

The procedure for calculating the actual hazard distance to a second degree skin burn condition from a LNG fire would involve a set of complex calculations. These calculations may be performed with the information indicated in the following steps:

1. Assuming a large LNG fire to radiate like a black body at, say, 1547 K, determination of the spectral radiance can to be made at a specified distance from the fire in an atmosphere of specified temperature and humidity. This is a very complex set of calculations using numerical codes developed by meteorologists and other scientists. The result of this calculation will be a spectral radiance graph (similar to the experimental data shown in Fig. 4) as a function of the wavelength. It is likely that in a normal relative humidity atmosphere (greater than 50%), all of the energy in the water vapor bands would have been absorbed in the atmosphere within a path length of about 100 m. A second point to note is that, on a time averaged basis the intensity of energy output (and its spectral distribution) from different heights of the fire surface will be different in large LNG fires or other hydrocarbon liquid fuel fires, which produce copious amount of black smoke. That is, the absorption (of the energy emitted from the burning regions of the fire) due to the shrouding effect of the black smoke layer around the fire has to be considered in these calculations. The calculation of the variation of the emissive power[4] with distance along the axis of the flame plume has been discussed by Raj [25].
2. With knowledge of the incoming radiant spectrum at the specified distance, the energy reflected by an unprotected skin can be calculated, as a function of the wavelength, using the data from Fig. 2. This will then lead to the calculation of the spectrum of energy entering the skin (i.e. $e_0(\lambda)$ of Eq. (1)). It is noted here that if the attenuation effects of clothing are to be considered this effect is taken into account in the determination of $e_0(\lambda)$.
3. Using the data shown in Fig. 3, and integrating over the entire wavelength band, the total absorption of energy that has penetrated at the skin surface is then determined.
4. Using the total energy absorbed in the epidermis and dermis, the temperature rise of the skin as a function of time can be calculated. The criterion for burn injury that may be used in this calculation is the critical temperature for second degree blister to appear on the skin surface, namely, 55 °C. Alternatively, the total energy absorption criterion may also be used.
5. Steps 1 through 4 are repeated with decreasing distances until the distance at which the second degree burn occurs over the exposure duration of 30 s.

It is needless to say that the above calculations are tedious and complex. An approximate method is illustrated below which provides an estimate of the percentage reduction in the hazard distance, without calculating the actual hazard distance. This procedure utilizes the information discussed in the previous sections.

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[4] “Emissive power” represents the overall energy emitted from a unit nominal surface area of an idealized shape of the fire. This shape is generally considered to be a circular cylinder with diameter equal to the fire base diameter and height equal to the mean “visible” height of the fire plume. In addition, if the fire plume is tilted by wind, the axis of the fire plume enveloping cylinder is tilted by the same angle.

In the calculation procedure illustrated below, the following assumptions are made:

(a) The intervening atmosphere absorbs all of the energy in the water vapor bands in the emission spectrum from a fire by the time the heat energy impinges on a person (who is exposed to fire radiant heat).
(b) The nominal value of heat flux (i.e. the integrated value of the spectral intensity over the entire IR wavelengths of the incident energy) incident on the person at his/her location is 5 kW/m$^2$, the criterion that is generally used for evaluating the hazard distance.
(c) The skin reflects 20% of the incident energy due to specular reflection at the surface of skin and scattering in the interior of skin thickness.
(d) Normally, within the skin, significant absorption of heat energy takes place in the water vapor bands. Because of the lack of water vapor bands in the incident heat flux, the absorption within the skin of the energy penetrating the surface is smaller. For the calculations illustrated a value of 60% absorption (over the skin thickness) of the energy penetrating the skin surface is assumed. This may be a conservative assumption.

Hence, the net energy absorbed by the skin = $5 \times (1-0.2) \times 0.6 = 2.4$ kW/m$^2$. Assuming that the hazard distance follows the inverse square law, it can be shown that

$$\frac{S_2}{S_1} = \sqrt{\frac{2.4}{5}} = 0.693 \qquad (6)$$

where $S_1$ is the estimated hazard distance from fire center to 5 kW/m$^2$ flux level using the conventional calculation approach and accounting for heat absorption in the intervening atmosphere due to water vapor, carbon dioxide and scattering due to dust particles, if any. $S_2$ is the modified radial hazard distance to second degree burn in 30 s using the data presented for skin heat absorption characteristics discussed above.

The above result indicates about a 30.7% reduction in the radial distance. However, it should be noted that a realistic large LNG fire would not be radiating at an intensity corresponding to a black body temperature of 1547 K throughout the fire plume. The energy output (or the emissive power) decreases rapidly with height as has been seen in the 35 m diameter LNG fire (Malvos and Raj [24] and Raj [25]). If the mitigation due to clothing is considered by assuming a factor of 2 reduction in the radiant heat flux incident on the skin surface then it can be shown by the same arguments, as above that the actual distance $S_2$ will be,

$$\frac{S_2}{S_1} = \sqrt{\frac{0.5 \times 2.4}{5}} = 0.49 \qquad (7)$$

The above result indicates about 50% decrease in the overall distance to hazard compared to the hazard distance calculated ignoring the skin properties and spectral characteristics of emission and atmospheric absorption.

## 7. Discussions

This paper has reviewed the knowledge on the classification and quantification of skin injuries when exposed to infrared (heat) radiation. The physical and thermal characteristics of the skin have also been discussed. A person exposed to low intensities of radiant heat experiences the sensation of "hotness." However, when the intensity, and the duration of exposure are large, the effects on a person may range from feeling a sensation of severe pain to suffering increasingly injurious effects leading to the formation of different degrees of burns, blisters, and in some extreme cases, fatality. Human skin is a complex system, primarily, composed of two layers of tissue. The upper layer ("epidermis") contains the melanin, the cell structure and the protein ("collagen") and the second lower layer ("dermis") consists of sweat glands, blood vessels forming the principal structure of the skin. Moisture is present both as liquid water in and as adsorbed water on cell walls. When heat radiation enters the skin it increases the skin temperature, highest temperature being at the surface and progressively decreasing at deeper layers. High heat loads result in increased sweating and blood flow, which aid in carrying the heat away. However, very high heat loads result in the destruction of cells and the coagulation of the collagen protein, resulting in burn injury.

It is seen that most of the heat absorption in skin occurs, in the NIR region, due to the skin moisture absorbing the energy contained in the water vapor bands in the heat energy incident on the skin surface. Also, a significant fraction of the heat incident on the skin in the NIR wavelengths suffers both specular and diffuse reflection at the surface and internal (back) scattering at various layers. The result of these reflection and scattering phenomena is that not all energy incident on the skin surface is absorbed to increase the skin temperature. In some wavelengths, the energy simply gets transmitted (with very little absorption) directly to the blood stream circulating in the dermis.

These experimental observations of skin structure and thermal behavior should be considered in the determination of the hazard distance. The current standards and regulations do not consider any of the realistic conditions of the exposed skin (or its thermal characteristics) to determine the real hazard distance from LNG fires. The criteria that are enshrined in the regulations and in standards are based on skin injury data from very small, laboratory scale, experiments (conducted over 50 years ago) in which the source of heat was extremely close (order of centimeters) to the surface of the skin and exposed only a small skin area. The skin surface area used in tests to date forms a very small fraction of the surface area of a person's skin that may be exposed in real life, to fire radiation. To use the data from small-scale tests and extrapolate them to the situation of exposure of a person to radiant heat from a large-fire source (the spectrum of which is modified in the intervening atmosphere) is incorrect. At the very least, the radiant heat absorption by water vapor in the atmosphere must be accounted for and its effect on the skin temperature increase must be considered. Once the energy in the water vapor bands are not prevalent in the radiation incident on the skin, the skin acts very much like a dry, porous tissue with significantly different reflective and absorptive characteristics.

Once these real conditions are considered in any hazard distance calculations it can be seen that a decrease in the hazard distance (for the same postulated hazard, namely, the second degree burn) will occur. Including more realistic consideration of the effects of clothing and the consequent decrease in the radiant heat flux incident on the skin will result in even more significant reduction in the hazard distance.

This paper has attempted to include all of the known skin properties and thermal phenomena and estimate the potential reduction in the hazard zone distance for human exposure to a LNG fire. The problem has not, however, been solved completely in all its complexity because such a research has not been undertaken. Real solutions to this problem should not only include the correct representation of the energy output from all parts of a large (smoky) LNG or other type of hydrocarbon fire, but also the spectral characteristics of the emission, the variation (reduction) in the spectral distribution of energy with distance and atmospheric conditions, the effectiveness of clothing on a person in reducing the total heat flux incident on the skin surface, the thermal and spectral characteristics of the skin vis-à-vis the spectrum of energy incident on the skin surface and the resulting temperature variation in the skin with time. This calculation can be performed without much difficulty with a computer, since most of the information of interest are known. Needless to say, more research is needed in the area of effectiveness of clothing and of the intervening objects. An attempt has been made by Raj [26] to include these phenomena in a risk-based assessment of the statistically determined "mean" area of potential skin burn hazard to people from large LNG fires. This approach considers the details of the distribution of population in urban and industrial settings, the distribution and density of buildings and the location of people with respect to them, realistic consideration of the effects of smoke obscuration in large LNG fires in reducing the magnitude of the actual radiant heat emission from large LNG fires, etc.

Recently, a series of field-scale tests with LNG fires has been conducted to measure the radiant heat attenuation factors for different types of civilian clothing. Also, in these experiments human exposure in civilian clothing to the full thermal radiant heat flux level close to 5 kW/m$^2$ was conducted. The results of these tests have been published recently in a report (Raj [27]) and may be published in the near future in a scientific journal (Raj [28]).

## 8. Conclusions

This paper has addressed the consideration of realistic properties of a human skin related to exposure to radiant heat in the near-infrared region of the spectrum. The available literature has been reviewed both on the LNG fire heat emission characteristics, and the reflective, absorptive and transmissivity properties of skin for thermal radiation. A model has been discussed for calculating the hazard distance to second degree burn criterion using the discussed skin property parameters and spectral signature of LNG fires. Based on the information provided in this paper the following conclusions are reached:

1. The human skin reflects significant fraction of infrared energy incident on its surface. The fraction reflected can be as high as 50% at certain wavelengths. The mean reflectivity, over the NIR wavelengths, is higher than 20%.
2. Significant fraction of the radiant heat emitted from fires, especially from those parts of a LNG fire that emit at a high intensity, is absorbed by the intervening atmospheric water vapor and carbon dioxide. Because of this atmospheric absorption, the spectrum of radiant heat impinging on a skin surface at any reasonable distance from the fire is devoid of energy in the water vapor bands.
3. The absorption of net heat penetrating the skin is dependent significantly on the moisture content of the skin. Skin is generally composed of water to a considerable percent of skin mass. Very high absorptivity values are seen at wavelengths corresponding to water vapor absorption bands.
4. Because of the atmospheric absorption of the radiant energy in the water vapor bands and the fact that skin also preferentially absorbs energy in the water vapor bands, the net energy absorbed by skin when exposed to large fire radiant heat is considerably less than is assumed to be absorbed in conventional hazard assessment studies.
5. The presence of clothing in between the incident radiant heat and the skin surface can further reduce the actual heat flux entering the skin, resulting in even slower skin temperature increase than has been calculated in the literature.
6. An approximate calculation procedure illustrated in the paper shows that (with very conservative assumptions) a reduction of 30% in the hazard distance obtained using current procedures is possible when the radiant heat absorption properties of human skin are considered properly. A reduction of 50% in the conventionally calculated hazard distance may result if, in addition, the protection provided by clothing on the skin is considered.

## References

[1] M. Hightower, L. Gritzo, A. Luketa-Hanlin, J. Covan, S. Tieszen, G. Wellman, M. Irwin, M. Kaneshige, B. Melof, C. Morrow, D. Ragland, Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water, Sandia National Laboratory Rep. #SAND2004-6258, U.S. Department of Energy, Washington, DC, December 2004.

[2] FEIS, Final Environmental Impact Statement/Environmental Impact Report for the Cabrillo Port Liquefied Natural Gas Deepwater Port, Federal Docket No. USCG-2004-16877, US Coast Guard, Washington, DC, March 2007.

[3] DFEIS, Draft Environmental Impact Statement/Environmental Impact Report, vol. I, Long Beach LNG Import Project, Federal Energy Regulatory Commission Docket No. CP04-58-000, October 2005.

[4] NFPA, Standard for the Production, Storage, and Handling of liquefied Natural Gas (LNG), 2006 ed., National Fire Protection Association, Quincy, MA 02169, 2006.

[5] ANSI/API 521, Guide for Pressure-Relieving and Depressuring Systems, fourth ed., American Petroleum Institute, Washington, DC, 1997.

[6] 49 CFR, Liquefied Natural Gas Facilities: Federal Safety Standards, Title 49, Code of Federal Regulations, Part 193, October 2005.

[7] 24 CFR, Environmental Criteria and Standards, Title 24, Code of Federal Regulations, Part 51, April 2005.

[8] SFPE Engineering Guide, Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation, March 2000, p. 8.

[9] EN 1473, European Standard on the Installation and Equipment for Liquefied Natural Gas—Design of On-shore Installations, prEN 1473:2005(E), Standard Version 2.1c2, Prepared by the Technical Committee CEN/TC 282, AFNOR Secretariat, Brussels. See "Installation and equipment for LNG," Table A.2, p 83, The Secretariat of which is held by AFNOR, 1 September 2005.

[10] K. Mitchell, NWP 50-Year Anniversary Symposium, NCEP Environmental Modeling Center, June 2004.

[11] P.K. Raj, Calculations of Fireplace Thermal Radiation Emission, unpublished work, 2004.

[12] K. Buettner, Effects of extreme heat and cold on human skin. II. Surface temperature, plain and heat conductivity in experiments with radiant heat, J. Appl. Physiol. 3 (12) (1951) 691–713.

[13] A.M. Stoll, L.C. Greene, Relationship between pain and tissue damage due to thermal radiation, J. Appl. Physiol. 14 (1959) 373–382.

[14] P.K. Raj, Calculations of Thermal Radiation Hazards from LNG Fires—A Review of the State-of-the-art, Paper #2, AGA Transmission Conference, St. Louis, MO, May 18, 1977.

[15] F.P. Lees (Ed.), Loss Prevention in the Process Industries, vol. 2, second ed., Butterworth-Heinemann, Oxford OX2 8DP, 1996. See section 16.22, "Fire Injury," p. 246.

[16] TNO Green Book, Methods for the Determination of Possible Damage, CPR 16E, Published by the Director-General of Labour, Netherlands, 1992.

[17] P.K. Raj, LNG pool fire spectral data and calculation of emissive power, J. Hazard. Mater. 142 (March (3)) (2007) 720–729.

[18] J.D. Hardy, C. Muschenheim, The radiation of heat from the human body. IV. The emission, reflection, and transmission of infra-red radiation by the human skin, J. Clin. Invest. 13 (1934) 817.

[19] J.D. Hardy, C. Muschenheim, Radiation of heat from the human body. V. The transmission of infra-red radiation through skin, J. Clin. Invest. 15 (1936) 1.

[20] J.D. Hardy, H.T. Hammel, D. Murgatroyd, Spectral transmittance and reflectance of excised human skin, J. Appl. Physiol. 9 (1956) 257–264.

[21] T. Dai, B.M. Pikkula, L.V. Wang, B. Anvari, Comparison of human skin opto-thermal response to near-infrared and visible laser irradiations: a theoretical investigation, Phys. Med. Biol. 49 (2004) 4861–4877.

[22] K. Martin, In vivo measurements of water in skin by near IR reflectance, J. Appl. Spectrosc. 52 (July (7)) (1998).

[23] W.M. Wolfe (Ed.), Handbook of Military Infrared Technology, Office of Naval Research, Department of the Navy, Washington, DC, 1965 (Available through the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402).

[24] H. Malvos, P.K. Raj, Details of 35 m diameter LNG fire tests conducted in Montoir, France in 1987, and analysis of fire spectral and other data, in: Paper Presented in Session T6005 LNG VI—Risk & Safety, AIChE Winter Conference, Orlando, FL, April 2006.

[25] P.K. Raj, Large hydrocarbon fuel pool fires; physical characteristics and thermal emission variations with height, J. Hazard. Mater. 140 (February (9)) (2007) 280–292.

[26] P.K. Raj, Spectrum of Fires in an LNG Facility: Assessments, Models and Consideration in Risk Evaluations, Report to US Department of Transportation under contract #DTRS56-04-T-0005, Technology & Management Systems Inc., Burlington, MA, June 2006.

[27] P.K. Raj, "Radiant heat attenuation by clothing and human tolerance to radiant heat: Field experiments with LNG fires," Phase 2 Technical Report (Contract DTRS56-04-T-0005) to U.S. DOT/PHMSA, Washington, DC, by Technology & Management Systems, Inc, Burlington, MA, March 2007. (Available for download from the DOT website, http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=150).

[28] P.K. Raj, Field tests measuring human tolerance to (LNG) fire radiant heat exposure, and attenuation effects of clothing and other objects, Submitted to the Journal of Hazardous Materials, August, 2007.