Harpur Hill, Buxton, Derbyshire, SK17 9JN

Telephone: 0114 2892000

Facsimile: 0114 2892160

HEALTH & SAFETY LABORATORY

Human Vulnerability to Thermal Radiation Offshore

HSL/2004/04

Project Leader: **S Jagger**
Author(s): **S O'Sullivan, S Jagger**
Science Group: **Fire and Explosion Group**

CONTENTS

EXECUTIVE SUMMARY

This report examines the consequences of exposure of offshore workers to differing levels of thermal radiation. It is considered that the consequences of such exposure are best determined using a dose / time relationship rather than exposure to particular levels of thermal radiation. During the preparation of this report several existing thermal radiation harm criteria and their scientific bases were reviewed. It was found that several factors, critical to offshore personnel injury, were not considered when developing most of the harm criteria currently used by offshore operators as part of their hazard assessment. These factors have been considered in this report and have led to a new estimation of the lethal dose required to cause 50% fatality.

Harm criteria have been estimated in dose units rather than setting limiting radiation levels in order to take account of the increased harm caused by intense, short duration radiation. In addition, recommending probit models of harm has been avoided both because of uncertainty of the dose–harm curve and in order to emphasise particularly important specific levels of harm at 1-5%, 50% and 100% fatality. LD_{50} is 2000 Thermal Dose Units $((kW/m^2)^{4/3}.s)$ and it is recommended that this criterion be adopted across the offshore oil and gas industry.

1. INTRODUCTION

This document examines the degree of injury caused by differing levels of thermal radiation. The study specifically considers the permanent offshore platform environment. This information is important both for design and risk assessment, but to date there has been confusion over which criteria are most relevant. Appendix A details the factors considered in arriving at the suggested harm criteria.

Due to the range of site specific factors and lack of data in some areas, it is not possible to clearly distinguish between 50% and 100% fatality. Nevertheless, the data presented in this document can serve as a single source for offshore thermal radiation harm criteria, which may improve consistency across all platforms in the treatment of this issue in duty holder safety cases.

2. SUMMARY OF INJURY AND FATALITY DATA

Table 1 shows the spread of selected experimental burn data for infrared radiation. Very little third degree burn data is available and some non-threshold data has not been selected. Ultra-violet radiation data has not been considered as typical emissions from hydrocarbon fires mainly comprise infrared radiation, which is found to produce burns at lower doses (Rew, 1996). Ultra-violet radiation data has been used historically and frequently since Eisenberg interpreted nuclear bomb fatalities as a thermal radiation probit (Eisenberg et al., 1975).

Table 1 **Burn vs. Thermal Dose Relationship**

Harm Caused	**Infrared Radiation Thermal Dose (TDU), $(kW/m^2)^{4/3}s$**	
	Mean	**Range**
Pain	92	86-103
Threshold first degree burn	105	80-130
Threshold second degree burn	290	240-350
Threshold third degree burn	1000	870-2600

See Appendix B for references to the burn data above.

It is expected that an individual either in pain from a thermal dose received or suffering from 1^o burns should escape rapidly as the injury should not be sufficient to impede movement, yet the pain will be too uncomfortable to bear standing still.

An individual with 2^o burns will have even greater motivation to escape, commonly referred to as the fight or flight response. However at this level of injury, any exposed skin will be very uncomfortable and difficult to use in contact with another surface. Simple tasks, such as turning door handles or dressing in survival equipment will take longer, if they are at all possible. Depending on the location and extent of injury, more difficult tasks, such as operating control panels or turning valves may be impossible.

With 3^o burns an individual will be in severe pain and will certainly realise that they are in immediate danger of loosing their life. Individual response is hard to predict. However fine control of injured extremities will be impossible and other functions will be severely impaired. Escape will probably incur further injury as skin may fall away from the wound. Individuals with 3^o burns should be considered as casualties who cannot evacuate unaided.

Table 2 summarises the estimated thermal dose to produce the relevant harm criteria. The values quoted take into account the factors considered in Appendix 2. The dose is relevant for a typical offshore population on a typical offshore platform, where the source of the radiation is a hydrocarbon flame from a jet-, pool- or flash-fire or a fireball.

Table 2 **Thermal Dose Harm Criteria Guidance**

Harm Caused	**Thermal Dose (TDU), $(kW/m^2)^{4/3}s$**
Escape impeded	290
1-5% Fatality offshore	1000
50% Fatality offshore with radiation only to the front or back (i.e. from a fireball).	1000
50% Fatality offshore	2000
100% Fatality offshore	3500

Table 2 shows the best estimates of harm criteria. The 50% fatality level (2000 TDU) is an estimate based on the assumption that, prior to clothing ignition, less than 50% of individuals will become fatalities and following clothing ignition more than 50% of individuals will become fatalities. As most offshore clothing is nominally identical, the threshold of piloted clothing ignition is taken as a conservative value. Where only one side of an individual is presented to a fire, only half the normal dose is required for the same effect. This will only occur with short duration (<10s) events.

1% fatality is a conservative estimate based on Rew (1996). Rew concluded that serious burns may be received or a small % of onshore workers would die following exposure to 1000 TDU. It is assumed that the training and clothing of offshore workers is generally superior to that of onshore workers, but the increased difficulty of escape etc. nulls this advantage. It is assumed that the exposure to 1000 TDU is evenly distributed to the front and back of the victim, due, for example, to a winding escape route.

As stated above, even 2^o burns impede escape, however unassisted escape is still possible until the onset of 3^o burns over a large body area or sensitive areas, or until clothing ignition occurs.

The 100% fatality level is difficult to distinguish from some lower levels. In the interest of setting a guiding figure, 3500 TDU is estimated. However, 100% fatality may occur at slightly lower doses. At 3500 TDU, un-piloted ignition of clothing will occur, thus even 100% clothed individuals will not survive. At this level of thermal dose, self-extinguishment is unlikely due to injury from heat transmitted through the clothing, unless fire protective clothing (PPE) is worn.

3. DISCUSSIONS AND CONCLUSIONS

Figures 1-4 present a comparison of commonly used fatality prediction probits. For the probit equations, discussion of figures below and references, see Appendix B. The harm criteria guidance in Table 2 has been plotted on Figures 1-3 in order to enable comparison with other author's advice. Figures 1-3 have been drawn at selected heat flux levels for illustrative and comparative purposes only. In particular, 2 kW/m^2 corresponds to strong sunlight. 5 and 10 kW/m^2 are heat flux levels at which fatality rates are frequently evaluated.

From Figures 1-3, it is clear that both Eisenberg's (1975) and Lees' (1994) probits are more optimistic than Tsao & Perry's (1979) probit. The harm criteria guidance in Table 2, reflecting a cautious best estimate, lies centrally within this range; more conservative than Eisenberg (1975) and more optimistic than Tsao & Perry (1979).

Figure 4 demonstrates the time to 2^o burns can be as low as 10 s for a 10 kW/m^2 heat flux. Where the flux is only 5 kW/m^2, 10 s exposure only results in the onset of pain. Although the logarithmic scale exaggerates the dose scale, Figure 4 indicates a longer duration between 2^o and 3^o burn injury than between other injuries. Some authors have reported a period of constant injury in this region of received dose.

Figure 1 **Fatality Predictions Using Probit Relations (2 kW/m^2)**

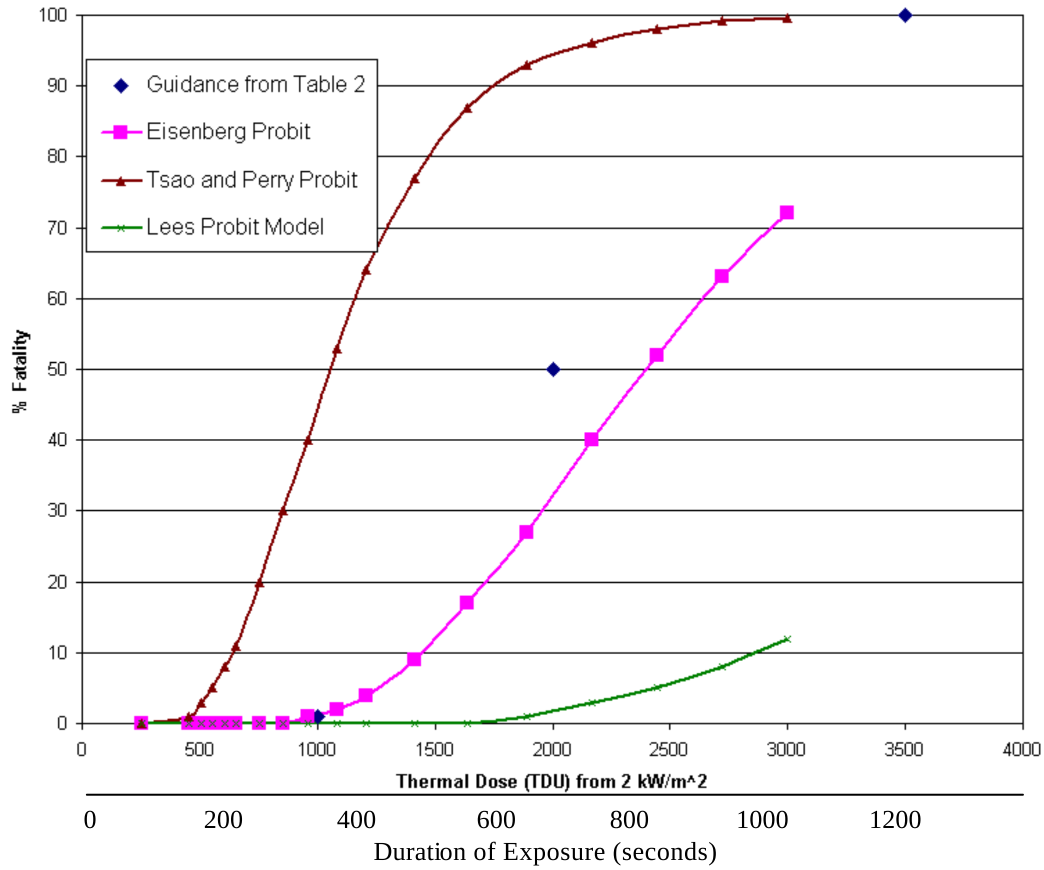


Figure 2 **Fatality Predictions Using Probit Relations (5 kW/m^2)**

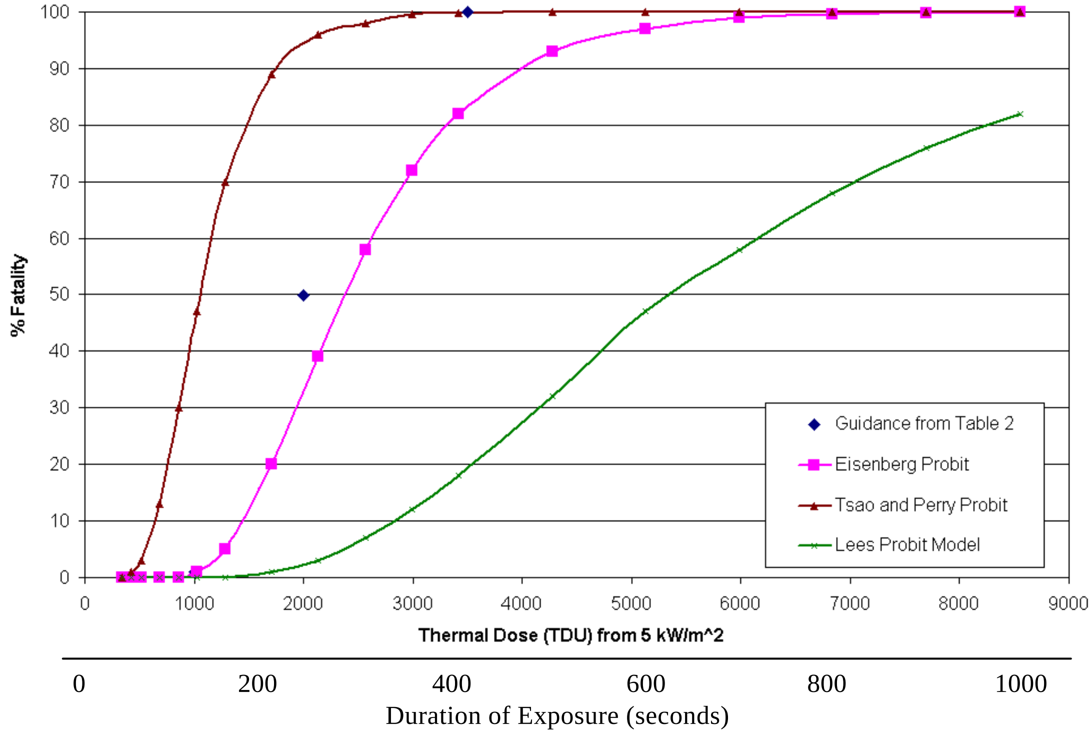


Figure 3 **Fatality Predictions Using Probit Relations (10 kW/m^2)**

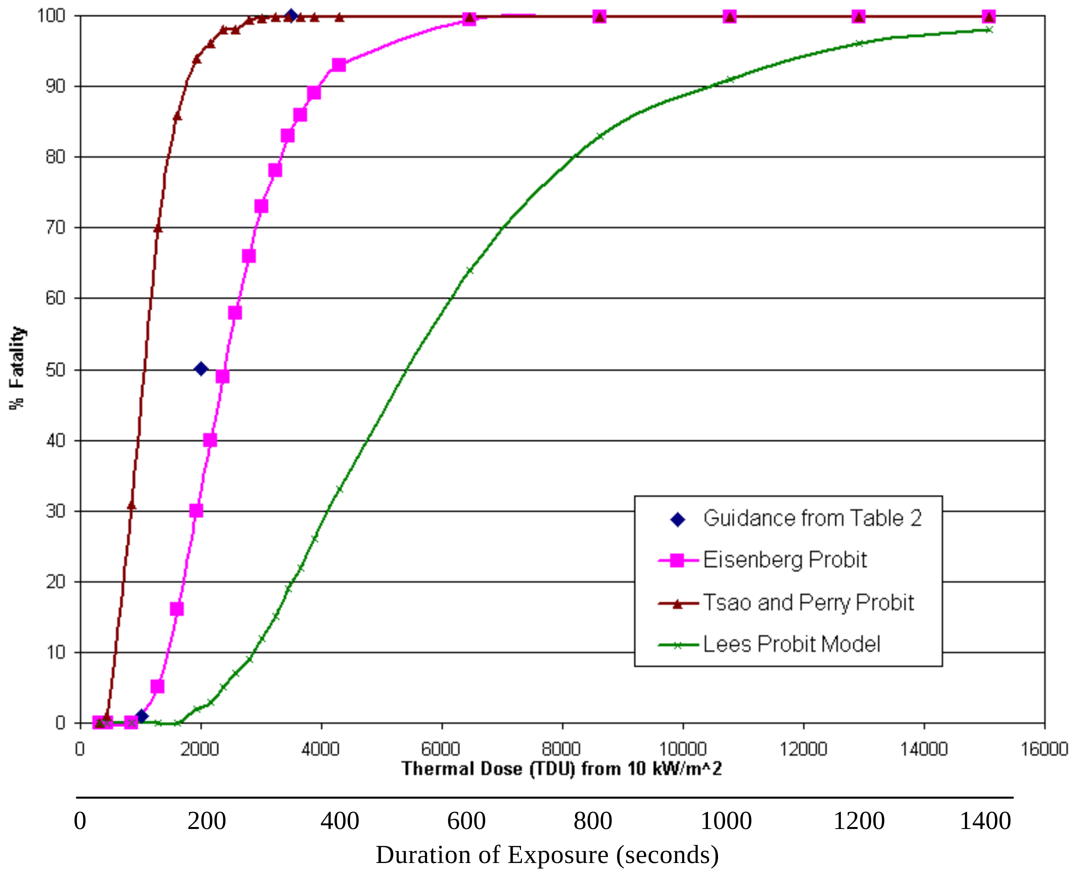
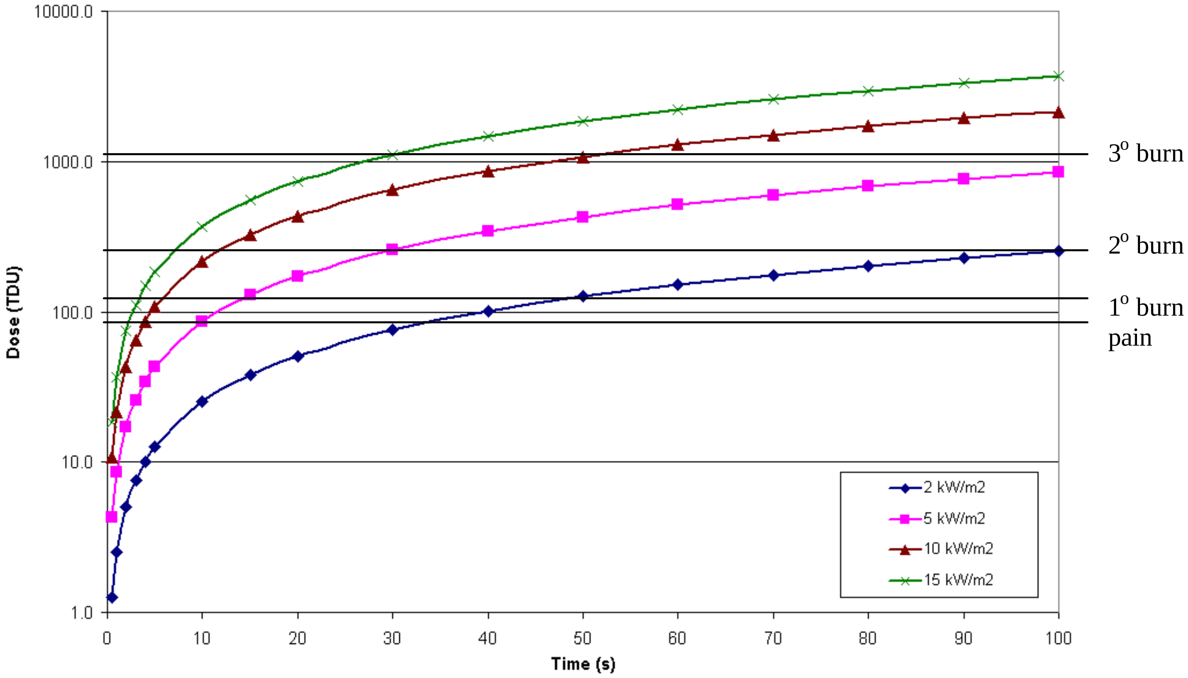


Figure 4 **Dose vs. Time Plot**



APPENDIX A

A1. SCOPE

Several literature studies have been conducted recently to quantify human vulnerability in response to thermal radiation. This note builds upon others' work by examining human vulnerability when individuals and hazards are offshore. This principally means offshore oil platforms, but may apply to other remote offshore locations. The objective is to derive an appropriate survivability criterion for use in consequence modelling and quantitative risk assessments (QRA) and revise the guidance provided in the OSD Permanent Background Note of Edmondson (1996). In so doing account will be taken of criteria used by HSE for the onshore situation and the main differences between this and the offshore environment. Those identified (not an exhaustive list) are:

- It may be more difficult to escape from incidents offshore and, due to restricted routes, it may be necessary to evacuate through a fire-affected zone.
- Offshore populations are likely to be fitter than the average UK population and also be more aware and better trained in fire safety issues.
- Offshore workers are likely to be better clothed than the general population and may be equipped with flame retardant clothing.
- Offshore workers may have less exposed skin than the general population onshore.
- In congested areas offshore some mitigation may be provided by plant through shielding.

.

A2. BACKGROUND

Any hot object emits thermal radiation which is received by humans in the vicinity. This radiation is reduced at distance, according to the inverse square law, and can also be shielded against with clothing or other solid barriers. Due to attenuation of the radiation survival is usually only in doubt in close proximity to highly emissive fires or following engulfment. Thermal radiation is a hazard because of its heating effect, which can be sufficient to burn the skin or ignite combustible materials such as clothing. Hymes (1994) has given a very comprehensive account of the effect of thermal radiation on the human body, paying particular attention to the mechanisms by which harm occurs. Over recent years acceptable and survivable criteria have been revised and reviewed for vulnerable populations (Daycock and Rew, 2000) and for conventional onshore fires (Rew, 1996) for HSE. Rew reviewed several original data sources and interpretations, deriving an LD_{50} criterion for thermal radiation, where LD_{50} denotes a dose at which 50% fatality is expected.

The level of thermal radiation required to produce a given level of fatality is commonly defined in thermal dose units:

$$\text{Dose} = I^{4/3}.t$$

$$1 \text{ Thermal Dose Unit (TDU)} = 1\ (\text{kW/m}^2)^{4/3}.\text{s},$$

where I is an incident thermal flux (kW/m^2) and t is time (seconds).

Rew (1996) has proposed 2000 TDU as the equivalent LD_{50} for incident thermal radiation onshore, subject to the following assumptions:

- Exposure of an average UK population distribution.
- An unclothed body area of 30% of the total skin area.
- Fatality assumed to be primarily dependent on full thickness burn area with probability of death related to the burn area model of Clark and Fromm (1987)
- Full thickness burns occur at a dose of 1000 TDU. This criterion is suitable for infrared radiation from hydrocarbon fires.
- The radiation dose is spread evenly over the back and front of the victim's body.
- Combustion product inhalation compounds the damage caused by thermal radiation, thus smoke inhalation is incorporated in this criterion.

This proposal for onshore hazards will be reviewed with reference to the relevant aspects of the offshore environment

A3. OFFSHORE SPECIFIC FACTORS

The principal factors that justify the use of different harm criteria in industrial situations onshore and offshore are discussed below where, in particular, these factors add to those considered by Edmondson (1992), Rew (1996), Daycock and Rew (2000), Lees (1994) and Hymes (1994).

- *It may be more difficult to escape from incidents offshore and, due to restricted routes, it may be necessary to evacuate through a fire-affected zone.*

Offshore workers exposed to a thermal dose less than the onshore LD_{50} may still be injured sufficiently as to make safe escape impossible, as escape may require a higher level of dexterity when compared with an escape from a less congested onshore facility. It is not clear what depth or extent of burn is sufficient to impede or prevent escape on typical offshore platforms. For example a 5 kW/m^2 received heat flux would cause pain in only 11 seconds. Further research may clarify this.

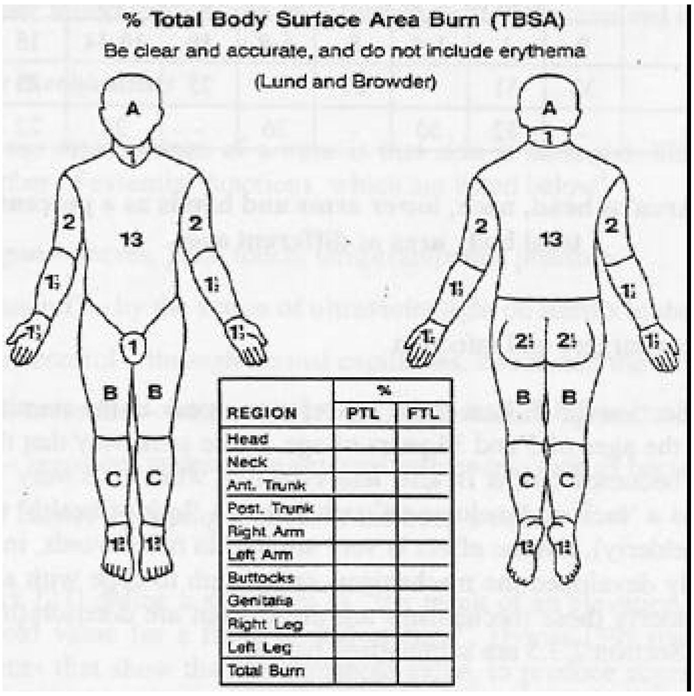
Data from Ingram for incapacitation shows that thermal stress or shock is not an immediate escape impediment. More likely, it is expected that using hot equipment with injured hands would be too painful, even in an escape scenario. It may also be psychologically impossible to escape through some fire-affected zones, particularly as further injury will definitely be sustained.

- *Offshore populations are likely to be fitter than the average UK population and also be more aware and better trained in fire safety issues.*

Young people are more likely to survive all types of burns and older people are more likely to die as a result of burns according to data presented by Bull (1971) and Lawrence (1991). As the age of offshore workers is generally between 20 and 60 there may be survivability differences. However, calculations from Bull's data have determined the population effect is to change the fatality rate for 30% burns from 50% for the general population to approximately 48% for offshore workers. Calculations on Feller's (1980) data shows the age effect to be from 57% burn area causes 50% fatality (general population) to 63% burn area causes 50% fatality (offshore population).

Training should improve fire and escape route awareness and is vital if some escape mechanisms are to be used at all. However, training that involves mustering out of doors may be confusing if incident radiation makes such mustering impossible. Insufficient data is available to determine the fatality rate improvement with training and this data clearly cannot be obtained experimentally. A cautious best estimate approach will be employed in order to account for this difficulty.

- *Offshore workers are likely to be better clothed than the general population and may be equipped with fire retardant clothing. Offshore workers may have less exposed skin than the general population onshore.*



The proportions of areas A, B and C vary with age. For adults:

Area A (½ of head)	= 3.5% TBSA
Area B (½ of one thigh)	= 4.75% TBSA
Area C (½ of one lower leg)	= 3.5% TBSA

Figure A1 Relative body areas – 'Lund and Browder Chart' (1999)

Typically all offshore workers wear hard hats, full overalls and sturdy boots such that only the hands (~6% body area), face and neck (~9% body area) are exposed. As shown in Figure A1, this is approximately 15%TBSA, for adults. At thermal doses less than those required to ignite clothing, it could be expected that only this 15% body area would be burnt. Even with full depth burns, 15% area alone is not sufficient to cause 50% fatality. Frequently, gloves are also worn, further reducing potential burn area.

Offshore workers may also wear flame retardant clothing. However Hymes (1994) counter intuitively predicts fire retardant cotton (his type 19) will ignite more easily than other types of clothing. He does not state if the retardancy reduces the rate of flame spread. Rew (1996) discusses fatality due to ignition and suggests that for all incidents, 30-40% fatality is likely following clothing ignition. However, where thermal radiation is the greatest hazard, speed of escape is critical and the ignition of clothing will hamper escape such that the assumption of 100% fatality may be justified.

- *In congested areas offshore some mitigation may be provided by plant through shielding.*

Although onshore industrial sites are often congested, few are as congested to the same extent and on as many levels as typical offshore platforms. From many locations, travel of only a few metres will be required such that there is no line of sight to the radiation source. As thin metal or 5mm thick glass is sufficient to significantly reduce infrared radiation, this will significantly affect escape. However metals may reflect much of the radiation so that increased intensity could be experienced in some confined locations.

Shielding effects are clearly site specific and event location specific. A detailed study of several platform designs, escape routes and potential incident locations could yield a classification system based on a level of confinement and associated mitigating factor, however no such technique is known.

- *First aid treatment may be administered more quickly offshore, but attendance at hospital or specialist burns unit will be significantly delayed.*

Hymes (1994) has studied such incidents as that at the Los Alfaques camp site (1978) in Spain. Although in that case very little first aid was given on site, burns victims were transferred relatively quickly to hospitals south in Valencia or north in Barcelona. The victims travelling south suffered the 165 km journey with no medical attention, however en route to Barcelona care was administered in two towns. During the first week the death rate in Valencia was double that in Barcelona, but over the next two months the death rates equalised. This might suggest that the level of primary and secondary care of burns victims has little influence on the overall long term death rates.

Despite this account, it is certainly not helpful that most offshore burns victims will be several hours by helicopter from the nearest burns unit, hospital or even doctor’s surgery. In mitigation, the level of medical training on site is usually superior offshore than onshore.

3.1 Types of fire

The types of fire encountered offshore will usually involve the combustion of large quantities of liquid or gaseous hydrocarbons. This was the type of fire considered by Rew (1996). He concluded that such fires emit mainly in the infrared part of the spectrum and fall into four distinct categories: pool, flash, jet fires and fireballs (BLEVEs – Boiling Liquid Expanding Vapour Explosions are a particular type of fireball involving pressurised liquefied gases). Table A1 gives the main characteristics of these events in terms of duration, size, radiation intensity, etc.

Table A1 **Characteristics of Process Fire Incidents**

Type	Size	Duration	Radiated Surface Emissive Heat Flux (kW/m^2)	Hazard
Pool fire (open)	Medium	Long	50 – 150	Radiation, smoke, engulfment
Pool fire (severe or confined)	Medium	Long	100 – 230	Radiation, smoke
Jet fire (open)	Medium	Medium/Long	50 – 250	Radiation, smoke
Jet fire (confined)	Medium	Medium/Long	100 – 300	Radiation, smoke
Flash fire	Large	Short	170	Engulfment
Fireball	Large	Short	270 (HID SRAG)	Radiation

Pool fires may form over liquid or solid surfaces and can spread over large surface areas, thus increasing the fuel burn rate. The vapourised fuel has little if any momentum and is easily affected by wind. In general pool fire hazards decay rapidly with distance but, at high speeds, the wind may cause significant flame tilt and the attacking of areas some distance from the seat of the fire. Depending on ventilation conditions, large quantities of smoke may be produced. This can make received radiation calculations more difficult but also increase fatality rates and incapacitation due to smoke inhalation, and prevention of evacuation.

Although flash fires are generally low intensity transitory events, the burning velocity is quite high and escape following ignition is not possible. Flash fires often remain close to the ground, where most ignition sources and personnel are present. It is usually assumed that those caught inside a flash fire will not survive while those outside suffer no significant harm.

Jet fires often have very high thermal radiation emissions, with local maxima up to 300 kW/m^2. Jet fires may burn for longer than flash fires and fireballs, but the effects are usually more restricted in space as the release is directed and momentum controlled so that it is largely unaffected by wind direction or strength.

Fireballs usually burn more fuel rich than flash fires and have a higher surface heat flux. As the cloud burns, it heats up the remainder of the fuel and entrained air, so that fireballs usually rise up while they burn, presenting a larger emitting surface to those exposed. Fireball durations can be predicted with Roberts' Model (Lees, 1994):

$$\text{Duration (s)} = 0.83 \times \text{Mass (kg)}^{0.316}$$

A 2.6 te flammable gas would take 10 s to burn and a 7.0 te cloud would take 13.6 s to burn. Although optimistic, it should be assumed that an individual would turn and flee a fireball after 10 s, thus the full exposure from a fireball might not only be to a single side of an individual. Fireballs and BLEVEs may result from a jet or pool fire directly impinging a pressure vessel. As the tank surface heats up, the steel weakens, while the internal pressure rises. At some point, the vessel will rupture catastrophically releasing its contents as a cloud.

A4. DIRECT EFFECTS

4.1 THERMAL RADIATION CAUSING DIRECT BURNS

The effect of thermal radiation is to initially warm the skin, which then becomes painful. Shortly after, the onset of 2^o burns occurs, with depth of burn increasing with time for a steady level of radiation. Ultimately, the entire thickness of the skin will burn and the underlying flesh will start to be damaged - 3^o burns. Table 1, Section 1 shows the typical radiation dose required to generate burns. Many factors account for the range of values found in the literature, including type of heat source and type of animal skin used.

4.2 BURNS CAUSING FATALITY

Rew (1996) looked for an equivalent LD_{50} for burns and the thermal radiation that caused burns. Looking at both the UK population distribution and medical data presented by Lawrence (1991) and Clark & Fromm (1987) among others, Rew concluded that as little as 30% burn area (unspecified burn type) is required to produce 50% fatality in conjunction with inhalation injury.

Other data takes account of more recent medical treatment techniques, which have improved survivability. For example, Davies (1982) presents data from Feller et al. (1980):

Table A2 **Burn Area For 50% Fatality**

Age Group (years)	Burn Area (%)
0-4	60.0
5-34	71.2
35-49	61.8
50-59	52.1
60-74	33.7
Over 75	19.6

The data in this table was reported by National Burn Information Exchange and corresponds to patients in hospital over the period 1976-79. 50% fatality means 50% of patients admitted to hospital die of their injuries (either 2^o or 3^o burns).

Davies also presents data from 15 other sources indicating a trend of increasing survival rates with time, up to 1981, when Griffiths et al. (1981) state that 50% of 15-44 year olds will die from 70% body area burns.

For reference, the fatality rate for different burn areas is tabulated below for the 40-44 year old age range. These statistics do not specify which burn type was present, principally because of the difficulty of assessing the burn depth, without causing further injury. Additionally, there is no indication of how much of the exposed skin has been burned or the cause of the burn.

The fact that only individuals treated at hospital are shown in the published statistics has been considered. Other individuals who may become fatalities before reaching hospital may be omitted.

Table A3 **Approximate Mortality Probabilities (1965-1970) Bull (1971)**

Body Area Burned (%)	Mortality Probability
78-100	1
68-77	0.9
63-67	0.8
53-62	0.7
48-52	0.6
43-47	0.4
33-42	0.3
28-32	0.2
18-27	0.1
0-17	0

4.3 TIME DEPENDENCE

For short duration fires, e.g. fireballs, account must be taken of delayed reaction. If all the thermal dose is on one side of a person (i.e. they don't turn around as they retreat), piloted ignition of clothing may occur at thermal doses as low as 900 – 1000 TDU. This is because an even thermal loading is assumed for longer duration fires where escape is involved. Assumed reaction time must be at least 5 seconds. For such short duration fires it may be overly conservative to assume 100% fatality for ignition of clothing, as the thermal radiation after the fireball has burned may be very low, allowing the approach of colleagues with fire extinguishers.

Fatality statistics do not usually discriminate between different survival durations, however delayed medical attention (as would be expected offshore) can only increase fatality rates. Additionally, over 1 – 5 days up to 70% of people with 20-30% area, 3^o burns will become 'incapacitated' (Ingram), whereas <5% will become incapacitated within 15 minutes. If the longer duration is considered important (e.g. in bad weather when helicopter rescue is impossible), the criteria may have to be adjusted to minimise long term incapacitation.

A5. INDIRECT EFFECTS

The indirect effects of thermal radiation, not immediately affecting exposed skin, are ignition of clothing, heating of walkways and stairs, the temporary refuge, inhaled air and smoke inhalation. Most of these contributory factors are difficult to analyse and quantify in a general way. The inhalation of smoke, heated air and other combustion products are a component factor in most burn and thermal radiation mortality statistics. The effect is discussed further in Section 5.2. The heating of walkways etc. is a platform specific effect. However if handrails are too hot to touch, this will impede escape and, if handrails are essential, further injury may be sustained during the whole time that the skin surface temperature is above 44^{o}C (Hymes, 1994). In the temporary refuge, thermal stress may lead to exhaustion and collapse.

5.1 EFFECT OF CLOTHING

Also discussed in Offshore Specific Factors

Heavy duty clothing, such as that worn offshore can block all incident thermal radiation from reaching the skin. Although the clothing itself heats up, the radiation causes no direct injury. The unclothed body area varies as some workers may not be wearing or may loose gloves and hard hats in a major hazard event. Even without gloves or hat, if an individual is wearing a long sleeved one piece overall and shoes, the exposed body area is less than 20%. As discussed in Section 4.2, very few fatalities can be expected from such a low burn area, unless the burns are particularly severe. Unfortunately, all useful clothing breaks down, melts or ignites after some thermal dose.

Clothing made from man-made fibres may melt or char instead of igniting. The contact of hot plastic etc. with the skin will cause severe 3^{o} burns and should be treated similarly to burning clothing. Similarly clothing that weakens and falls apart under heating cannot be assumed to fall away without further injury to the victim, and should be treated similarly to burning clothing.

Clothing can ignite in two ways. At very high doses no ignition source is required as spontaneous ignition occurs. At lower doses, piloted ignition can occur in the presence of a spark, burning brand or other ignition source.

Lees (1994), Hymes (1994) and the Green Book (TNO, 1992) all quote clothing ignition doses and models, mainly referencing Wulff (1973) and Hilado and Murphy (1978). Some doses are not quoted in the same form as used in this report. In particular, the Green Book states that the intensity exponent in the dose relationship is practically equal to 2 for the data in Hilado and Murphy. Although the Green Book does not indicate if the ignition of fabric in Hilado and Murphy's experiments was piloted or spontaneous, Lees quotes the Green Book for the same dose relationship and goes on to derive a piloted ignition dose of 1800 TDU for a 5 second duration exposure.

Lees (1994) also highlights an inconsistency between Hymes' (1994) and (1983). Some data used for the calculation of time to ignition tabulated in Hymes (1983) (and the Green Book, 1992), is not given in Hymes (1994). Furthermore a vital equation in Hymes (1983) is not included in Hymes (1994). The reason for these omissions is not known.

Given these significant inconsistencies and consideration of the appropriateness of the data, it is not possible to state a single figure at which clothing ignition will occur. Two scenarios are worthy of more detailed consideration.

In the case of a 5 s exposure to a fireball, where piloted ignition is likely, Lees' (1994) approach seems reasonable. Lees considers a thermal dose of 3.5 x 10^4 $(kW/m^2)^{4/3}$.s for a 5 s exposure. This dose is then equivalent to 1800 TDU. 1800 TDU matches the results from Lees' well and is assumed to apply to an exposure of a single side of a fabric or individual only. Both calculations fit with Hymes' (1983) quoted figure of 1100 – 4000 TDU for piloted ignition.

In the case of a >60 s exposure to radiation while escaping, piloted ignition is unlikely. Spontaneous ignition doses are also difficult to pinpoint. However it is clear that most fabrics require doses in excess of 3000 TDU (Lees, 1994) before spontaneous ignition. Thus the fatality rate will approach 100% before ignition, simply from the severity of burn to exposed skin.

Although piloted clothing ignition does not lead to 100% fatality (Rew, 1996), with injury to exposed skin, it contributes to the 50% fatality rate. In both exposure scenarios, the cautious best estimate is to accept that significant injury will occur before ignition and that 2000 TDU remains a reasonable estimate of 50% fatality offshore.

5.2 SMOKE INHALATION

Smoke consists of several toxic components in varying amounts. Particulates obscure vision and clog the airways, making escape more difficult while carbon monoxide and others are toxic in small quantities. In addition, smoke is usually hot and oxygen depleted. Smoke inhalation could kill without associated burns, but is more often a contributing factor. As a result it is not usually possible to distinguish between burn and smoke induced fatality. This should be considered when morbidity data is correlated with burn or fire data. The toxicity of individual components is discussed in other HSE documents.

5.3 STRUCTURAL EFFECTS

In addition to the problem of heated escape routes, the structure can reflect or shield thermal radiation. Confinement can lead to the channelling of hot air, smoke or flames and sometimes to an increased burning intensity. These effects would generally not affect the vulnerability criteria. However it has been assumed that the thermal radiation is incident on one side of an individual at any one time. Generally, advanced computational techniques make complex structural effects too expensive to consider. However, if structural effects were considered, the harm criteria may need to be revised. Shielding is considered as an offshore specific factor.

A6. CONCLUSIONS

Although several mitigating factors are present offshore, the most significant difference between offshore and onshore fire hazards is ease of escape. Escape during a major process incident will be difficult without injury as hot surfaces must be avoided, routes selected to avoid fire engulfment in the plume and escape completed sufficiently quickly to avoid new escalating effects. Depending on the ultimate method of escape, it may be necessary to board a lifeboat or life raft and done a survival suit, which are all difficult operations even without injury. It is for these reasons a cautious best estimate of significant levels of thermal dose should be specified as lethal offshore.

The heightened response in life threatening situations should allow the operations mentioned above to be performed with some burns. However available data suggests that for all burn types a minimum of 30% burn area is required for 50% fatality. As discussed previously, this is not possible offshore prior to ignition of clothing. Nevertheless, extended exposure to radiation, below the dose required for spontaneous clothing ignition, can only be expected to cause fatality.

Both spontaneous and piloted ignition of clothing data are subject to considerable variations and inconsistencies across the literature. A review of the best referenced and reasoned literature leads to the conclusion that piloted ignition contributes to fatality, but spontaneous ignition only occurs after the 90 – 100% fatality level is reached.

At 2000 TDU both of the following may be expected across a range of individuals:

(a) clothing ignition leading to high fatality rate (event specific)

(b) no clothing ignition, but:

- some 2^o burns to exposed skin and,
- no 3^o burns and,
- reduced dexterity and some escape impediment, assuming,
- the radiation is spread evenly, front and back.

It is likely that the combination of injuries (a) and (b) is quite close to 50% fatality probability. However the degree of escape impediment is ultimately site specific.

The considerable uncertainty in this field must be emphasised and the LD_{50} treated as a 'conservative best estimate'. For very specific fires or platforms where it is desired to model shielding effects, more detail can be applied to find a different LD_{50}. However, where uncertainty exists in modelling and where constraints do not allow a full consideration of individual circumstances, it is recommended that LD_{50} = 2000 TDU is used.

1000 TDU has been estimated as the dose received for 1-5% fatalities offshore. 3500 TDU is an upper estimate of the dose received for 100% fatalities offshore.

A7. REFERENCES

Bull J P (1971)
Revised Analysis of Mortality Due to Burns
The Lancet, Nov 10, 1971

Clark W R and Fromm B S (1987)
Burn Mortality – Experience at a Regional Burn Unit
Acta Chirugica Scandinavica Supplementum 537, Stockholm

Davies J W L (1982)
Physiological Responses to Burn Injury
Academic Press

Daycock J H and Rew P J (2000)
Thermal radiation criteria for vulnerable populations
Health and Safety Executive Contract Research Report 285/2000

Edmondson J N (1996)
Human Vulnerability – Permanent Background Note: PBN/TU4/3/2
Health and Safety Executive (Internal Note)

Eisenberg N A, et al., (1975)
Vulnerability model. A simulation system for assessing damage resulting from marine spills
Final report SA/A-O15 245 (US DoT, US coast guard),

Feller I (1980)
National Burn Information Exchange Newsletter 1, No. 2,

Feller I, Tholen D and Cornell R G1(980)
Improvements in Burn Care 1965 – 1979
J. Amer. Med. Assoc. 244, 2074-2078

Griffiths R W, Cross N L and Laing J E (1981)
A Low Volume Burn Resuscitation Regimen, Assessment of Performance by Probit Analysis
Brit. J. Surg., 68, 225-228

HID Safety Report Assessment Guide;
http://www.hse.gov.uk/hid/sragmgh/criteria/section5.htm#Table 5; Health and Safety Executive

Hilado C J and Murphy R M (1978)
Ignition and Flash-fire Studies of Cellulosic Materials
Fire and Materials, vol. 2, no. 4, 173-176

Hymes I (1983)
The physiological and pathological effects of thermal radiation
UK AEA SRD R275

Hymes I, Boydell W and Prescott B L (1994)
The physiological and pathological effects of thermal radiation
HSE/AEA/SRD R275 (Issue 2)

Hymes I, Boydell W and Prescott B L (1996)
Thermal radiation: The physiological and pathological effects
Major Hazard Monograph Series
Institution of Chemical Engineers

Lawrence J C (1991)
The Mortality of Burns
Fire Safety Journal, 17

Lees F P (1996)
Loss Prevention in the process industries
Butterworth-Heineman

'Lund and Browder Chart' (1999)
Body surface area chart used in hospitals and burns centres
Distributed by Smith and Nephew Pharmaceuticals Ltd., Goulton Street, Hull

Rew P J (1996)
LD_{50} Equivalent for the Effect of Thermal Radiation on Humans
Health and Safety Executive Contract Research Report

Wulff W (1973)
Fabric Ignition
Tex. Res. J., October 1973

APPENDIX B

B1. BURN INJURY DATA SOURCES

Table B1 **References to data in Table 1 of the main report** (Rew, 1996 and Hymes, 1994)

Injury Type	Infrared Radiation Thermal Dose (TDU)	
Pain	86-103	Stoll & Green (1958)
First degree	c. 80	Mehta et al (1973)
	130	Tsao & Perry (1979)
Second degree	240	Stoll & Green (1958)
	270-410	Stoll & Green (1958)
	c. 350	Mehta at al (1973)
	290-540	Williams et al (1973)
	730	Arnold et al (1973)
Third degree	c. 500	Mehta at al (1973)

Table B1 shows considerable disparity between experimental data, which may be due to the difficulty in determining the exact burn severity. For this reason it has been assumed that the higher 2^o burn dosages do not relate to threshold burns. Also, as the 3^o burn data is inconsistent with some of the 2^o burn data, other sources have been used instead.

B2. PROBIT FUNCTIONS

Probit harm functions have been developed and used because, unlike linear harm functions, they account better for extremes of injury. Probit functions are based on the statistical normal distribution so that between 5 and 95% fatality, a small increase in thermal dose results in a small fatality rate increase. At high fatality rates (>~95%) a much larger dose increase is required for the same fatality rate increase. This could be described as a fatality 'tail off'. Similarly at low fatality rates (<~5%) the rate of rise of fatality with dose is low.

Linear models cannot account for this tail off at the extremes of fatality rate and are weaker because of this. However it is unlikely that there will ever be a sufficiently large sample of injuries recorded from a well defined event to confirm without doubt the validity of a particular probit or that the normal distribution is to be preferred for this application.

Eisenberg (1975) developed a probit because of the availability of data from a unique pair of events, where the cause of the injury was known and a very large sample of injuries was present. Unfortunately, this nuclear data from Hiroshima and Nagasaki, contains many uncertainties. For example, it is known that the UV radiation from a high temperature nuclear source is reflected more easily than infrared radiation from a fire, by human skin. The injuries were sustained on individuals not clad in typical UK industrial clothing and medical treatments were relatively crude, not benefiting from the improvements which have occurred over the past 60 years. Although Tsao and Perry (1979) attempted to account for the ultraviolet / infrared effect, it remains that these functions were developed for onshore burn fatalities. It is not straightforward to modify the function to account for the effect of being offshore.

For the purposes of risk assessment it should be sufficient to know what is the required dose to induce pain, onset of fatalities (i.e. 1-5%), 50% fatality probability and 95-100% fatality probability.

Table B2 **Probit equations used in Figures 1-3 of the main report**

Source	**Probit Equation**
Eisenberg et al (1975)	$Y = -14.9 + 2.56 \ln V$
Tsao & Perry (1979)	$Y = -12.8 + 2.56 \ln V$
Lees (1994)	$Y = -10.7 + 1.99 \ln V'$

Where Y = probit function,

$V = I^{4/3}t$ = thermal dose $(kW/m^2)^{4/3}s$,

$V' = F.I^{4/3}t$ = effective thermal dose $(kW/m^2)^{4/3}s$, and

F = factor accounting for variation in exposed skin area (0.5 for normally clothed population and 1.0 if clothing has been ignited).

The probit function, Y, can be converted to a mortality rate using a table, such as that given by Finney (1971) and presented in Lees (1994).

In Figures 1-3, F = 0.5 has been used for the Lees probit function. The plot shows that the harm criteria guidance in Table 2 are within the extremes of existing estimates for onshore fatality and slightly on the conservative side.

B3. REFERENCES

Arnold G, Fisher A and Frohnsdorff G (1973)
Hazards from burning garments
Final report for GIRCFF Gillette Research Institute, NTIS: COM-73-10957

Eisenberg N A, et al. (1975)
Vulnerability model. A simulation system for assessing damage resulting from marine spills
Final report, AD/AO15/245

Finney D J (1971)
Probit Analysis
Cambridge University Press

Lees F P (1994)
Loss Prevention In The Process Industries
Butterworth-Heinemann

Mehta A K, Wong F & Williams G C (1973)
Measurement of flammability and burn potential of fabrics
Massachusetts Institute of Technology, Summary report DSR Project 73884 NSF Grant No. GI-31881 NTIS: COM-73-10960

Stoll A M and Green L C (1958)
The production of burns by thermal radiation of medium intensity
ASME Paper No. 58-A-219

Tsao C K and Perry W W (1979)
Modifications to the vulnerability model: A simulation system for assessing damage resulting from marine spills (VM4)
ADA 075 231, US Coast Guard NTIS Report No. CG-D-38-79

Williams, et al. (1973)
Measurement of flammability and burn apparel and the relation of hazard to test methods
MIT, Summary Report DSR Project 73884 NSF Grant No. GI-31881 NTIS: COM-73-10960

APPENDIX C

C1. SAMPLE CALCULATION OF HARM

This report has reviewed thermal radiation harm criteria, for application in offshore risk assessment. In order to use this data the thermal radiation at a point must be predicted for the scenario under assessment. This Appendix uses a sample calculation to demonstrate how the consequence assessment can be carried out. The equations used in this example apply to differential elements, or, in practice small objects. Lees (1994) states that this is generally taken to include the human body.

In order to calculate the received heat flux at the target from the flame at a given location, view factors can be used. The view factor is a geometrical factor that accounts for the proportion of radiation received from a source that emits equally in all directions. The view factor of interest is from the fire to the target. Equation 1, from Kay (1994) quoting Wiebelt (1966), can be calculated to determine the view factor from small, vertical targets, e.g. people, and cylindrical, vertical fires. Lees (1994) lists references to sources where functions for alternative geometrical arrangements are relevant.

$$F_{t\text{-}f} = \frac{1}{pD}\tan^{-1}\left(\frac{L}{\sqrt{D^2-1}}\right) + \frac{L}{p}\left[\frac{A-2D}{D\sqrt{AB}}\tan^{-1}\sqrt{\frac{A(D-1)}{B(D+1)}} - \frac{1}{D}\tan^{-1}\sqrt{\frac{D-1}{D+1}}\right] \quad \ldots\ldots(1)$$

where

D = distance to receiving target from cylinder axis / radius of cylinder = c / b,
L = length of cylinder / radius of cylinder = a / b,
$A = (D+1)^2 + L^2$ and
$B = (D-1)^2 + L^2$.

Atmospheric transmissivity is ignored and surface emissivity is assumed to be included in the Surface Emissive Power (SEP) term.

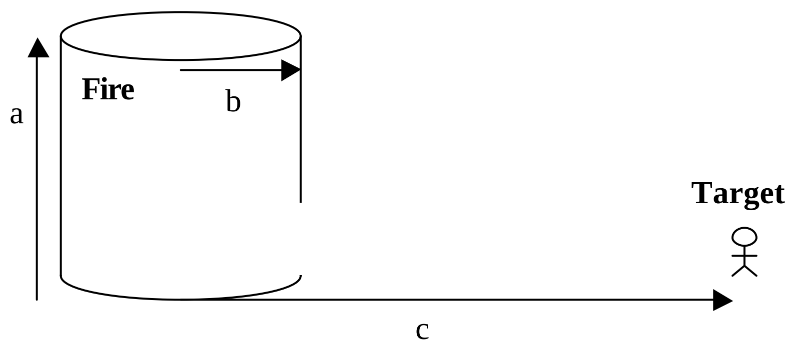


Figure C1 **Thermal Radiation Calculation Scenario**

Considering a target 25m from the axis of the fire and assuming a 10m diameter pool fire is the heat source, the received radiation can be calculated. Assume soot formation does not obscure the first 10m of flames and there is no flame tilt. Using typical values of SEP, from Table A1, 150 kW/m^2 SEP is used.

For this case:

$$
\begin{aligned}
D &= 25 / 5 \\
&= 5 \\
L &= 10 / 5 \\
&= 2 \\
A &= (5+1)^2 + 2^2 \\
&= 40 \\
B &= (5-1)^2 + 2^2 \\
&= 20
\end{aligned}
$$

$$\rightarrow \quad F_{t\text{-}f} = 0.0532$$

The received radiation flux is:

$$
\begin{aligned}
q_{in} &= SEP \times F_{t\text{-}f} \\
&= 150 \times 0.0532 \\
&= 7.99\ kW/m^2
\end{aligned}
$$

To find the time to 2000 TDU (LD_{50}):

$$
\begin{aligned}
\text{Thermal dose} &= I^{4/3}.t \\
t &= 2000 / 7.99^{4/3} \\
&= 125s \text{ or } 2{:}05
\end{aligned}
$$

C2. REFERENCES

Wiebelt J A (1966)
Engineering Radiation Heat Transfer,
Holt, Rinehart and Winston

Kay D (1994)
Thermal Radiation Heat Transfer From Flames to Receiving Targets,
UKAEA, report AEA/CSHSE R1006/R for the Health and Safety Executive

Lees F P (1994)
Loss Prevention in the Process Industries,
Butterworth-Heinmann