Thermal radiation criteria for vulnerable populations

Prepared by
WS Atkins Consultants Ltd
for the Health and Safety Executive

CONTRACT RESEARCH REPORT
285/2000
Thermal radiation criteria for vulnerable populations

J.H. Daycock and P.J. Rew
WS Atkins Consultants Ltd
Woodcote Grove
Ashley Road
Epsom
Surrey
KT18 5BW

A Dangerous Dose criterion of 1000 (kW/m²)⁴5°C of thermal radiation has been derived by the Health and Safety Executive for an average population with a standard level of clothing. The likelihood of fatality for a given severity and area of burn is strongly dependent on age, and ‘vulnerable’ populations, such as children and the elderly, are more likely to be fatalities than an ‘average’ population. HSE presently use a Dangerous Dose criterion of 500 (kW/m²)⁴5°C for these groups, which is re-assessed in this study.

The approach used to derive the Dangerous Dose criterion for an average population is reviewed, together with medical and experimental data relating to the effects that thermal radiation has on humans. The many factors that affect human response are considered, and the differences between the response of children and the elderly to those of an ‘average’ population are identified. For children, the main differences include: a reduced ability to tolerate the infection and surgery associated with serious burns, a greater area of exposed skin, and more severe consequences associated with scarring. In the elderly, infection and surgery are also more of a risk than for younger adults, pre-existing conditions are more frequent and more likely to increase fatality, and skin is typically thinner, resulting in more severe burns from the same dose. These factors are considered in detail, and related to the actual mechanisms of fatality that occur in the body, in order to provide a sound basis for recommending dose criteria for vulnerable populations.

The differing responses of ‘average’ and ‘vulnerable’ populations are considered, together with comparisons between the likely areas of exposed skin and the thresholds of ‘severe’ burns used by the medical profession. It is concluded that, although they may be tolerated in small areas in an average population, full thickness burns should be prevented in both children and the elderly. This level of burn is related to thermal dose levels and it is concluded that the Dangerous Dose criterion of 500 (kW/m²)⁴5°C is reasonable for both children and the elderly, although this value could realistically be increased to 600 (kW/m²)⁴5°C. Conservatism and uncertainties associated with the approach taken to derive this result are presented. Limitations of the use of thermal dose units, H35, rather than skin burn depth models or other units, are also discussed and proposed.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the author alone and do not necessarily reflect HSE policy.
CONTENTS

1. INTRODUCTION 1
   1.1 Background 1
   1.2 Objectives and scope of work 1
   1.3 Methodology 2
   1.4 Report outline 2

2. LITERATURE REVIEW 4
   2.1 Background 4
   2.2 General 7
   2.3 Elderly population 10
   2.4 Children 14

3. FATALITY MECHANISMS IN VULNERABLE POPULATIONS 19
   3.1 Burn response mechanisms 19
   3.2 Oedema 19
   3.3 Hypovolaemic shock 20
   3.4 Scars 21

4. DANGEROUS DOSE CRITERIA 23
   4.1 Outline of approach 23
   4.2 Severe burn limit 23
   4.3 Supporting evidence from medical incident data 29
   4.4 Conclusions 32

5. TDU EQUIVALENCY 35
   5.1 Upper and lower bounds 35
   5.2 Possible disadvantages of thermal dose units 37
   5.3 Alternatives to thermal dose units 39

6. SUMMARY AND CONCLUSIONS 45
   6.1 Overview 45
   6.2 Dangerous dose criteria for vulnerable populations 45
   6.3 Thermal dose units equivalency 48

7. REFERENCES 49

APPENDIX A: GLOSSARY OF MEDICAL TERMS

APPENDIX B: REVIEW OF PROBIT & LOGIT FUNCTIONS DEVELOPED FROM INCIDENT DATA

APPENDIX C: EVACUATION CHARACTERISTICS

APPENDIX D: SMOKE INHALATION

iii
1. INTRODUCTION

1.1 Background

Two previous projects by WS Atkins for HSE have considered the effects of thermal radiation on people. The first was a review of human response to thermal radiation. One of the conclusions of this project was that the use of a Dangerous Dose criterion of 1000 (kW/m²)² was reasonable for an average population with a standard level of clothing. The purpose of the second project was to derive an LD₆₅ dosage for thermal radiation, again for an average population. The LD₆₅ dosage was then used by HSE as the basis for defining the SLOD (Significant Likelihood of Death) criterion of 1800 (kW/m²)².

In deriving the above thermal radiation criteria, it was found that the likelihood of fatality was strongly dependent on the age of the exposed population. Medical data suggests that, for the same severity and area of burn, older people are more likely to be fatalities than younger people. At present, HSE use a Dangerous Dose criterion of 500 kW/m² for ‘vulnerable populations’. A ‘vulnerable population’ is defined as one that includes people who may not respond effectively to evacuation procedures in an emergency, and is typically assumed to comprise both elderly people and children.

The purpose of this study is to review the Dangerous Dose criterion for vulnerable populations in the light of available medical and experimental data. The need for a revised criterion has been assessed and consideration given to whether separate values should be defined for elderly people and children. The latter is based on response to thermal radiation, both in causing fatality and injury, but also considers the escape characteristics of these population groups during a fire incident.

1.2 Objectives and scope of work

1.2.1 Objectives

- To review medical and experimental data relating to the effects of thermal radiation on vulnerable populations.

- To define a Dangerous Dose criterion for vulnerable population groups divided, as necessary, between elderly people and children.

- To review the TDU (thermal dose unit) definition, i.e. I²t, and its application to very long or very short fire exposures.

1.2.2 Scope of work

This study considers the thermal effects caused by major fires on both elderly people and children. The range of fires considered includes those normally associated with major hazards installations, such as pool fires, jet fires, fireballs and flash fires. Overpressure effects are not included, but probability of fatality and the degree of burning likely to be sustained are considered.

The study aims to assess the direct thermal effects on each population, but other factors such as contact with the flame and smoke inhalation must also be considered. In particular, the escape characteristics of each population are identified, and all parameters are compared with those identified for an ‘average’ population.
1.3 Methodology

1.3.1 Literature search

A literature search has been undertaken in order to obtain medical, incident and experimental data and thermal radiation effects modelling published since the first WSA review was undertaken, i.e. 1995. The literature search also includes publications relating to the range of thermal dose definitions used in assessing fire effects on personnel.

1.3.2 Review fatality mechanisms for vulnerable populations

Medical data has been reviewed in order to determine the key mechanisms for fatality of vulnerable populations exposed to thermal radiation. Thus consideration has been given to the variation in likelihood of fatality with age for similar burn severity and area, and the contribution of medical complications such as renal failure, pulmonary sepsis and inhalation injuries. The variation of skin depth with population age, and thus the possibility of increased burn severity for the same radiation dose, has also been assessed. For an average population, it is typically assumed that only full thickness burns contribute to fatality. This assumption has been reviewed and considered given to whether fatalities within a vulnerable population may result from partial thickness burns.

1.3.3 Define Dangerous Dose criteria for vulnerable populations

Based on the results of Task 2, current Dangerous Dose criteria for vulnerable population groups have been assessed and revised criteria proposed. Elderly people have been considered separately from children due to their different responses to burn area and severity. This task has also considered the escape characteristics of the vulnerable population groups, i.e. delay before escape, movement to shelter (if at all), and whether this has an impact on the proposed criteria. Note that the criteria have been based on standard UK levels of clothing.

1.3.4 Review TDU equivalency and usage

Dangerous Dose and SLOD criteria for thermal radiation effects are based on thermal dose units (TDUs) which are defined as $I^* t$, where $I$ is the incident heat flux and $t$ is the duration of exposure to that flux. A review has been undertaken of alternative dose definitions, for example, TNO use a dose for ignition of clothing defined as the total incident radiation energy, $I_t$, while some design codes simply use the incident heat flux, $I$, to define safe levels of radiation on personnel or equipment. Note that this task has assessed whether the current definition is valid for different exposure durations, noting the considerable uncertainty in deriving the Dangerous Dose and SLOD criteria, rather than proposing an alternative definition of a TDU.

1.4 Report outline

The report covers each of the items given in the methodology outlined in Section 1.3.

Section 2 summarises the various literature and information that was reviewed by Hockey & Rew [1] in the first phase of the study. This concentrates primarily on the actual effects that thermal radiation has on humans, and on the various references that model or discuss the impacts and threshold limits of thermal dose. Further information that has been gathered since the first phase of the study is presented and discussed. The emphasis is on information relating to vulnerable populations, although general information is also included where appropriate.
Section 3 describes the actual mechanisms of the body's response to thermal radiation, in terms of both damage and fatality, with particular reference to vulnerable populations.

Section 4 combines the knowledge gathered about fatality mechanisms and the different aspects affecting burn severity in vulnerable populations, in order to recommend dangerous dose criteria. The approach is based on widely used medical definitions of 'severe' burns, combined with 'conservative but realistic' estimates of the dose to cause such burns. This basic approach is supported by dose estimates derived from incident data. The proposed criteria for both children and the elderly are compared, and recommendations made about the most realistic dose level. Areas of uncertainty and recommendations about limitations of the dose are presented.

The use of thermal dose units is reviewed in Section 5, with particular respect to determining a realistic range for which thermal dose units are effectively in representing the impact of radiation. This is done by considering the theoretical limits of the use of thermal dose units, and the realistic limits based on models of typical fire incidents. Alternative methodologies are discussed, such as the use of skin temperature and burn depth models, as well as heat flux ($I$) and energy ($H$) units of measurement. Recommendations are made about the limits of the thermal dose unit and the effectiveness of any alternatives.

Section 6 presents the conclusions of the report and summarises both the main points that have been identified from literature and the key areas where further research may be of benefit.
2. LITERATURE REVIEW

A brief summary of the published data relating to thermal radiation effects on humans, which was identified in a review by Hockey & Rew [1], is given in Section 2.1. Additional data that has been published, or made available, since the above review is presented in the following sections. This is related in particular to the elderly (Section 2.3) and children (Section 2.4), with more general information presented first in Section 2.2. Any overview of such information will inherently cover the actual mechanisms that lead to burns and fatality, although these mechanisms are dealt with more specifically in Section 3.

2.1 Background

2.1.1 Thermal effects models and methodologies

Most of the methodologies for the prediction of the effects of thermal radiation are developed from work by Eisenberg et al [2]. Eisenberg et al used results presented by White [3] detailing the effects on humans of the ultraviolet radiation from the nuclear incidents at Nagasaki and Hiroshima. This model is still widely used, since it is obviously inappropriate to conduct further experiments that involve the burning of humans, or animals. However, experimental data suggests that models based on ultraviolet radiation can over-predict (by a factor of more than 2) the dose levels that would produce an equivalent injury from the infrared radiation that is emitted by major fire events. In light of this, the original model produced by Eisenberg has been modified by a number of authors, including the TNO ‘Green Book’ [4] and Tsao & Perry [5].

These methodologies can be used to estimate the dose required to achieve a certain level of burn, either directly or through the use of a probit function. The TNO approach determines the size of the burn (measured as a percentage of total body surface area, TBSA) as the area of skin that is not covered by clothing. This is based on the theory that clothing offers protection from radiation (up to the relatively high level at which the clothing will ignite). For a given area of burn, mortality charts, which were pioneered by Bull & Squire [6], are used to determine the probability of fatality for a given age. Other methodologies use probit functions to relate age, burn area, and other factors, to the probability of fatality. For an average population, the results of some of the methodologies reviewed by Hockey & Rew are summarised in Table 2.1. Dosage is measured in thermal dose units (TDU), $d^2 t$, where $d$ is the heat flux, in kW/m$^2$, and $t$ is the exposure time, in s.

<table>
<thead>
<tr>
<th>Model</th>
<th>Dosage (kW/m$^2$)$^2$ for Probability of Fatality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1% (Dangerous Dose)</td>
</tr>
<tr>
<td>Tsao &amp; Perry (1979) [5]</td>
<td>420</td>
</tr>
<tr>
<td>HSE – Kinsmann (1991) [7]</td>
<td>1000</td>
</tr>
<tr>
<td>TNO Green Book (1992) [4]</td>
<td>520</td>
</tr>
<tr>
<td>API (1990) [8] – assumes 1min exposure</td>
<td>700</td>
</tr>
</tbody>
</table>

Table 2.1 Comparison of models for the effects of thermal radiation, Hockey & Rew (1996)

Although the HSE dosage appears to be the least conservative of the values presented in Table 2.1, Hockey & Rew discuss a number of mitigating factors which indicate that the Green Book model, for example, is possibly over-conservative. These factors are summarised briefly below.
The methodology of the Green Book compares the area of a partial thickness burn against a mortality chart, which relates the area of both partial and full thickness burns to fatality. Full thickness burns make a substantially greater contribution to fatality than partial burns and the methodology may be very conservative in this respect. (Note that partial thickness burns correspond to '2nd degree' burns and full thickness to '3rd degree'.)

There have been significant improvements in care since the mortality chart used by the Green Book was developed. Based on a series of mortality charts produced by Lawrence [9, 10], survivability is estimated by Hockey & Rew to have increased by more than 20%.

The area of burn is determined from the total area of unclothed skin. Because of the irregular, rounded nature of the body shape, and assuming that the exposed person faces in one direction, the actual burn area will be less than half of the 'available' area of skin which the Green Book methodology assumes.

From consideration of these and other factors, Hockey & Rew conclude that "maintaining a dosage criterion of 1000 (kW/m²)⁴⁵⁰'s, for an average population with a standard level of clothing seems reasonable". It should be noted that the facts and considerations given above greatly simplify the derivation of the HSE's recommended 1000 (kW/m²)⁴⁵⁰'s criterion and further consideration of the selection of this value is discussed in Section 4.2.1.

Hockey & Rew also review a number of reports on major fire incidents and compare the recorded injuries and fatalities with those predicted by the models described above. They find that all of the models tend to over-predict the thermal radiation effects that were actually recorded in the incidents.

Burns are defined as either 'partial' or 'full' thickness, according to the ease with which the burn might heal itself, which determines the severity of the burn. Partial and full thickness burns correspond approximately to the 'traditional' definitions of 'second' and 'third' degree burns, respectively. The basic structure of the skin is illustrated in Figure 2.1, which shows examples of the extent of partial and full thickness burns.

![Diagram of skin layers](image)

**Figure 2.1 (a) Partial Thickness Burn (b) Full Thickness Burn**
A burn which does not penetrate the outer layer of the skin, the epidermis, is referred to as a superficial, or first degree, burn. To become serious, a burn must destroy the epidermis (which is around 0.1mm thick) and some portion of the dermis, which is the secondary skin layer that contains blood vessels, hair follicles and sweat glands. The skin can heal itself by growing from the edge of the wound or from the hair follicles or glands, hence a burn is classed as partial thickness while some portion of the dermis remains. When the dermis (which can be up to 5mm thick but typically around 2mm) is completely destroyed, and the burn extends into the subdermal layer, the skin is unable to heal itself and the burn is classed as full thickness.

2.1.2 Factors affecting response to radiation

As indicated above, the key factor affecting the probability of fatality, for a given depth of burn and burn area, is age. The reasons for variation of fatality with age are discussed in more detail elsewhere, but include reduction in skin depth with age, an increase in the occurrence of pre-existing medical conditions with age and a reducing tolerance to surgery. There are further factors, in addition to age, which have a significant impact on survivability and the review by Hockey & Rew [1] discusses these. The main points are listed briefly below and are described in more detail in Sections 2.2 to 2.4.

- inhalation injury;
- pre-existing medical conditions;
- medical complications arising from burns (renal failure, pulmonary sepsis, etc.);
- clothing levels;
- speed and type of medical treatment;
- part of the body that is burned.

A number of statistical (probit and logit) functions have been developed which use incident data to combine some of the above factors in an attempt to predict the impacts of burns. They can be very useful in predicting at what point high levels of fatality occur, as used by Rew [11] in the determination of a 50% fatality criterion. Since they are based on limited incident data, they are of less use at the extremes, such as for 1% fatality, as is required in this case. However, they can be used to draw important conclusions about general trends, particularly with respect to age, and can also be used to predict other useful factors, such as 2nd degree burns. A number of such functions are assessed in Appendix B and the key conclusions from this appendix are presented in Section 2.2.

2.1.3 Factors affecting radiation dose

Exposure time as well as the intensity, duration and wavelength of the source fire determine the level of dosage received. Exposure time is determined either by the duration of the fire or by the escape characteristics of the exposed person or population, which can be split into the reaction time, speed of escape and distance to safety. Hockey & Rew [1] compare the various factors affecting the hazard range (in terms of thermal dosage) for a series of fire types and sizes. The resulting hazard ranges were found to be less sensitive to differences in escape parameters than to differences in the actual dose criterion. They also note that the differences in the various dose criteria, as shown in Table 2.1, are of a similar magnitude to the uncertainty in current modelling of process fire events.

---

1 Appendix A gives brief explanations of the medical terms that occur commonly in burns discussions.
Since dose criteria are measured in thermal dose units, which are determined from both radiation intensity and time of exposure, escape characteristics are ‘accounted for’ in the thermal dose measurement and do not need to be considered further in the scope of this study. It is still prudent to remember that, as well as responding to the physical effects of a given dose differently, ‘vulnerable populations’ are also vulnerable to actually receiving larger doses because of their differing escape characteristics. Some consideration of how escape characteristics vary with age is included in Appendix C.

2.1.4 Non-fatal injury (morbidity)

In addition to modelling of fatality, many of the models can be used to determine ‘serious’ burn levels, at which scarring or disfigurement occurs. Hymes et al [12] proposed a criterion based on the threshold dose for partial thickness burns, beyond which serious disfigurement can occur. From the experimental data presented by Kinsmann [7], Hockey & Rew [1] suggest that a dosage of between 240 and 730 (kW/m²)⁴⁰会议精神 will produce partial thickness burns. They state that “towards the higher end of this range, a significant proportion of the dermis will be damaged and scarring will be likely”.

Determining what level of scarring is ‘unacceptable’ is clearly a very difficult subject. However, scarring and disfigurement are very important considerations in the effects of thermal radiation and are discussed in more detail in Sections 2.3.3 and 3.1.4.

2.2 General

2.2.1 Incident data

In a topic area such as human response to burns the general rule is that ‘there are no rules’. Examples of patients treated at the McIndoe Burn Centre, given by Ryan [13], such as an 80 year old who survived 80% TBSA burns and a 23 year old who died from 20% TBSA burns (which are by no means exceptions), illustrate that the response of individual patients can vary enormously. In these circumstances it is invaluable to be able to identify trends from incident data, although it is important to treat any such trends with a high degree of caution.

If ‘typical’ differences between, for example, an ‘average’ adult and an ‘average’ child are to be identified it is essential to acknowledge – and, where possible, address – the limitations of the data. The main points that should be considered when looking at incident data from hospitals or burn centres are discussed briefly below.

- Data is based on patients actually treated, and does not account for fatalities who never reach hospital (and also minor burn victims who may be treated outside of burns wards or units). Similarly, Clark & Fromm [14] state that the crude mortality rate is generally higher in burns units than in hospitals since, even in cases with the same burn size, the more serious injuries will be treated by specialist burns units. They also estimate that up to half of all burn fatalities occur before the victims reach the healthcare system.

- Hospitals rarely differentiate between different causes of burns – since cure is their overriding interest, not cause – and burns data will include contact, chemical, electrical and even sun burns, which are not relevant to thermal radiation from industrial fires as considered here. It should be noted that Lawrence [15] states that, in his studies of burn victims, only 2% of burn victims suffer from ‘thermal radiation burns’.

7
• In a similar way, the wide range of burns included will include house fires and other scenarios where inhalation injury is more likely than in cases where exposure to radiation occurs at a distance (as is most prevalent in the circumstances of interest here).

• Different data sets will adopt different approaches to defining factors such as cause of death and severity of burns. In particular, differentiation between fatality through burns and through inhalation injury is notoriously difficult. Furthermore, determining the area and depth of burns is not an exact science.

Hockey & Rew [1] review many of the statistical analyses of incident data that are available (which are presented in Appendix B). Some of the overall conclusions that can be made from their review, i.e. those relating to general effects rather than specifically to vulnerable populations, are listed below.

• Rittenbury et al [16] indicate that around 2% of patients with partial thickness only (no full thickness) burns died.

• Moores et al [17] and Pruitt et al [18] suggest that the extent of full thickness burns is not independent of the total area of burn. Several authors use both full thickness and partial or total thickness burn areas in their correlations.

• Rittenbury et al, Moores et al and McCoy [19] all indicate that race and sex can have some effect on the mortality for a given burn. Given that this study is interested predominantly in the implications of age, it is assumed that any variations caused by sex or race are consistent at each age level.

• Rittenbury et al [20] also suggest that a wide range of 'complications' can effect mortality at the lower levels of fatality, but for more significant burns the number of factors of influence is reduced. They suggest that there are many contributing factors at the 1% fatality level, while at the 5% fatality level only age and post-burn liver complications, in addition to total burn area, are significant.

Further analysis of the statistical models has been performed in Appendix B, and is discussed in more detail in Sections 2.3 and 2.4, relating to the elderly and children, respectively.

A number of authors present additional incident data which represents general hospital or burn centre admissions, rather than just for the young or elderly. Some points that are of relevance to any population are presented below.

• Burdge et al [21] analysed elderly patients and evaluated the total burn surface area (TBSA) and also the area of full thickness burn. These figures were averaged for each relevant data set and indicate that full thickness burns made up approximately half of the total burn area.

• Brigham & McLoughlin [22] present a widespread review of burn incidence in the United States and give results illustrating the significant decline in burn admissions between 1971 and 1991 (with a decline in deaths of around 50%).

• They quote a figure that illustrates some of the danger in using figures derived from hospital data, which is that, of 5500 recorded fire deaths in 1992, only 1400 occurred in burn centres or hospitals. Note that the remaining 4100 deaths (75%) could be from either (a) deaths caused by burns at the scene, or en route to hospital, or (b) at hospital from other causes, such as smoke inhalation or trauma. Similarly, Barillo & Goode [23] found
in their study of fire deaths that 554 out of 705 burn fatalities (79%) occurred before victims could be treated in hospital.

- Another reason for caution in using hospital incident data is given by Barillo & Goode, who state that fire death rates in North America (where most of the incident data discussed here originates) are twice as high as they are in Western Europe and Japan.

- Data presented by Forjuoh [24] suggests that only 5% of cases involving the ignition of clothing prove to be fatal. This contradicts to some extent the assumptions that have been made in previous assessments by Hockey & Rew [1], and others, who assume that ignition of clothing results in 100% fatality. However there is an important distinction which must be made between contact ignition (from, say, a flame or cigarette) and ignition of clothing due to radiation (which is of interest in this case). Forjuoh's data, based on hospital admissions, may be disregarded since it will primarily include contact ignition where removal of the clothing will eliminate the hazard. In incidents involving radiation from a fire event, the radiation will be of a very high level in order to ignite clothing, and will remain as a substantial source of burn even if the clothing is removed. An equally important factor is that ignited clothing will significantly hamper escape, leading to an increased dose on the un clothing areas of skin. Thus, although acknowledging that it is potentially conservative, Hockey & Rew concluded that the assumption of 100% fatality in the event of clothing ignition from radiation is reasonable.

2.2.2 Smoke inhalation

Settle [25] states that inhalation injury, causing damage to the pulmonary system (i.e. the lungs), has become the largest single cause of death in patients treated at the Yorkshire Regional Burns Centre. In terms of the mechanisms of damage, inhalation injury is independent of burn injury and internal damage from the breathing in of hot smoke can cause fatality without the presence of burns. Burns and inhalation injury are, however, caused by the same circumstances and are inevitably linked. In fact, it is often impossible to determine whether fatality has been caused by response to a severe burn or by the associated inhalation injury.

The situation of interest in this study is the impact that radiation from industrial fires may have on the general public, who will typically be off-site, typically at some distance from the fire source. In these instances, burn victims are much less likely to be trapped or subject to smoke inhalation. Nevertheless, smoke inhalation is a very important factor in the response to burns and should not be ruled out. It is, however, important to consider the reduced incidence of smoke inhalation in this study when assessing mortality charts and other fatality criteria. They are generally derived from a range of situations, which will inevitably include many cases where smoke inhalation has increased the rate of mortality.

As discussed above, it is difficult to quantify the extent of inhalation injury. Some conclusions may be drawn from the probit model of Clark & Fromm [14], presented in Appendix B, which are summarised below.

- Inhalation injury has some impact on survivability even at very small burn areas.

---

2 Lees [28] assumes that ignition of clothing occurs at 1800 (kW/m²)⁴⁸, although the exact value will depend on the type of fabric involved. Many authors have assessed clothing ignition in more detail and their results are summarised by Lees [26] and Rew [1].
• Its impact becomes more significant as burn size increases up to a limit of around 70% TBSA full thickness burn area, at which point the probability of survival is already very low, even without inhalation injury occurring.

• Inhalation injury is more significant to elderly patients, even for small burn areas.

• Inhalation injury can also be seen to be more significant to children than adults, although the difference is relatively small compared to the difference between adults and the elderly.

Further discussion of the effects and extent of inhalation injury, based on a number of references, is given in Appendix D.

2.2.3 Skin depth factors

One of the most important aspects of burn injuries, which is not well documented at present, is the part of the body which is affected. The reasons for the importance of this are that:

• The depth of skin varies considerably around the body (typically a dermal depth of around 5mm in the back to just 0.1mm in the eyelids) and can also reduce with age. Thus, the same dose can produce different depths (i.e. severity) of burn.

• Certain parts of the body are more at risk to oedema, which can cause swelling to the extent that breathing is stopped. This is covered in more detail in Section 3.1.2.

Another key variable that can result in the same dose producing different levels of burn severity is the initial temperature of the skin. This is described by Lees [26] and Maillette & Birk [27], and suggests that pre-cooling of skin can significantly improve the survivability from a given dose. The impact that skin temperature has on burn severity does not vary with age, so is not significant in terms of the determination of a dose criteria for vulnerable populations.

Temperature models, based on skin temperature, thickness, and other effects, can be used as an alternative to the use of thermal dose units in measurement, and prediction, of burn severity and fatality. The work of Lees [28], Lawton et al [29] and other authors, which focus on burn depth and skin temperature, is discussed briefly in Section 5.

2.3 Elderly population

2.3.1 Burn response characteristics

Identical burns can be more significant to elderly persons due to:

• increased mortality (reduced tolerance to the mechanism of burns);
• pre-existing medical problems;
• thinning of the dermis, and atrophy of skin appendages;
• general health (surgery is more difficult, and infection more likely).

Exposure duration can be longer for elderly persons due to:

• reduced mobility;
• increased reaction time.
The above summary of the main factors that distinguish the elderly from an average population, in terms of survivability in a thermal radiation incident, is based on the literature that has been reviewed. The first set of the above factors are those which affect response to radiation, and thus the probability of survival, and are discussed further in the following sections.

The second set of factors are given to emphasise the fact that the elderly are also ‘vulnerable’ in terms of escape, as discussed in Section 2.1.3, and so more likely to receive a larger dose from a given fire incident. This is not dealt with further here, but some consideration of how escape characteristics vary with age is included in Appendix C.

It should be noted that, at this stage, it is not necessary to strictly define what age is ‘elderly’, but in most references the elderly are defined as persons 60 years of age or older.

2.3.2 Mortality

The increasing risk of mortality as age increases, for a given burn, is covered by almost all of the methodologies, models and probit functions. Fire burn admissions of all ages are reviewed by Forjoh [24], who confirms that injuries are more likely and more serious in the elderly population. Some of the key points relating to the elderly, derived from the statistical functions described in Appendix B, are summarised below.

- Analysis of different functions with respect to specific contributors to fatality, which can occur at all ages, is presented in Appendix B. This illustrates that complicating factors, such as oedema, inhalation injury and pre-existing medical conditions, can have greater impacts on the mortality rate in the elderly.

- Note that the above point is based on the probability of fatality given that these complicating factors occur. The increased incidence of such factors in the elderly is a separate issue, which will also increase the mortality rate of the elderly.

- Probit analysis by a range of authors indicates that there is a steady increase in mortality with age, from an early level (around 20 years old), for a given burn area. This increase becomes more marked around the age of 60, and increases rapidly beyond this age.

- The rate of increase in mortality with age is also higher for larger burn areas.

In addition, incident data from several sources, which considers the effects on the elderly in particular, is available and is discussed briefly below.

Burdge et al [21] present data collated in Ohio State University’s surgical burn treatment section, relating specifically to the elderly (defined here as persons 60 years of age or older). Anous & Heimbach [30] present similar data from Washington State, for a slightly larger set of 125 patients, evaluated between 1980 and 1983.

Both Burdge et al and Anous & Heimbach evaluate the probability of survival for different burn areas. Both found a very low probability of survival for burn areas of over 40% TBSA (there were no survivors in Burdge et al’s assessments), and a high probability of survival for burn areas of less than 20% TBSA (greater than 80% survivability was found in both studies). Between these upper and lower burn areas the survival rate is not so clear. Burdge et al found a probability of survival of 82%, while Anous & Heimbach reported a survival rate of just 28%. Even this simple comparison illustrates that, when using incident data:
• Very broad conclusions (such as declaring the chances of the elderly surviving as being good for below 20% burns, and very poor for greater than 40% burns) can be made.

• Drawing more detailed conclusions (such as estimating the probability of survival for a specific burn) is very difficult indeed.

Presumably based on both their own analysis and data from the National Burn Information Exchange, which they present, Burdge et al conclude that “49% TBSA burns are usually fatal” for elderly populations. They state that this level of survivability has increased from just 10% TBSA in the 1940’s, and 30% TBSA in 1971. However, they conclude that the improvement in burn care, which has resulted in these increased limits, has not “decreased the mortality rate in the elderly, in the same way as it has done for other age groups”. In a similar vein, Annous & Heimbach conclude from their own results that survival of elderly patients is “impossible for burns over 70% TBSA”.

These simple conclusions are supported by the data summarised in Appendix B.3.1. This indicates that fatality is consistently low (less than 10%) below a burn area of 10% TBSA, and consistently high (more than 90%) beyond 40% TBSA. It may be said from the combined assessments shown in Appendix B.3.1 that survival of elderly patients is almost impossible for burns of more than 60% TBSA. This compares with an equivalent value, for ‘highly probable fatality’ in both average populations and children of between 80 and 100% TBSA.

Although covering all types of fire and burn injury (including smoke inhalation cases), Barillo & Goode [23] present NFPA estimates which suggest that elderly populations (over 65) have a risk of fire death twice as high as that for an average population. This is also supported by comparisons of the probit data, which are detailed in Appendix B.3.2.

2.3.3 Pre-existing medical problems

An important point identified in the study by Burdge et al [21] is that almost ¾ of the elderly patients that were assessed had “pre-existing medical conditions”. This term is generally used in burns care to describe existing illnesses which can reduce (sometimes very significantly) the chance of survival, such as heart disease, pulmonary problems, renal failure\(^3\), diabetes, stroke, or alcohol problems. The mechanisms that take place in the body in response to a burn, which are described in Section 3.1, can significantly exacerbate such conditions, which can greatly increase the probability of fatality. The extent to which such illnesses occur varies considerably (for example, diabetes can be mild or very serious, which will affect burn response proportionately), and is difficult to quantify. There is little data that quantifies the occurrence of such conditions in the elderly and none to compare against for ‘average’ populations.

It is important to note that such conditions can occur at any age, and not just the elderly. Pre-existing medical problems are simply more common in the elderly and, since they considerably increase the mortality rate from burns, contribute to increasing the overall risk of fatality from burns at the upper end of the age scale.

The discussion in Section 2.2.1 indicates that, even for elderly populations, a patient would ‘typically’ be expected to survive a 20% burn area. In the same assessment that led to this conclusion, Burdge et al treated a patient with only 10% surface area burns who died from a myocardial infarct due to a pre-existing condition. The Lawrence chart [10] indicates that a

\(^3\) Appendix A gives brief explanations of the medical terms that occur commonly in burns discussions.
healthy 23 year old would ‘typically’ be expected to survive a burn area of up to 50%. However, Ryan [13] reports that a recent 23 year old fatality, examined at the McIndoe Burn Centre, died from a burn area of less than 20%, largely because he had been suffering from pneumonia.

The above examples are given to illustrate the range of variation in response to burns that can occur because of the existence of other medical conditions in a patient. They are not extreme cases, patients can die from far smaller burns if other health complications are present, nor are they rare. However, it is fair to say that a ‘typical’ adult would not have any significant pre-existing condition, while a ‘typical’ elderly burn victim may be expected to have some form of existing condition, if only a relatively minor one.

2.3.4 Thinning of the dermis

The thickness of skin, in general, decreases with increasing age and Clark & Fromm [14] postulate that older people have thinner skin and so may suffer a larger or deeper burn for a given heat dosage. This view is supported by Burdge et al [21] who state that the ‘thinner skin’ effect is due to both thinning of the dermis and atrophy of skin appendages. There is little analysis available to support this, although it becomes visually apparent in the very old, and it is reasonable to assume that there is a gradual reduction in skin thickness from early adult life onwards.

Although skin depth varies around the body, the average thickness will be less in older adults. The severity of a burn is directly indicated by the depth to which it penetrates, so it follows that the elderly will, generally, receive a more severe burn from a given dose than their younger counterparts.

2.3.5 General health

In addition to the increased likelihood of specific illnesses (i.e. pre-existing conditions) occurring in older burn victims, general health also decreases with age. East et al [31] refer to this in terms of stamina and endurance, and suggest that the health peak in humans is between 5 and 34 years of age. Clearly, a less healthy body will be less likely to cope with any form of injury, and in burns this manifests itself in the following areas.

- The various mechanisms of burn response in the body are described in Section 3.1, but essentially involve the thinning of the blood, resulting in clinical shock and various side-effects. The consequences of this effect occur at lower levels of fluid loss, which is directly related to burn size, in less healthy (i.e. older) bodies.

- There is a high risk of infection through burn wounds and (again in general) the elderly will be less healthy and less able to prevent, and to cope with, infection and its related risk of disease, etc.

- The basic process of skin grafts and blood transfusions, which often occur repeatedly in burn treatment, place the body under a certain amount of strain. Again, these effects are more serious in a less healthy body.

Burdge et al [21] discuss the conflict in treatment caused by the latter two points. Because of the risk of infection, early closure of the wound, through excision and grafting is desirable. They reference work by Deitch & Clothier [32] who demonstrated a decreased mortality when early closure of the burn wound is performed. This is not always possible because of the risks posed by the actual surgery and Burdge et al state that grafting of the burn wound
has been used less frequently in the elderly population than in younger patients, for this reason.

Clearly, general health varies from person to person, and many ‘elderly’ people are healthier, and more able to cope with a burn, than much younger adults. However, it is fair to say that a ‘typical’ elderly person will be less healthy than their younger counterparts.

Moyer [33] reports that the elderly who die from a burn injury die more rapidly than younger adults suffering from a similar injury. They suggest that this is due to the elderly being less able to tolerate internal changes that are brought about by burns and the related surgery.

2.4 Children

2.4.1 Burn response characteristics

Identical burns can be more significant to children due to:

- increased mortality (reduced tolerance to the mechanism of burns);
- scarring, or morbidity, is even less desirable;
- more exposed skin;
- surgery is more difficult, and infection more likely.

Exposure duration can be longer for children due to:

- reduced mobility, and dependence on adults, for the very young;
- increased reaction time;
- less predictable behaviour.

The above summary of the main factors that distinguish children from an average population, in terms of survivability in a thermal radiation incident, is based on the literature that has been reviewed. The first set of the above factors are those which affect response to radiation, and thus the probability of survival, and are discussed further in the following sections.

As for elderly populations, in Section 2.3.1, the second set of factors are given to emphasise the fact that children are also ‘vulnerable’ in terms of escape, and so more likely to receive a larger dose, from a given fire incident. Some consideration of how escape characteristics vary with age is included in Appendix C.

Incident data on hospital admissions for burn injuries, such as the American National Burn Information Exchange (NBIE), reported by East et al [31], shows that a disproportionately high number of children suffer burns – approximately a third of all burn victims are children. Similarly, both the McIndoe Burn Centre in East Grinstead [34] and the Pinderfields Burn Centre in Wakefield [35], state that, on average, children make up a third of their admissions, and various other authors report a similar proportion of child patients. Of child burn victims, East et al state that around 50% are below the age of 4 years old. These figures refer to all types of burn, which includes scalds and domestic accidents where young children are clearly more accident prone. The situation of interest here is radiation effects from industrial fires where it can be assumed that anyone in the vicinity of the incident will be equally likely to be exposed to the fire, irrespective of age.

It should be noted that, at this stage, it is not necessary to strictly define the age range for which a person is a ‘child’. Although, generally, children are considered to be between 0 and
16 years of age, the response to burns can vary considerably in this range (particularly from 0 to 5 years), and some authors consider narrower age bands.

2.4.2 Mortality

In Lawrence's [10] mortality chart, the probability of surviving a burn of a particular size increases steadily with decreasing age. This general pattern is followed by several other authors, including several of the probit analyses that are presented in Appendix B. However, probit analysis by East et al [31] indicates that survivability increases with decreasing age only to a limit of around four years of age, where survivability then decreases slightly. Similarly, Clark & Fromm [14] also state that "probit analysis confirms that the ability to withstand a major burn peaks during the adolescent years", based on analysis at a regional burn unit in New York. They indicate that mortality rates in very young children, for a given burn, are higher than for older children, and mortality increases rapidly then beyond the age of 30.

It is possible that the improved response to burns in very young children shown by some authors, such as Lawrence, is due to greater prioritisation of medical care towards very young patients. And several other explanations may be postulated. However, both the evidence presented elsewhere in this report and the general medical approach to burns treatment, support the findings of East et al and Clark & Fromm. In other words, that young children are more at risk from a given radiation dose than adults.

An additional explanation for the suggestion by Lawrence, and other authors, that mortality may be lower in children than adults, is that children are growing. This can have negative consequences with respect to burns, as discussed in the following section, but can also be a benefit. The growth of children, particularly at very young ages, is continuous and provides a natural boost to the normal healing process. This factor should be noted in mitigation of the many negative aspects of burn effects that apply to children, which are presented in the following sections.

2.4.3 Scarring, or morbidity

East et al [31], Lawrence [36], and other authors, discuss the impact of scars on children. Although obviously undesirable at any age, scars and permanent disfigurements will be particularly traumatic to children and many recent papers suggest that there should be a shift towards the use of dose criteria based on the threshold of scarring or disfigurement. Generally, dose criteria are based on consideration of fatalities, which occur around the threshold of full thickness burns. Hymes et al [12] suggest that the dose criterion be set at the 2nd degree (partial thickness) burn threshold. Clark & Fromm [14], Maïllette & Birk [27], and other authors indicate the importance of not overlooking morbidity factors, although Clark & Fromm acknowledge that fatality is the only indicator of burn effects that is practicable at present.

Clearly, severe scarring arising from thermal radiation should be identified as unacceptable. However, determining what level scarring must reach to become ‘unacceptable’ is a difficult, and potentially emotive, subject. Although measuring, modelling and setting limits for scarring in children is just as difficult as it is for adults, it is an area where distinctions can be made between ‘children’ and average or elderly populations. These points are discussed below and further discussion of how these factors may be incorporated into dose criteria considerations is given in Section 4.2.2.
• The ‘social’, or psychological, factors associated with burns morbidity are the most difficult to assess. Scars or disfigurements, particularly of the exposed areas that are at most risk in radiation incidents, can be very traumatic at any age. While it will be a terrible experience for an emotionally mature adult, it can be said that it will be even more damaging for a child. While living with scars is difficult, growing up with scars is extremely difficult. (That is, acts of ‘growing up’ such as developing socially and emotionally, making friends, finding work, etc, are dramatically affected).

• Many adults who survive serious burns but are left with disfigurements will require help, and this will often place heavy demands (financial, emotional and physical) on their immediate family. Whatever the cut-off point may be, in terms of burn size and severity, that begins to affect the families of adult victims, it will be substantially lower for children. Again, the effect is impossible to quantify but the families of scarred or disfigured children will inevitably be affected more than those of adults.

• The above two examples are quite subjective, and can be difficult to quantify, let alone quantify. The difference between adults and children in terms of the physical effects caused by morbidity is much clearer. Lawrence [36] and Ryan [13] discuss the implications of ‘contracture’ which is the result of damaged, or grafted, tissue shrinking or tightening during healing. This can significantly affect movement – resulting in partial disablement, and often deformity. (Physiotherapy can usually relieve but not prevent this effect.) Although it does not produce fatality, this consequence of thermal radiation may be described as unacceptable for adults. However, there is a very definite distinction in children, because their scar tissue will not grow, while the rest of their body does. In other words, the ‘contracture effect’ continues to worsen for as long as a child continues to grow.

An example of the extent of the impact that scarring can have is seen from one of the outpatients treated by the McIndoe Burn Centre, described by Ryan [13]. Severely burned at a few months of age, an overseas patient was eventually transferred to the UK to receive the specialist treatment that was needed as part of his initial recovery. Now 15 years old, the patient attends school near East Grinstead, needing to remain close to the burn centre there, in order to receive regular treatment.

The length of treatment involved in the above example is more common in children than adults, but is by no means exclusive to children. It does, however, illustrate the permanence of the dramatic changes that burns morbidity can have on people.

2.4.4 Increased skin exposure

In addition to being generally more accident prone and being less likely to escape from a fire incident, children are smaller than adults. Thus, as Lawrence [36] suggests, the same mug of hot coffee that might produce a 1% TBSA burn on an adult, could cause 5% TBSA burn for a small child. However, this is not so relevant when considering radiation effects, since the area of burn is generally determined by the area of exposed skin (which is independent of the size of the victim).

However, even assuming the same type of clothing, the exposed area of skin is generally greater in children than adults. A child’s head grows much less than the rest of the body and so starts off as a much higher proportion of the total area. The TNO Green Book [4] uses data based on the Dutch population to determine that the face, neck, hands and lower arms of an adult make up 20% of the body area, while the same parts form around 30% of a young child’s body. The exact percentage varies with age and is given in some detail by the Lund
and Browder chart (distributed by Smith & Nephew [37]), shown in Figure 2.2. This chart is used widely in the medical field, and also gives comparable areas to those used by TNO.

![Figure 2.2 Lund and Browder chart used for measuring area of burns](image)

Note that other guides to the components of body surface area are given by the Rule of Nines and Brandwonden — which are reported by Hockey & Rew [1], TNO [4] and Settle [25]. These are more simplistic, and Settle’s guide to the treatment of burns states that they are invaluable for quick initial estimates of patients burn area. However, Settle recommends that the Lund and Browder chart should always be used for accurate assessment of burn area when more time is available.

The TNO Green Book’s assumption of 30% exposed area for young children when the head, neck, hands and lower arms are exposed is borne out by the figures presented in Table 2.2. It should, however, be noted that this applies to very young children (below the age of 2 or 3) who, if not completely shielded by a pram, might be expected to be wearing a slightly higher level of clothing. Older children will have exposed areas closer to that of an adult population. Since the level of clothing worn varies considerably, according to many factors (including weather, time of day, activity and personal behaviour and taste), the exposed area is simply an estimate of a ‘typical’ level of clothing. To maintain consistency with the approach used for adults, a normally clothed child is also assumed to have the head, neck, hands and lower arms exposed. The corresponding area of exposed skin is taken from Table 2.2 as being 30%. This is slightly biased towards younger children in the interests of conservatism and to provide a clear distinction between adults and child.
<table>
<thead>
<tr>
<th>Chart</th>
<th>Area as % of total body area at each age, or age range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Lund &amp; Browder</td>
<td>33</td>
</tr>
<tr>
<td>TNO, Green Book</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.2 Area of head, neck, lower arms and hands as a percentage of total body area at different ages.

2.4.5 Increased risk from surgery and infection

As discussed in Section 2.3.5, East et al [31] refer to a peak in the stamina and endurance of humans between the ages of 5 and 34 years of age. In the same way that the body is known to deteriorate as it becomes old, it is also less effective when it is very young. This can be described more as a 'lack of development' rather than a 'lack of health' (as it can be crudely described in the elderly), but the effect is very similar. In other words, in the very young, the body has not fully developed the mechanisms or strength to cope with abnormal conditions, whereas in the elderly these mechanisms are present but are deteriorating. The same points that are given in Section 2.3.5 are summarised below.

- The various consequences of fluid loss are triggered at a lower level in very young children.

- The very young will be less able to prevent, and to cope with, infection and its related risk of disease, etc.

- The various effects of skin grafts and blood transfusions are more serious in a body that is not fully developed.

General health varies from person to person, at all ages, although the reduced ability of very young bodies to cope with a burn may be considered a reasonably constant factor, compared with the variation in general health that can occur in adults. Again, it seems reasonable to say that a 'typical' young child will be less able to cope with the above aspects than their adult counterparts. This effect is demonstrated by the greater incidence of 'toxic shock syndrome' in children, as reported by McAllister et al [38], which is discussed briefly in Section 3.1.3.

It should be noted that the above factors are less significant in older children, and the 'lack of development' consequences become less important around the ages of 5 to 10 years old.

It is noted here that pre-existing conditions can have a significant impact on the survival of a burned child, as they can at all ages. It is suggested by East et al [31] that pre-existing conditions are more common in young children than in adults. However, it is assumed here that the existence of pre-existing conditions in children is not significantly different, both in terms of frequency and its impact on mortality, from that of an 'average' population.
3. FATALITY MECHANISMS IN VULNERABLE POPULATIONS

In order to characterise the differences in response to thermal radiation at different ages, it is important to understand the mechanisms in the body that deal with burn injuries. Sections 3.1 to 3.4 give a basic introduction to the medical factors that are involved in burns.

3.1 Burn response mechanisms

The most obvious disadvantage of a burn is that skin is damaged. Skin is an organ, which performs a number of essential functions, which are listed below:

- Sensory organ – nerves, pain, touch, temperature and pressure.
- Makes Vitamin D – by the action of ultraviolet light on sterols in the skin.
- Temperature control – through dermal capillaries, sweat, and the air cell effect of hair.
- Secretion & excretion – water, salt, sebum, bacteriostatic agents, etc.
- Protection – keeps out undesirable external influences, such as bacteria.
- Waterproof barrier – keeping in most of the body’s fluids.

Maillette & Birk [27] define a skin burn as “the result of an elevation in tissue temperature above a threshold value for a finite period of time”. Hynes [39] summarises data from a number of sources that show that the threshold value, to produce superficial burns, is 44°C. Also, it is damage to skin which can lead to scarring (discussed separately in Section 3.4).

The greater the depth and/or area of a burn, the greater the impact on the functions listed above will be. All of these functions can contribute to damage or fatality. In particular, body heat and fluid are lost through the interruption to the skin covering, and the possibility of infection becomes much greater. However, it is the loss of fluid that has by far the most serious effect, in terms of potential fatality, and this is by no means restricted to loss through the actual burn area.

Immediately after a burn is sustained there is an increased permeability of the capillaries, which will continue for about 48 hours. This causes the capillaries to leak water, electrolytes and small proteins into the tissue. Thus, in addition to the fluids, or plasma, that will be lost through the actual burn, fluid is lost from the blood stream to tissues below or around the burn area. The effect of this is to thin the blood, which may be explained using the ‘minestrone soup’ analogy [13]. The useful components of blood, such as red blood cells and nutrients, can be equated to the vegetables in minestrone soup. These are not lost but the water or plasma that carries them around, which is like the stock in minestrone, does leak out as described above. This leaves the ‘vegetables’ which are now unable to circulate around the body.

The consequence of the reduced circulation is hypovolaemic shock, and the result of the leakage into the tissue is oedema. Both of these can have extremely adverse effects, ultimately resulting in fatality, which are discussed in the following sections.

3.2 Oedema

Oedema is defined by Collins [40] as “an abnormal accumulation of fluid in the tissues of the body, causing swelling”. As described above, oedema results from changes in capillary

Appendix A gives brief explanations of the medical terms that occur commonly in burns discussions.
permeability causing plasma to leak from the damaged area into tissues. Settle [25] states that oedema will begin to occur beneath the areas damaged by a burn within minutes of the burn occurring. The consequences of such swelling can vary considerably around the body. Oedema itself can have little significance away from vital organs, but excess swelling around respiratory organs, and other key organs or limbs, can be fatal (Judkins [41] states that “facial burns always swell grossly”). Ryan [13] suggests that a reasonably large burn to the back, where the skin is also thicker, can be easily treated, while a superficial burn to the face, neck or chest can result in fatality, primarily because of the threat posed by oedema.

This is one of the key reasons that a certain dose, resulting in the same burn area, can have very different consequences depending on the part of the body affected. In other words, an identical dose and burn area, in people of the same age and level of health, treated immediately, can still produce different responses. The variation in skin depth around the body has a similar effect.

Note that in addition to the respiratory problems caused by oedema, circumferential burns can have similar consequences. Damaged skin cannot stretch, resulting in a ‘tourniquet effect’ which can impede blood flow to essential tissues, causing further damage, and can cause breathing difficulties when present in the neck or chest areas.

As stated above, the potential consequences of oedema are most significant around respiratory organs and other key limbs and organs. This may have implications for the approach of TNO [4], which has been widely adopted by other authors, which assumes that the face, neck and hands are the main body parts to be affected by thermal radiation from fire events.

The size and depth of burn which causes oedema, and the extent to which oedema must occur to produce fatality, is (like most aspects of radiation effects) very difficult to determine. Settle indicates that the development of oedema cannot be prevented, once a burn has occurred. However, it is only dangerous in certain parts of the body and if intubation, tracheotomy, or other medical treatment, is received in time, the danger to life may be controlled.

In the event of oedema occurring, fluid will be lost and hypovolaemia may occur. Unlike oedema, this can be prevented, or its effects minimised, if prompt medical treatment is available to replace fluid, as described in the following section.

3.3 Hypovolaemic shock

It is important to note that in this case (and correctly speaking, in all cases) ‘shock’ is a medical term, and not to be confused with the common perception of it being an emotional or mental response. Dietzman and Lillhei [42] define shock as “the inability of the circulatory system to meet the needs of tissues for oxygen and nutrients and the removal of metabolites”.

In the case of hypovolaemic shock these failings of the circulatory system are caused by the loss of plasma, i.e. the ‘menstrue’ effect, as described in Section 3.1.

The consequences which come under the umbrella of hypovolaemic shock are widespread. The main points described by Thorne & Ryan [43] are listed below.

- The volume of blood and plasma in the vessels is decreased and less blood is able to be pumped to and from the heart.
- The circulation is lessened to the kidneys and urine output is diminished.
• The greater the loss of plasma, the more concentrated become the red blood cells and the viscosity of the blood increases. This causes micro-thrombosis of fine peripheral capillaries.

• Haemoglobin is released into the blood stream as red blood cells are destroyed at the time of the burn. These cells appear in the urine, blocking the renal tubes and leading to renal failure.

It can be seen that each of the above effects is related to at least one of the ‘pre-existing medical conditions’ that are referred to in Section 2.3.3. Where such conditions occur, the body is already weakened and a much smaller degree of hypovolaemia can cause the same potentially fatal effects. It should, however, be emphasised that the above effects do not need the presence of a pre-existing condition for them to become fatal.

There are a number of additional factors, which are more traditionally associated with shock, such as breathing difficulty, disorientation, thirst and coldness. Settle [25] describes these as compensatory mechanisms, which serve to maintain blood flow until the last possible moment. They are symptoms of inadequate perfusion of the body tissues and are essentially side-effects which are only treated by the restoration of circulation, i.e. the treatment of the primary problem, hypovolaemia.

Settle states that once a third of the total volume of blood has been lost, the shock will be at a severe stage and the patient’s life will be in danger. He states that, for example, this stage will be reached 3-4 hours after a burn is experienced in the case of extensively (50% TBSA or more) burn cases.

Any size of burn will instigate oedema, but the size at which oedema can lead to significant thinning of the blood determines when a burn is classed as ‘major’. Settle suggests that 15-20% TBSA is the limit (at which fluid replacement by intravenous infusion is required) for adults. For children, and the elderly, this limit is reduced to 10-15% TBSA. Most hospitals or burns units use the lower limits of the above scales (i.e. 15% in adults, 10% in children and the elderly) to determine when burns are ‘major’. Lawrence [36] refers to the same limits as ‘shock cases’, where the point at which “patients would almost certainly not recover” without prompt fluid resuscitation. Settle also indicates that for greater than 30% TBSA, the burns are classed as ‘extensive’ and fluid replacement becomes both “essential and urgent”.

A variation of the effects of shock is staphylococcal toxæmia, or ‘toxic shock’, which is described by McAllister et al [38]. Their discussion indicates that children are particularly susceptible to this form of shock, and that once ‘shock’ has occurred the mortality of the condition is approximately 50%.

3.4 Scars

Superficial burns, which affect only the outer surface of the skin (the epidermis) are not treated as significant in consideration of radiation effects. Similarly, they have little impact in terms of morbidity, and Thorne & Ryan [43] indicate that they will usually heal within 7 to 14 days leaving no scarring.

Partial thickness burns, which are those that penetrate the outer surface of the skin and a proportion of the dermis, can produce scarring. Both the depth and area of burn is significant in the extent of lasting damage. If some of the dermis remains, it can regenerate, through the division and spread of surviving cells. Small areas or relatively shallow burns can heal with minimal scarring. Usually, partial thickness burns will heal within 14 to 21 days, but for
significant cases skin grafting is often necessary. Skin grafting can prevent or minimise the extent of scarring, but in larger cases scars will remain.

Full thickness burns indicate that the dermis has been completely destroyed and the subcutaneous tissue, and even muscle and bone, are affected. These burns will not heal without skin grafting.

Skin grafting involves the use of thin layers of skin from healthy parts of the body to heal potentially deeply damaged areas. This means that usually, to compensate for the disproportionate volume of ‘good’ skin to damaged skin, the skin is ‘meshed’ (cut in a lattice style) which allows it to be stretched over a wider area. The extent to which this is done determines how severe the scarring will be. Lawrence [36] discusses the various skin graft options in some detail. It is possible to perform skin grafting so that scarring is minimised, or even prevented. This depends on enough ‘donor’ skin being available and usually only applies to small burn areas. Generally, it should be assumed that any burn requiring skin graft will leave a permanent scar. (It should also be noted that scars can also occur in the areas from which skin is grafted, although these are generally not serious and the areas are chosen to minimise their impact.)

The consequences of scars have been discussed in Section 2.4.3. As well as the traumatic and social consequences of the actual scarring, the affected skin shrinks as it heals, producing contracture, which can lead to disability and deformation. Even for small areas of full thickness burn, it should be assumed that permanent scarring will occur. Lawrence suggests that skin grafting is required for full thickness burns greater than the area of a 50 pence piece. The severity of partial thickness burn required to cause scarring can only be estimated. It is reasonable to assume, for the purpose of this study, that if a continuous area of greater than 5% TBSA, with an average depth of more than half of the dermis, is destroyed then scarring will be permanent to some extent.

Until a wound is completely covered, there is a high risk of infection, which can lead to the development of septicaemia, septic emboli and blood borne pneumonia. These in turn can lead to lung disease, which Settle [25] suggests is one of the most common causes of death in burn patients, and various other serious health risks.

All of these aspects - the risk of infection, and the often repeated requirement for skin grafting and anaesthetics - can be far more dangerous to children and the elderly than to an average adult. Irrespective of the burn injury itself, the bodies of the very young and the very old are less well equipped to deal with infections and the strains produced by the various aspects of surgery, as well as the actual trauma of being involved in such an incident. Both Ryan [13] and Lawrence [36] discuss the unquantifiable aspect of response to burns that Ryan describes as ‘fortitude’. It is relatively easy to understand that, as Lawrence suggests, some persons readily come to terms with the after effects of their burn (i.e. scarring) while others never do. It is also the case that, irrespective of age, pre-existing conditions or other factors, certain people will respond differently to the same burn. This can manifest itself in all of the aspects that have been discussed here, from the level of blood dilution that causes shock, to the bodies response to surgery and skin grafting. Clearly, this is not an aspect that can be accounted for in the determination of dose criteria, but it is an important factor, which will always limit the ‘success’ of attempts to predict burns response in individual cases.
4. DANGEROUS DOSE CRITERIA

4.1 Outline of approach

A dangerous thermal dose is defined by Rew [11] as “the dose at which serious burns may be received, or a small percentage of the population may die”. This is generally taken to correspond to a 1% fatality level. Although a number of statistical analyses are available which model and measure the mortality rates produced by thermal radiation, there are also a large number of uncertainties involved in the human response to thermal radiation. Thus, using any of these assessments at the lower limit (i.e. 1%) of fatality, and even obtaining trends from a sample of them, is difficult.

In contrast, the level at which “serious burns may be received” is well defined. The medical profession, at least in the UK, define a serious burn as being one covering greater than 10% of the total body surface area (TBSA) in children and the elderly, and 15% TBSA for an ‘average’ population. (This limit is used by Settle [25], Lawrence [36] and Ryan [13], and is used in most hospitals and burns units in the UK.) These limits generally refer to partial thickness burns, and any area of full thickness burn is classed as ‘severe’. This definition is inherently conservative, since all patients who are potentially at risk need to be identified in hospitals. The burns referred to here are assumed to follow the more traditional definition of ‘total’ burn area, which is predominantly made up of partial thickness burns, but may include a small proportion of full thickness burns.

These limits, together with the exposed area assumptions described above and further assumptions about the depth of burn that can be classed as ‘severe’, may be used to define a dangerous dose criteria. This approach is described in Section 4.2, where the above limits are used to re-evaluate the dose criterion for average populations, and then to propose dose limits for children and the elderly.

The proposed limits may be supported by use of the incident data analyses referred to above. In addition to assessing the 1% fatality level indicated at different ages by various authors, fatality rates at the ‘severe’ burn areas can be determined. As discussed above, there will be considerable uncertainty associated with this approach, although it will be very useful in a ‘supporting’ role. Incident data has been reviewed in detail in Appendix B and key conclusions that support the approach given in Section 4.2 are set out in Section 4.3.

Section 4.4 presents the overall conclusions from these assessments.

(Note that, for simplicity, the original dose criterion for an average population is referred to in the following sections as the adult dose. Clearly, the elderly are also adults, but this definition provides a simple set of dose criteria – allowing distinction between children, adults, and the elderly.)

4.2 Severe burn limit

4.2.1 ‘Average population’ dose criterion

The ‘adult’ (or average population) dangerous dose is based upon the fact that 20% of the body area is unclothed, in a ‘normally dressed’ population sample. The clothed area can also become burned at high levels of radiation due, primarily, to clothing ignition, which Lees [28] estimates to occur at approximately 1800 (kW/m²)⁴⁹s. However, the dose criterion is set significantly below this level, at 1000 (kW/m²)⁴⁹s (or TDU), so it can be assumed with reasonable confidence that only unclothed areas will suffer burns at radiation levels relating to a dangerous dose.
The two key factors are those affecting burn area, and burn depth:

- The dose level that may result in full thickness (or 3rd degree) burns is given by Hinshaw [44] as being between 1050 and 1750 (kW/m²)s. The 1000 (kW/m²)s adult dose limit approaches the lower end of this range, so it is possible that deep partial thickness and some full thickness burns may be sustained at this dose.

- An exposed person can only face in one direction at the same time and so the maximum burn area is assumed to be half of the total unclothed area. This is a conservative assumption since, as detailed by Rew [11] and Lees [28], the irregular, often rounded, geometry of the body, means that the effective area receiving radiation will be between half and a quarter of the total area available.

Thus, if 20% of the body area is unclothed, the 1000 TDU dose limit effectively means that a mixture of partial and full thickness burns may occur over a maximum area of 10% TBSA. This is below the limit for ‘severe’ burns, of 15% TBSA, used by the medical profession and also includes a certain amount of margin for error. This margin is welcome, since there is a high degree of uncertainty in the estimates of dose to cause partial and full thickness burns, and the level of clothing will also vary considerably.

There are, however, implications posed by the threat of oedema in the exposed areas, as discussed in Section 3.2. Oedema may have little impact when produced by burns to the hands or arms, but poses a threat to life in burns to the face or neck. Zawacki et al’s [45] probit function (presented in Appendix B) implies that oedema makes only a very small contribution to the risk of fatality, in adults below the age of 60, at burn levels of less than 20% TBSA.

It should also be noted that the consequences of oedema can be mitigated by medical treatment. However, the purpose of determining a dose criterion is to specify what level of radiation is ‘unacceptable’. It is assumed that if a person is burned to the extent that they have to rely on prompt medical treatment to survive, the level of ‘acceptability’ has been exceeded, even though in the majority of cases, treatment should be received in time to prevent fatality. This point is emphasised by the data presented in Section 2.1.1, which indicates that around half of all burn fatalities occur before the burn victim reaches the ‘healthcare system’.

4.2.2 Children

In children, it is assumed that 30% of the total body area is unclothed, in a ‘normally dressed’ case (Section 2.4.4). Using the same approach as for the ‘average’ population, with half of the available area being conservatively assumed to be burned, a 15% TBSA burn area may occur, which exceeds the 10% TBSA ‘severe’ burn threshold. Thus, the area of burn that may occur using the adult dose criteria is unacceptable in children. In addition to this the depth, or severity, of burn that this dose level can produce should also be considered.

As discussed in Section 4.2.1, a dose of 1000 TDU is close to the threshold of full thickness burns, hence there is a likelihood of some full thickness burns occurring and the partial thickness burns that do occur will be deep. The discussion presented in Section 2.4.3 illustrates that deep second degree burns can result in permanent scarring, and other problems, and should be classed as unacceptable in children.

There are, thus, two important aspects to setting the dose criterion for children:
• The area of burn can exceed the ‘severe’ burn limit, and so the dose that is received must be minimised to ensure that the depth of burn is shallow enough to counter the increased area.

• The depth of burn that is tolerated by adults, at the sort of burn area being considered, is too high for children and so the depth of burn should be shallow enough to prevent morbidity (i.e. scarring) as well as fatality.

To achieve both of these aims it is suggested that, in addition to full thickness burns, deep levels of partial thickness burns are also classed as unacceptable. In this way the threat of oedema will be reduced (though still present) and the risk of scarring will be minimised. Even in the thinner areas of skin, and allowing for uncertainties in predicting dose levels, the risk of any full thickness burns occurring should also be eliminated. Thus, the risks posed by infection and surgery, which can have much greater effects on children, will also be minimal.

The limit could be set at a level that will prevent partial thickness burns occurring at all. However, at the relatively small total burn area being considered, this may be excessively conservative. Thus, it is recommended that the criterion be set at a limit which will tolerate superficial, or shallow, partial thickness burns, but prevent deeper partial thickness burns.

A simple estimate of this ‘mid-range’ partial thickness burn level can be obtained by taking the mid-point of the dose range for producing partial thickness burns given by Hockey & Rew [1], after Kinsman [7]. They state that partial thickness burns occur between dose levels of 240 and 730 (kW/m²)⁴/₃’s, and suggest that deeper, more severe, burns occur at the upper levels of this range. Thus, 500 (kW/m²)⁴/₃’s is a reasonable approximation to the point at which partial thickness burns become serious.

Although there are a number of conservatisms involved in the above approach, which may make the use of a 500 TDU dose criterion reasonable, there are a number of uncertainties in this final step (assigning a dose level to a mid-range partial thickness burn) which must be considered.

• Hymes [39] notes that there is considerable evidence to suggest that a region of constant damage exists between the 240 and 730 TDU levels. That is, a 240 (kW/m²)⁴/₃’s dose may produce as much damage as a 730 (kW/m²)⁴/₃’s dose.

• The above dose range for 2nd degree (partial thickness) burns is lower than that given by a number of other authors.

• Even if the dose to produce partial thickness burns is set with reasonable confidence, it is based on an average skin thickness of around 2mm. This average value is reasonable for the exposed areas that are relevant here, but the variation in skin depth that occurs around the body should be considered.

The key recommendation of this section is that the dangerous dose level for children should be set at a limit that prevents deep partial thickness burns from occurring. An initial estimate suggests that this dose will be of the order of 500 (kW/m²)⁴/₃’s, although the above points indicate that more detailed consideration is required, and this is presented in Section 4.2.4.
4.2.3 The elderly

Using the same approach as given above for children and ‘adults’, if 20% of the body area is unclothed in the elderly, a burn area of 10% TBSA must be anticipated. This is on the threshold of the severe burn level, as used by the medical profession. At this burn area, 1000 (kW/m$^2$)$^{43}$/s is considered to be tolerable for adults (as described in Section 4.2.1) since the dose should not produce full thickness burns, and any small proportion that does occur may be tolerated.

In the elderly, who have thinner skin, a 1000 TDU dose is likely to produce a more significant proportion of full thickness burns. The various factors which account for increased mortality in the elderly are accounted for to some extent by the fact that the ‘severe’ dose limit is set at 10% TBSA, rather than 15% TBSA as for younger adults. However, this guideline is based on a general burn being predominantly partial thickness, and full thickness burns of any area are also considered to be ‘severe’, particularly in the elderly. In fact, probit analysis of incident data, as discussed in Appendix B, suggests that 10% TBSA of partial thickness burns only, can produce fatality levels of more than 1% in the elderly.

To ensure that the level of fatality arising from this area of burn is kept to a minimum (i.e. 1% or less) it is recommended that the dose limit should be set to ensure that partial thickness burns are not of the deeper variety. Because of variations in skin depth, and uncertainties in setting dose levels, this serves the purpose of limiting the extent of partial thickness burns so that, although some deep partial thickness burns may still occur, full thickness burns should be largely prevented. Thus, the ‘mid-range’ partial thickness burn threshold that is recommended for children in the previous section is also appropriate to the elderly.

As for the previous section, the key recommendation is that the dangerous dose level for the elderly should be set at a limit that prevents deep partial thickness burns from occurring. The actual dose that relates to this is discussed in more detail in the following section, although an initial estimate suggests that it is approximately 500 (kW/m$^2$)$^{43}$/s.

4.2.4 Partial thickness burn dose limit

The discussions in Sections 2 and 3 present the wide range of factors that produce burn injury, and illustrate how variable the response to a single dose can be. Despite this, through the use of practical but conservative definitions of severe dose levels, the previous sections give reasonably conclusive arguments for the depth and area of burn that can be classed as unacceptable, or dangerous, in vulnerable populations. The key step in setting a realistic value of dangerous dose criterion is to determine a realistic level at which this type of burn can occur. The various correlations between dose and burn severity that are available give a wide range of values, which indicates the uncertainty that is attached. This section considers these estimates in more detail, in order to confirm or revise the initial dose estimate that is given in Section 4.2.2.

It should be noted that fatality limits are independent of the limits to produce a certain depth of burn, although they are often used together. The level of dose essentially determines the depth of burn, and from this various authors have estimated levels of fatality. Thus, although there is often reasonable agreement between the dose to 1% fatality and the dose to 3rd degree, or full thickness burns, these limits are not the same. This is clearly shown by the probit assessment by Zawacki et al [45], presented in Appendix B, which shows that at certain ages and burn areas 2nd degree burns alone can produce fatality rates of greater than 1%. An other example is shown by Hymes [39], who quotes a dose to produce 2nd degree burns of 1200 (kW/m$^2$)$^{43}$/s, while proposing a 1% mortality threshold of 1060 (kW/m$^2$)$^{43}$/s.
The range of partial thickness burn thresholds (which are usually quoted as 2\textsuperscript{nd} degree burn thresholds) reported by Hockey & Rew [1], is between 240 and 730 (kW/m\textsuperscript{2})\textsuperscript{4/3}s. This is based on experimental work, using infra-red radiation sources, by a number of authors. As discussed in Section 4.2.2, the variation in possible threshold values reflects the different experimental techniques employed, such as using animals and various types of radiation source. Other key factors are the variation in skin depth and initial skin temperature that will effect the results. Hymes refers to a similar range but determines this to be the range at which blistering occurs, and suggests that the effect of blistering is to create a dose range of constant damage.

This range of dose values for the threshold of 2\textsuperscript{nd} degree burns, from Hockey & Rew, is shown in Table 4.1, together with estimates from a number of other sources. These additional estimates are included for comparison, and are discussed briefly below.

- Hymes quotes a value for the threshold of 2\textsuperscript{nd} degree burns of 1200 (kW/m\textsuperscript{2})\textsuperscript{4/3}s, based on the work of Hinshaw [44], which has also been used extensively in work by Lees [28]. This value is included for reference, although Hinshaw’s experiments were conducted using a carbon arc lamp, which produces ultra violet wavelength radiation. As discussed in Section 2.1.1, data based on ultra violet radiation can significantly under-predict the severity of burns that would occur under the equivalent dose of infra-red radiation.

- The probit function produced by the TNO ‘Green Book’ [4] relates the dose (in thermal dose units) to the probability of 2\textsuperscript{nd} degree burns occurring, and is presented in Appendix B.8. Taking the 0.1 to 0.9 probability range as being a realistic dose range at which 2\textsuperscript{nd} degree burns are ‘very likely’, the function gives a range of between 550 and 1300 (kW/m\textsuperscript{2})\textsuperscript{4/3}s, which can be taken as a estimate of the partial thickness burn dose range. (Note that the 0.5 probability level occurs at a dose of 850 (kW/m\textsuperscript{2})\textsuperscript{4/3}s.)

- The British Standard code BS5908 [46] quotes dose levels from fireballs in terms of energy, \textit{It}. The threshold for 2\textsuperscript{nd} degree burns that is given is 250 kJ/m\textsuperscript{2}. Given that fireballs have a typical duration of 5 to 30s, this dose limit can be converted to thermal dose units, giving a range (from 30s down to 5s fireball duration) of 500 to 920 (kW/m\textsuperscript{2})\textsuperscript{4/3}s.

The latter two of the above cases represent estimates of the ranges of 2\textsuperscript{nd} degree burn thresholds from other models, which are only valid for the purposes of comparison, while the Hymes value is based on ultra violet radiation, rather than the infra-red radiation emitted by fires. Thus, the most reasonable range of results the set of experiments summarised by Hockey & Rew, which indicates that the threshold of 2\textsuperscript{nd} degree burns occurs between 240 and 730 (kW/m\textsuperscript{2})\textsuperscript{4/3}s.

Also shown in Table 4.1 are dose levels from the same sources, which indicate the threshold dose required to produce full thickness (or 3\textsuperscript{rd} degree) burns. Again taking the value proposed by Hockey & Rew as being the most realistic, the threshold of 3\textsuperscript{rd} degree burns will occur at approximately 1000 (kW/m\textsuperscript{2})\textsuperscript{4/3}s. This value is supported by the widespread use of 1000 TDU as a dose limit for both 1% fatality and the threshold of full thickness burns.
<table>
<thead>
<tr>
<th>Source</th>
<th>Thermal dose (kW/m$^2$)$^{43/5}$</th>
<th>2$^{\text{nd}}$ degree burn threshold</th>
<th>3$^{\text{rd}}$ degree burn threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 5908 (1990) [46]</td>
<td>Converted from 'energy' dose</td>
<td>500 - 920</td>
<td>870 - 1600</td>
</tr>
<tr>
<td>TNO (1992) [4]</td>
<td>Probit function (0.1 to 0.9 probability)</td>
<td>550 - 1300</td>
<td>n/a</td>
</tr>
<tr>
<td>Hymes (1983) [39]</td>
<td>Based on the work of various others</td>
<td>1200</td>
<td>2600</td>
</tr>
</tbody>
</table>

**Table 4.1 Comparison of predictions of dose ranges to cause 2$^{\text{nd}}$ and 3$^{\text{rd}}$ degree burns**

The extent of the partial thickness burn range (and the range of values shown in Table 4.1) is as much an indication of the variability in depth of burn that can occur at a given dose, as it is of the uncertainty in predicting dose levels. Thus, rather than attempt to refine the range further, it is prudent to accept the uncertainty in the partial thickness burn dose threshold and allow for it in setting dose criteria. Two approaches can be taken in estimating the 'mid-range' partial thickness dose level, which are presented below.

1. The limits referred to in Table 4.1 represent the threshold of partial thickness burns, although the range indicates that they can occur at the same dose as the lower end of the full thickness threshold range. Taking the lower end of the partial thickness burn range can be assumed to guarantee that if a partial thickness burn does occur, it should be of minimal depth, i.e. making little or no impact on the dermis. Similarly, at the lower end of the full thickness burn range, any full thickness burn should not extend further than the dermis. Hymes and Lees both state that the dose to burn depth relationship is linear through the dermal region. (Lees uses this fact to estimate the depth of burn for a given dose, although this is based on a threshold of 2$^{\text{nd}}$ degree burns of 1200 (kW/m$^2$)$^{43/5}$, from Hymes.) Thus, a 'mid-range' partial thickness burn will not occur at a lower level than the mid-point of the lowest estimates of 2$^{\text{nd}}$ and 3$^{\text{rd}}$ degree burn doses. Thus a conservative estimate of the dose criteria for children, and the elderly, is halfway between 240 and 1000 (kW/m$^2$)$^{43/5}$, i.e. around 620 TDU.

2. Given the uncertainty in the value of dose to produce partial thickness burns, the threshold level can be used rather than attempting to define a mid-range value. Since vulnerable populations can tolerate some degree of partial thickness burn, there is sufficient conservatism in this approach to take the mid-point of the possible range, rather than stay at the lower end. Hence, a value of 485 (kW/m$^2$)$^{43/5}$ can be proposed, based on the above range of 240 to 730 (kW/m$^2$)$^{43/5}$ for partial thickness burns.

The above approaches indicate that the thermal dose criterion for vulnerable populations should be between 485 and 620 (kW/m$^2$)$^{43/5}$. This indicates that the initial estimate of a 500 TDU dose criterion for vulnerable populations proposed by the HSE is reasonable. The approach outlined above is conservative and the assumptions and possible uncertainties associated are summarised in Section 4.4.
4.3 Supporting evidence from medical incident data

The various analyses of medical incident data that have been reviewed in detail in Appendix B can be used to support the assumptions and conclusions presented in Section 4.2. As discussed in Section 2.2.1, there are a wide range of uncertainties associated with incident data, in addition to the inherently variable nature of human response to radiation. Thus, the incident data discussed in this section is used to 'support' the above assumptions only and not to make any direct conclusions.

All of the discussion in this section is based on more detailed analysis which is presented in Appendix B.

4.3.1 1% fatality levels

From comparison of several probit and logit models (listed in Appendix B) produced from incident data, the following approximate values of total burn area that produce 1% fatality can be derived.

Adults – 10 to 40% TBSA;
Children – 25 to 45% TBSA;
The elderly – 1% TBSA.

From these simple values it is clear that, despite the uncertainty in the values, almost any level of burn can result in 1% fatality. This is based on 'total' burn area, which is assumed to include some degree of full thickness burn. Hence, incident data confirms that a dangerous dose criterion for the elderly should ensure that no full thickness burns can occur, and that any burn should be minimised.

It should be noted that the significant fatality at very low burn is influenced by a number of complications (such as oedema, pre-existing conditions and inhalation injury), which are more common in the elderly than younger populations. This is why fatality rates become significant in the elderly even for very small burns, while in 'adults' the fatality rate remains negligible until the burn area becomes substantial. The effects of such complicating factors are discussed in more detail in Section 4.3.4.

The fairly broad range of burn areas that produce 1% fatality in both adults and children indicate the range of responses that occur in humans (under the same, or similar, conditions) as well as the uncertainty in incident data. In both cases, it can be seen that if burn areas of between 10 and 15% TBSA occur (due to half of the area of skin not covered by clothing being available to radiation burns), the fatality rate should generally remain below 1%.

Thus, the burn areas for 1% fatality given above suggest that 'general' burns (predominantly partial thickness, with some full thickness) may be tolerated by both children and adults with exposed skin areas of normally clothed populations. The 'general' burn level corresponds approximately to the threshold of full thickness burns (i.e. some part of the skin will receive full thickness burns) and suggests that the dangerous dose criteria of $1000\,\text{(kW/m}^2\text{)}^{2.49}$s is reasonable for both populations.

The discussion given in Section 4.2 indicates that there are other factors in addition to fatality that should be considered, which mean that the dose for children should be lower than the above full thickness burn threshold. Also, as well as the uncertainty in the prediction of fatality, especially at 1% fatality levels, which apply to all ages, there are further considerations relating specifically to children in the use of incident data, as discussed below.
Most functions based on incident data suggest that the response to burns becomes worse with age, at all burn levels, implying that young children have lower fatality rates than adults for similar burns. In contrast, some authors, as well as the medical profession as a whole (not to mention basic intuition), suggest that there is a peak in response to burns, around the age of 10 to 20 years old, and that very young children are more vulnerable to burns than adults. It is important to note that the apparent contradiction between some data sets may be partly explained by the fact that, by growing more quickly than adults, children can in many cases respond better to a given burn. This generally only applies up to a given level of burn severity, but may explain why incident data based on actual mortality rates can indicate a lower level in children. However, the many factors discussed in Section 2.4 indicate that the general effect on children is worse, even if the actually mortality rate does not reflect this. Two further explanations for the differences are described briefly below.

- Very young children are greater priorities in receiving medical treatment, which may result in them surviving burns that would be fatal to other age groups.
- The general trend in burn response is for mortality to reduce with age. Many of the probit functions may be based on data extrapolation which simply extends the mortality reduction down to very young ages.

4.3.2 General fatality levels

The same arguments, as presented above for 1% fatality levels, apply to all use of incident data for children, and particularly to comparisons between children and adults. Hence, no further use of fatality data for children is made here. However, trends can be seen in the differences in mortality rates between ‘adults’ and the elderly, which is illustrated by the burn areas for a range of fatality levels given in Table 4.2. The burn area to produce equivalent fatality rates in the elderly is less than half that for average populations, and the difference is more significant at lower fatality rates. A basic conclusion that can be made from Table 4.2 is that the burn area to cause 1% fatality in the elderly is approximately a third of that to cause 1% fatality in ‘adults’.

A dangerous dose is concerned with doses between partial and full thickness depths, which is a linear region of dose against burn depth. Thus, a very simple assumption that can be made based on the values in Table 4.2 is that the dose for the elderly should be around a third of that for adults (since it is between 29 and 44% for the fatality rates covered). This clearly over-simplifies the approach, and is over-conservative, but the resulting dose of around 330 (kWm⁻²) gives an indication of the level that a conservative vulnerable dose criterion might be set at.

<table>
<thead>
<tr>
<th>Fatality rate</th>
<th>Burn area required to produce fatality (% TBSA)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adults (age 5-44)</td>
<td>The elderly (age 60-74)</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>Average</td>
</tr>
<tr>
<td>50%</td>
<td>39 - 65</td>
<td>52</td>
</tr>
<tr>
<td>10%</td>
<td>18 - 35</td>
<td>27</td>
</tr>
<tr>
<td>1%</td>
<td>5 - 30</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 4.2 Comparison of ‘adult’ and elderly fatality levels
4.3.3 Fatality at ‘severe’ burn levels

‘Severe’ burns are defined in Section 3.3 as the total burn area at which fluid replacement becomes essential to prevent the onset of hypovolemia, based on the guidelines used in the medical profession.

The different models that have been used in the preceding sections, to estimate the burn areas required to cause certain fatality levels, may also be used to assess the fatality levels at the burn areas that are relevant to dangerous dose criteria. The fatality produced by partial thickness only and full thickness only burns may also be assessed, although the number of models that are available is limited in these cases. Again, more detailed investigation is presented in Appendix B.4, while the main points are summarised for each age group in the following text.

In adults, a ‘severe’ burn threshold of 15% TBSA burns is assumed and the normal area exposed to burns (half of the unclothed area) is around 10% TBSA. As described in Section 4.3.1, incident data suggests that the fatality level will be below 1% at these burn areas, with ‘general’ burns (where ‘general’ burns refer to those where the burn depth is likely to be a mixture of partial and full thickness). If burns of full thickness depth cover an area of 10% TBSA the fatality rate will be around 1%. This, again, indicates that the full thickness burn threshold (of around 1000 TDU) provides a reasonable dangerous dose criterion for normally clothed adults.

As in the other assessments presented above, incident data relating to fatality only gives similar results for children and ‘average’ populations. However, the area exposed to radiation burns in children will be greater than for adults, at 15% TBSA. This suggests that, while a mixture of partial and full thickness burns may be tolerated in terms of 1% fatality, full thickness burns alone are likely to exceed 1% fatality at this area of burn. Thus, the available incident data confirms that the threshold of full thickness burns is too high to be used as a dangerous dose criterion for children.

Because of the increased likelihood of pre-existing conditions occurring and the more severe impacts of inhalation injury, and other complications, almost any area of ‘general’ burn can exceed 1% fatality in the elderly. (Around the 10% TBSA burn level, fatality in the elderly will be between 1 and 20%). Clearly, burns of full thickness depth only will increase the fatality rate further. Hence, the dose criterion of 1000 TDU is too high to be tolerated as a ‘dangerous’ dose in the elderly. The limited data sets that are available indicate that, with partial thickness burns only, the fatality rate between 10 and 20% TBSA burns in the elderly, without ‘complications’, is between 0.5 and 1.5%. This level can rise to over 8% if ‘complications’ are present. Given that inhalation injury is far less likely in cases of radiation burns, it may be assumed that, in terms of 1% fatality, partial thickness burns will be tolerated by the elderly in most cases, but that the deeper partial thickness burns should be avoided. Hence, the incident data on 1% fatality levels supports the assumptions presented in Section 4.2.3, where the dangerous dose threshold for the elderly is determined to be ‘mid-range’ partial thickness burns.

4.3.4 Complicating factors

Quantifying the effect that ‘complications’ can have on fatality is difficult, if not impossible, since each and every human will respond differently to each type of complication, of which there are many different forms, and each can occur to a different extent. Detailed incident data on such complications is not generally recorded because of the wide range of impacts that they can have, and because assessing the extent to which each complication occurs is extremely difficult.
Nevertheless, very simple conclusions relating to the variations in the impact that complications have with age can be made from certain probit or logit functions. Zawacki et al [45] include factors for the presence of “airway oedema” and “abnormal oxygen pressure”, and Clark & Fromm [14] include a term for “inhalation injury”, in their models. Note that although it is a specific condition, abnormal oxygen pressure may be assumed to be representative of the relative impacts of general pre-existing conditions. By comparing the results of each model with and without the relevant factors, the relative impact of each with respect to age and burn area may be assessed. The overall conclusions that may be drawn are presented briefly below:

- Oedema and abnormal oxygen pressure do not generally increase mortality in burns below 10% TBSA in the elderly and below 20% TBSA in adults and children.

- Beyond these burn areas they reduce the survivability as burn area increases at all ages, but by a greater proportion in the elderly.

- Inhalation injury can reduce survivability at any burn area at any age. However, the impact of inhalation injury increases with both area and age. For example, for 10% TBSA burns the survival rate is reduced by 5% in adults and children if inhalation injury occurs, and by 20% in the elderly.

Inhalation injury is less prevalent in radiation burn cases, since the exposed population is typically at some distance from the actual fire source, and can be seen to have a relatively small impact on adults and children at the burn areas that are of concern here. The effect is more significant in the elderly at these burn areas.

Airway oedema and pre-existing conditions are less likely to have an impact on burns below 10% TBSA. This indicates that, at the exposed skin areas and radiation doses associated with a ‘dangerous dose’, such complications should not have a substantial impact. However, they start to become important factors in the elderly around this level and should not be dismissed.

4.4 Conclusions

As discussed in Section 4.1, a dangerous thermal dose can be defined as “the dose at which serious burns may be received, or a small percentage of the population may die”. This can be taken, generally, to correspond to a 1% fatality level, or the point at which burns become unacceptable (or ‘severe’).

Using the same approach as used in deriving the ‘average’ population dangerous dose criterion, it is assumed that the area of skin exposed to burns will be half of the unclothed area. This equates to likely burn areas of 10 and 15% TBSA in the elderly and children respectively. These burn areas can be compared against the medical profession’s recommended limits for ‘severe’ burns and, with various assumptions regarding response to burns at different ages, be used to suggest dangerous dose criteria for each vulnerable population.

- In children, burns of 15% TBSA exceed the 10% limit which is used to define a severe burn by the medical profession. In addition to exceeding the severe burn limit, burns of this level are much more likely to produce scarring, which is particularly undesirable in children, and even more so in exposed areas such as the face or neck. Thus, it is suggested that the dose limit should be set so that partial thickness burns do not become
deep. This should minimise the risk of scarring and eliminate the chance of full thickness burns and fatalities occurring in all but the most extreme cases.

- In the elderly, burns of 10% TBSA just meet the ‘severe’ burn criteria. However, this limit is based on a burn area that is assumed to be predominantly partial thickness, and, because of the elderly’s thinner skin, a higher proportion of full thickness burns may occur. Also, analysis of incident data suggests that there remains a relatively high mortality rate in the elderly even with only partial thickness burns of around 10% TBSA. It is thus recommended that the dose limit is set such that significant partial thickness burns cannot occur.

Hence, for different reasons, the dangerous dose for both children and the elderly is suggested to be ‘mid-range’ partial thickness burns. The dose level at which this occurs is estimated at between 500 and 600 (kW/m²)⁴/₃. The lower of these values is recommended as it is both the most conservative and maintains consistency with the existing HSE dangerous dose criterion for vulnerable populations. This is primarily based on estimates of the threshold of partial thickness burns which can range from 240 to 730 (kW/m²)⁴/₃. The key uncertainties in defining the dangerous dose criterion are summarised below.

- Human response to burns is extremely variable and any depth of burn, beyond the most superficial, has the potential to cause fatality in extreme cases.

- Depth of skin varies around the body (and with age) so assumptions about the dose level to produce a certain burn severity may also vary.

- Experimental analysis of depth of burn caused by certain doses is dependent on the type of skin tested and the type of radiation source used. Measurement techniques are also highly variable, since the point at which burns become ‘2nd degree’ is often difficult to determine. All of these uncertainties may lead to the wide range in estimates for the dose required to produce partial thickness burns.

- There is evidence that there is a range of constant damage for second degree burns, where the same depth of burn may occur for a range of doses (between 240 and 730 (kW/m²)⁴/₃).

- The assumption of 20% unclothed area in a normally dressed population is extremely variable (according to weather, fashion, activity, etc.).

In mitigation of the above uncertainties, there are several conservative assumptions that have been made in the approach used:

- The 10 and 15% TBSA limits for severe burns are used in hospitals and burns units to determine at what point burns become significant and intravenous fluid replacement is required. This limit is inherently conservative to ensure that all patients who might be at risk are covered.

- The above limits, for both children and the elderly, are based on partial thickness burns, which should ensure that no full thickness burns are experienced. Although there are risks in extreme cases, due to oedema, inhalation injury and pre-existing conditions, the risk of fatality from small areas of partial thickness burns is very small at all ages, even without medical treatment.
• The basic assumption that half of the unclothed area is burned is conservative. Since the geometry of the body is irregular and rounded, the actual burn area will typically be closer to a quarter of the 'available' skin area.

• Although there is a wide range in the estimates of the dose for partial thickness burns, these refer to the threshold of partial thickness burns and the limits for 'mid-range' partial burns will be significantly higher.

A number of models based on incident data have been assessed in some detail, as discussed in Section 4.3, with particular respect to variations in the response to thermal radiation with age. These are based purely on fatality and are of limited use in directly determining a set of dangerous dose criteria. However, the overall conclusions that can be drawn from this data produce further support for many of the assumptions that have been used in determining the recommended dangerous dose for vulnerable populations of 500 (kW/m²)²s.
5. **TDU EQUIVALENCY**

5.1 **Upper and lower bounds**

5.1.1 Limitations of thermal dose units

Thermal dose units, or TDUs, are based on a combination of the radiation intensity, \( I \), and the exposure time, \( t \), as shown below.

\[
\text{Thermal dose, } L = I^{0.6} t^{0.6} \text{ (kW/m}^2\text{)}^{0.6} \text{s}
\]

In practice, the exposure time when dealing with fireballs and flash fires is the same as the fire duration, which is usually less than 30s, as indicated by Rew [11] and BS 5908 [46]. With longer duration incidents, such as pool and jet fires, the exposure duration is determined by the escape time, which can vary considerably but is typically around 1min. In theory, however, the exposure time can be far greater. Although a fire will never be infinite, if escape is not possible from a pool or jet fire the exposure time can be much greater than 1min. (Escape is often not possible due to existing disability, event-related injury or access to shelter being blocked. It is also possible that, at very low radiation intensities, people are unaware of the need to escape and simply stand and watch a fire event.)

As indicated above, the large time component of very long exposures can give a high thermal dose, in TDUs, even when the actual radiation intensity is at a harmless level. For example, if an exposure time of one hour is assumed, a dose of 2000 \( (\text{kW/m}^2)^{0.6} \text{s} \) will be produced by thermal radiation of just 0.6 kW/m\(^2\) intensity. Although 2000 \( (\text{kW/m}^2)^{0.6} \text{s} \) is above the dose level that would normally be assumed to produce full thickness burns, and thus a high probability of fatality, a radiation intensity of 0.6kW/m\(^2\) is less than that typically received from the sun. (Van Wingerden et al [47] indicate that radiation from the sun is between 0.8 and 1.2 kW/m\(^2\), with 1kW/m\(^2\) being the typical level on a “clear, hot summer day”.) Clearly, spending an hour in the sun can produce painful superficial burns in some people, but would not be expected to produce full - or even partial - thickness burns.

Thus, the use of thermal dose units can over-predict the effects of thermal radiation for long exposure times. This will always be conservative, with respect to dose criteria, but can be very unrealistic in extreme cases. The levels of exposure time and intensity at which this occurs are investigated in the following section, which relates these ranges to the dangerous dose criteria and general use of TDUs. Similarly, at the other end of the scale, a very short duration of exposure, with a high radiation intensity, may also produce an unrealistic TDU value, and this effect is discussed briefly in Section 5.1.3.

5.1.2 Low intensity, long exposure time

Some values at the lower range of thermal radiation intensity are given in Table 5.1, with their associated causes or consequences.

<table>
<thead>
<tr>
<th>Intensity, ( I ) (kW/m(^2))</th>
<th>Effect</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 to 1.2</td>
<td>Solar radiation</td>
<td>Van Wingerden (1994) [47]</td>
</tr>
<tr>
<td>1.0</td>
<td>Level tolerated by clothed man</td>
<td>Lees (1996) [28]</td>
</tr>
<tr>
<td>1.5</td>
<td>Threshold of pain</td>
<td>Lees (1996) [28]</td>
</tr>
<tr>
<td>1.6</td>
<td>No discomfort for long exposures</td>
<td>Van Wingerden (1994) [47]</td>
</tr>
</tbody>
</table>

Table 5.1 Effects of low intensity thermal radiation
As discussed above, sunlight may be tolerated by humans for almost infinite periods, without experiencing anything more than superficial burns. Thus, supported by the other values given in Table 5.1, a radiation intensity of 1kW/m² is assumed to be a ‘safe’ level of radiation (i.e. one which would not be considered to be a hazard in a risk assessment), which can be used to investigate the realistic limits of TDU usage. The exposure times for the existing dangerous dose criterion for average populations, together with the value proposed in Section 4 for vulnerable populations, are listed in Table 5.2 at the above radiation intensity. The equivalent values for an intensity of 2kW/m² are also shown, for reference.

<table>
<thead>
<tr>
<th>Thermal Dose (kW/m²)²·8⁴/s</th>
<th>Exposure time at 1kW/m² intensity</th>
<th>Exposure time at 2kW/m² intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 (Vulnerable)</td>
<td>8min 20s</td>
<td>3min 20s</td>
</tr>
<tr>
<td>1000 (Average)</td>
<td>16min 40s</td>
<td>6min 40s</td>
</tr>
</tbody>
</table>

Table 5.2 Exposure times for low radiation intensities at Dangerous Dose Criteria

These exposure durations will only occur in extreme instances, where very long duration fires occur with no escape allowed. Although they will be relatively conservative, the values given in Table 5.2, assuming the use of thermal dose units, appear to be reasonable. Although longer exposure times, from even lower radiation intensities, will reach the above dose levels when the dose is not really ‘dangerous’, it is assumed that such radiation intensities are too low to be of interest in practical assessments. (That is, dangerous dose criteria are used in risk assessments and safety cases, where radiation intensities below 1kW/m² would not be considered.) Thus, it is suggested that the above dangerous dose criteria may be used without any limits being set on the appropriate exposure time or intensity. If unrealistic values are used, the resulting dose will conservatively predict a dangerous dose.

Beyond the dangerous dose criteria, i.e. for exposure times beyond those given in Table 5.2, the resulting dose (in TDUs) will approach the level at which full thickness burns are predicted to occur. The dangerous dose criterion for average populations is close to the full thickness burn threshold, and Table 5.2 suggests that this is produced after 16 minutes by a radiation intensity of 1kW/m². Although, as acknowledged above, the TDU produced below these levels is potentially unrealistic, it is suggested that the above values are used as a cut-off point. Thus, it is suggested that thermal dose units cannot give a realistic indication of the relative risk associated with thermal radiation if the radiation intensity is less than 1kW/m² and the exposure time greater than 15 minutes. The likelihood of exposures outside of these ranges occurring, or being of interest, is low, but if so, the dangerous dose (or realistic dose) equivalent might be used as a radiation intensity of 1kW/m², instead of a thermal dose of 500 or 1000 (kW/m²)²·8⁴/s. This is proposed as a more realistic threshold than using thermal dose units for long exposure times, but will still be very conservative (since 1kW/m², is of no real significance in risk assessment terms).

Note that although the use of thermal dose units may be acceptable up to around 15 minutes, it will be conservative, and most experimental data assessing burn impacts is only quoted up to around 100s duration.

5.1.3 High intensity, short exposure time

At the other end of the scale, an instantaneous exposure to a high intensity of radiation (such as the typical fireball peak of around 300kW/m²) would not indicate a high value of TDU. For example, if the exposure time was taken as a tenth of a second, the TDU would be only
200(kW/m²)³⁴⁵. This is below the dangerous dose criterion for vulnerable populations, while an intensity of 300kW/m² would normally be expected to be ‘dangerous’ for any exposure time. However, such small exposure times do not occur in practice, and the minimum exposure from fireballs, given by BS 5908 [46], is around 5s. Even in an extremely short duration of 1s, the TDU value would be 2000(kW/m²)³⁴⁵, which exceeds the dangerous dose criteria and so may be considered to be realistic. Thus, it is assumed that, even for very short duration exposures, the use of thermal dose units is appropriate (for risk assessments, etc.), both in terms of ‘dangerous dose’ and ‘general’ radiation levels.

5.2 Possible disadvantages of thermal dose units

The primary reason for the use of thermal dose units is to measure the effect of thermal radiation on humans. The impact of a certain intensity of radiation dose is dependent on the time for which it is received. As described in Section 2, a range of analyses are available so that a certain level of dose can be related to depth, and therefore severity, of burn. A key advantage of TDUs, in terms of risk assessments, is the fact that the calculated dose is effectively the cumulative dose. Thus, the use of TDUs is flexible so that, if required, the total dose can be made up of a combination of intensities – for example, as escape progresses and the victim receives a reducing intensity of radiation.

Some possible disadvantages of the use of thermal dose units are discussed in the following sections, and potential alternatives are presented in Section 5.3.

5.2.1 Variation of heat flux

Although thermal dose can be calculated in stages, as escape progresses, it is primarily based on the assumption of a constant heat flux. Maillet & Birk [27] discuss how the impact of a given dosage may alter if it is made up of a varying heat flux, although they report that very little research into this area has been conducted. Experiments have been performed by Evans et al [48], who compared heat pulses of the same duration and total dosage, but with varying shapes. They found that the same dose made up of constant or varying heat flux produced identical burns, in clinical terms, although they observed that varying heat fluxes produced more severe burns in terms of severity of immediate pain and the extent of blistering.

More recent assessments, based on experimental observations and use of a skin burn model, by Lawton & Cooper [49] and Lawton [29], produce similar conclusions. They find that heat fluxes that vary with time (particularly those that increase with time) require a lower total dose to cause burns than the equivalent constant heat flux. Lawton & Cooper quantify the difference through their model, which is discussed further in Section 5.3.3, and conclude that the difference is “not serious”.

These analyses indicate that varying heat fluxes may have more severe effects than would be calculated based on constant flux, although the difference does not appear to be significant. There are a number of uncertainties associated with the measurement and prediction of thermal dose, which suggest that the relatively small difference between different shapes of flux can be neglected. In particular, estimating both the duration and intensity of fire incidents can be quite uncertain, as discussed by Hockett & Rew [1]. It is usual to use an upper bound approximation to a constant flux, which would generally be more conservative than if a more detailed (varying) flux pattern was calculated. There are also uncertainties associated with the exact impact of a particular dose, in terms of depth of burn that results. In addition, as discussed throughout Sections 2 to 4, there is considerable variation in the response of humans to a particular dose, even when the same area and depth of burn are produced.
It is therefore considered that variation in heat flux is not of significance in general assessments. In the case of dangerous dose criteria, which is of interest in this report, there is no effect at all, since the conservatisms included will more than account for any small change in impact caused by varying the radiation intensity. Two key points that further suggest that variation of heat flux can be neglected are given below.

- Derivation of dangerous dose criteria has been based, in part, on incident data, which will include all types of heat pulse.

- Comparison with actual fire incidents, by Hockey & Rew [1], shows that the effects on people are consistently lower than those predicted by modelling techniques.

5.2.2 Form of thermal dose units

The initial form of measuring thermal dose, so as to relate it to injury or fatality factors, was to take a simple product of radiation intensity and time. Lees [26] refers to this as thermal dose, D, where \(D=I t\). This form of dose is used by BS 5908 [46] to give limits for exposure to radiation from fireballs. Lees states that work, by a number of authors, has shown that this can underestimate the effect of radiation at higher intensities and that a better correlation is to use a thermal load (referred to as the thermal dose in this report), \(L\), where \(L=I^nt\).

Eisenberg et al [2] proposed that the index, \(n\), should take the value of 1.33 (4/3) when correlating fatality data, and 1.15 for non-fatal injuries. Various authors have subsequently adopted this approach and Hymes [39] proposed that a value of 1.33 provides adequate correlation in both fatal and non-fatal cases, which has also been widely followed. Hence, the equation given below is used by most authors as the definition of thermal dose, in thermal dose units.

\[
\text{Thermal dose, } L = I^{0.3} t \left( \text{kW/m}^2 \right)^{4/3} \text{s}.
\]

Use of the above equation, by many authors, has showed that taking the index, \(n\), as 1.33 provides reasonable correlation between radiation intensity, time and injury effects. It provides the best correlation that is available without conducting further experiments or using a number of different correlations, across different ranges. (Again, detailed refinement of the correlation is of little benefit given the uncertainties associated with fire scenario predictions and the actual impact of each dose on different people under different conditions.) However, the following points illustrate some possible limitations in the current form of the equation.

- Eisenberg et al's work was based on ultra-violet data, from nuclear radiation incidents. Subsequent work by other authors, such as Tsao & Perry [5] and TNO [4], has modified their probit functions, which relate dose to fatality or injury, to account for differences between ultra-violet (UV) and infra-red (IR) radiation. However, their correlation which relates the radiation intensity and exposure time to the dose has not been changed. It may be that the relative proportions of the impacts of intensity and exposure time also vary between UV and IR radiation, although this is difficult to assess from the data that is available, and any variation in the overall effect is likely to be small.

- The original work by Eisenberg et al also resulted in separate correlations for fatality and non-fatal injury considerations. Hymes' proposal that the same proportion (using \(n=4/3\)) is adequate for both cases has been widely adopted, although this suggests that, particularly in non-fatal cases, the correlation is more approximate. Thus, when dealing with injuries, rather than fatality, the use of thermal dose units may over-predict the
impact of thermal radiation. However, as indicated by Hymes, the variation in results produced by the use of the two values of index will be relatively small.

- As discussed in Section 5.1, the above correlation for thermal dose is not valid at all ranges. It may be possible to propose different values of \( n \) for different ranges, but it has been shown in Section 5.1 that \( P^D/t \) is reasonable across the range of intensities and exposure times that will realistically be experienced. At values where the dose becomes less realistic it will always be conservative, and only extreme incidents are likely to produce combinations of intensity and time that are likely to lead to unrealistic thermal dose values.

5.2.3 Variation of burn severity for a given dose

As discussed above, and also within Sections 2 to 4, the response of different individuals to a given dose will vary considerably. This variation has been ascribed to a number of factors, ranging from the ‘fortitude’ of an individual to their age and the presence of pre-existing medical problems.

One of the main factors is the variation in skin depth around the body. Various experiments and analyses, in particular by Lees [28], have demonstrated that there is reasonable consistency in relating thermal dose (in TDUs) to the depth of the burn that is received. However, simply relating the depth of burn to severity of burn, i.e. determining whether it is partial or full thickness, depends on the part of body affected and so is generally only given in reference to an average skin depth. The initial skin temperature and the temperature of the actual radiation source also affect the actual burn depth, which can in turn vary the impact that a given dose has.

Defining a burn as full or partial thickness, from the depth of the burn, is an essential step in estimating the impact of a given dose or radiation source. Lees combines the use of thermal dose units with specific analysis of the depth of burn received, and a number of authors develop models based on skin and skin temperature effects rather than TDUs. These approaches are considered further in Section 5.3.

5.3 Alternatives to thermal dose units

5.3.1 Modifications to \( P/t \)

Although it can have direct use in approximating the impact of radiation at very long exposure times, the effect on humans of a radiation intensity, \( I \), is dependent on the exposure time. Hence, the use of radiation intensity alone as a measurement of dose severity is of potential benefit only beyond the useful range of the radiation dose (in thermal dose units).

Using the energy, \( It \), is the most simple form of estimating the impact of radiation and is used by BS 5908 [46], and other authors. Direct data, or interpretation of limits derived for given values of \( I \) and \( t \), can be used to determine threshold limits of \( It \), which indicate the severity of burn produced. Experimental data, quoted by Lees, shows that this simple correlation tends to under-predict the impact of radiation at high radiation intensities, hence the more common use of \( P/t \). At lower radiation intensities, with long exposure durations, \( It \) may be more accurate than \( P/t \). However, in these extreme cases, long exposure times will still tend to dominate and introduce an over-conservative value of dose, when the actual intensity is too low to cause significant damage. Hence the use of \( It \) is less accurate over normal ranges and only marginally better at the extremes, so is not a realistic alternative to thermal dose units.
As discussed in Section 5.2.2, there are arguments which suggest that using a value of n of 1.33 (4/3) in \( I^{4/3} \) does not accurately indicate the severity of dose at all values of I and t. The experimental data from which the correlation was derived is relatively old, and not based on infra-red radiation, but is believed to give a reasonable approximation and is the best that is available. Since further experiments involving the burning of people are not desirable, revisions to this correlation are impractical. However, there is evidence to suggest that a value closer to n=1.15 is more realistic when dealing with injury rather than fatality. It is increasingly common in burn assessments to consider injury or morbidity rather than mortality, and greater consideration of the use of \( I^{1.15} \) would be of benefit in the future.

5.3.2 Thermal dose units and burn depth analysis

The review of thermal radiation effects, which is presented in Section 2, discusses a range of assessments of radiation impact, from which it can be seen that there are two basic approaches.

- Probit or logit functions, such as those proposed by Eisenberg et al [2] and TNO [4], can be used to relate the thermal dose directly to fatality, or burn severity.

- Estimates of the burn area can be used in conjunction with mortality charts, or probit functions, to predict the likely fatality rate.

In the approach used in Section 4, and in other attempts to derive dangerous dose criteria, a combination of the above methods is used. Knowledge of the dose required to produce a certain severity of burn is combined with knowledge of the burn area that is likely to occur, in order to determine at what point a dose becomes ‘dangerous’.

Lees [28] proposes a model which uses the linear relationship between dose and burn depth (between the thresholds of partial and full thickness burns) to determine more detailed estimates of the actual burn depth. More detailed prediction of the depth of burn, rather than directly estimating the severity of burn, has the following advantages. (Note that ‘burn severity’ refers to the classification of a burn, i.e. as either superficial, partial or full thickness.)

- If the part of the body that is affected is known, then more detailed estimates of the skin depth, and thus the relative depth of the burn, can be made in order to provide more accurate estimates of the ‘severity’ of the burn.

- Similarly, allowances can be made for the skin thickness around the body if the age is known, and the relative depth of skin with age is estimated.

- Of particular relevance to the approach outlined in Section 4 is the fact that, if the skin thickness of a part of the body is known, the burn can be defined to greater detail than simply ‘full’ or ‘partial’ thickness. Thus, in many cases, partial thickness burns can be split into grades of ‘shallow’ and ‘deep’ partial thickness burns.

The model proposed by Lees adopts a reasonably basic approach with respect to dose and skin depth. The burn depth component of the function, as described above, is derived from the relatively simple linear function between dose and burn depth. The dose is also related to mortality through the use of Lawrence’s [10] mortality chart and relatively simple assumptions relating the average mortality to an average burn depth (and then assuming that fatality is also linear with respect to both dose and burn depth). However, additional factors,
such as clothing ignition and effective incident radiation, are also considered in order to produce the final probit function shown below.

\[ Y = -10.7 + 1.99 \ln L' \]

where: \( Y \) is a probit indicator of fatal injury,
and: \( L' \) is the thermal radiation dose, \( I^{0.75t} \left( \frac{(W/m^2)^{0.5}}{10^5} \right) \),
where: \( I \) is the thermal radiation intensity (W/m²),
and: \( t \) is the exposure time (s).

Having developed the above model, Lees gives two main conclusions:

- "There is scope for the separate elements to be progressively refined".
- The model is structured so that it can be adapted to different uses, other than to determine basic mortality.

The latter point has already been alluded to in that burn depth can be used to determine the severity of burn in more detail, rather than to directly obtain the fatality. In order to do this the former point must be considered, particularly with respect to the dose thresholds used as boundary conditions. Lees uses the basic burn depth against dose relationship that is proposed by Hymes [39], based on experimental work on pigs by Hinshaw [44]. As discussed in Section 4.2.4, the threshold values for partial and full thickness burns given by Hymes are significantly higher than those proposed by other sources (Table 4.1). A very simple modification has been used in Section 4, where the dose for partial thickness burns lies between 240 to 730 (kW/m²)²/₃'s, while Hymes and Lees take the threshold of partial thickness burns as being 1200 (kW/m²)²/₃'s (which corresponds to a burn depth of approximately 0.1mm).

It is suggested that the basic approach can be of considerable use in improving burn predictions and criteria, if the following points are addressed.

- Further investigation is recommended to justify the assumption of a linear relationship between thermal dose and burn depth (in the partial thickness burn range).
- More careful consideration of the boundary conditions is required, since the whole series of results is based around these values. There is a great deal of uncertainty in data presented by different authors on both the depth of burn that causes partial or full thickness burns and, more critically, the dose at which these burn depths occur.

### 5.3.3 Skin effects models

The actual process of skin burns is caused by cells being destroyed by chemical processes at raised temperatures. Thus, the use of thermal dose is, effectively, a means of determining the temperature rise and its subsequent impact. While thermal dose is most practical in terms of representing the effect of a given fire event, several authors propose models which use temperature to determine skin damage, which is more practical in terms of representing the actual medical impacts. Although models which relate temperature to the depth of burn represent the actual process of damage more accurately than thermal dose, determining the temperature of skin is very difficult. It is clearly not realistic to determine a victim's skin temperature throughout an actual incident, and most models use correlations between experimentally measured temperatures and the dose that produces them. Hence, thermal dose
units and temperature models are closely linked, and skin temperature models are presently used in conjunction with, rather than instead of, thermal dose analysis.

The most basic form of linking cell damage and temperature is based on the well-known Arrenhius equation, which was adapted by Henriques [50].

\[
\frac{\mathrm{d}o}{\mathrm{d}t} = A \exp\left(-\frac{B}{T}\right)
\]

Where, \(o\) is the thermal damage, and \(T\) the cell temperature. Henriques determined the constants \(A\) and \(B\), from experimental data, and the resulting equation has been used and developed by a range of authors. Lees [26] presents a similar model developed by Buettner [51], and discusses its subsequent development by Stoll & Chianta [52].

One of the key points identified in the work of these authors is that a threshold temperature for the onset of pain is quite clearly defined. Skin damage begins to occur at around 45°C, where pain is experienced, and increases rapidly beyond this level. Stoll & Chianta suggest that the rate of damage approximately trebles for every 1°C temperature rise above 44°C. Another key point identified by several authors, and reported by Lees, is that skin damage continues to occur for a period of time after the heat source is removed. This effect is also discussed by Lawton [29] who refers to this process as ‘afterburning’.

More detailed variations of such models have been developed, and some of these are discussed briefly by Maillette & Birk [27]. They include the ‘bioheat equation’, which uses the heat transfer through the skin in a more complex equation. This includes detailed functions which represent complexities of the body, such as cooling through blood perfusion and internal heat generation through metabolism. It is based on temperature, but also uses the incident heat flux (which creates the temperature rise) to establish boundary conditions. The model can be solved through finite-element analysis or, in a simplified form, analytically.

There is clearly a great deal of potential for more accurate modelling of burn effects through models based on temperature. However, the models so far developed can be very complex and are not readily applied to practical situations, where the injury produced by a certain level of fire event is required. A more recent model has been developed, and reported in papers by Lawton [29], Lawton et al [53] and Lawton & Cooper [49], which addresses some of the above points (i.e. complexity and applicability to fire incidents) and warrants further consideration.

The model develops the initial equation derived by Henriques, given above, in order to determine the relationship between burn depth and distance from a given radiation source. By solving the equation that they derive based on known dose levels and burn depths, they produce further expressions relating the exposure time to the heat dose (in units of kJ/m², i.e. energy, \(I\)). They use these expressions to iterate the burn depth model to find the critical dose, for that burn depth, at the required radius for the incident fire source. Some of the key points arising from the model are listed below, and discussion of the implications to broader issues is given where appropriate.

- As discussed in Section 5.2.1, the model can be evaluated for both constant and varying heat flux. The impacts of equivalent dose levels with different pulse shapes are compared and it is suggested by Lawton that more severe burns occur in varying pulse cases, although the difference is not significant.
• The original model, presented by Lawton & Cooper [49], was based on skin burns criteria which was derived from nuclear data, as used by Eisenberg et al [2]. TNO [4] and others have revised Eisenberg et al’s thermal dose probit function, to account for the differences between the UV radiation from nuclear explosions and the IR radiation produced by fires. In the same way, Lawton modifies the original model to account for lower temperature heat sources (i.e. those that produce IR rather than UV radiation).

In terms of skin burns, it is the reflectance and absorption which is of significance, and that varies according to the wavelength of radiation emitted. Lawton [29] states that around 40% of the radiation from high temperature sources, such as nuclear explosions (around 6000°K), is reflected and the remainder penetrates the skin to a depth of around 2mm. Thus, the temperature rise is spread across a relatively wide thickness of skin and is relatively small. For fire sources that emit IR radiation from lower temperature sources (around 2000°K) only 5% of the radiation is reflected and the remainder is absorbed in a thin layer of skin at the surface, resulting in higher temperatures and greater damage.

Lawton’s modelling of low temperature sources indicates that the heat dose to produce partial thickness burns can be 5 to 5 times greater in UV than IR radiation. This range compares with the same factor being determined as 2.23 by Tsao & Perry [3] in their modification of Eisenberg’s model.

• Since it is based on experimental data, the model covers a finite range of exposure times, between 0.5 and 50s (which is sufficient to cover the majority of fireball incidents). Even over this slightly limited range, their results indicate that the heat dose for ‘third degree’ burns is much larger than that for ‘second degree’ burns at short exposure times, but there is little difference between the two thresholds for longer exposure times. Lawton & Cooper [49] state that this effect is due to heat having sufficient time to diffuse and produce a more uniform temperature rise throughout the skin at longer exposure durations.

It should be noted that Lawton & Cooper’s use of ‘2nd and 3rd degree’ burns corresponds to burn depths of 0.1 and 0.5mm respectively. The thresholds for partial and full thickness burns, based on an average skin thickness of around 2mm, are taken as being closer to 0.1 and 2mm, respectively, in the analysis presented in this report. Nevertheless, the increased depth of burn for the same total dose, as exposure duration increases, will have the same effect on the distinction between partial and full thickness burns. (In other words, the difference between the dose to cause each type of burn will decrease as exposure time increases, although the gap between the two will remain larger than that for ‘2nd and 3rd degree’ burns given by Lawton & Cooper).

Previous assessments which relate thermal dose to burn depth do not appear to have identified the latter of the above points, which suggests that 2nd and 3rd degree burns can be produced at the same dose for longer exposure durations. Typically, authors have identified distinct thresholds for each type of burn, which apply to all exposure times. This may explain the certain amount of overlap that exists between estimates of the dose thresholds for partial and full thickness burns (as can be seen in Table 4.1). It is recommended that further consideration is given to confirm this effect, but some of the implications of this are listed below.

---

Lawton’s assumptions regarding optical properties of skin are based on the work of Buehner [51], which concentrates on radiation sources of below 1500°K and above 4000°K.
• The possibility of full thickness burns occurring at the same dosage as partial thickness burns further supports the approach used in Section 4, where dangerous dose criteria for vulnerable populations are based on burn depths well below the full thickness burn threshold.

• The suggestion that burn depth increases according to the time of exposure, rather than simply the total dose level, has implications for the validity range of the use of thermal dose units. It may be that, for accurate determination of burn depths, different values of the index, \( n \), are required for different exposure times, or that both the total dose and the time of exposure need to be considered. This suggests that the penetration of a burn into skin can be represented by either thermal dose or temperature considerations, while the subsequent spread of the temperature (and damage) is also dependent on the time for which the dose is received.

• There is also an implication for short exposure times. Due to the effect of afterburning the dose may be more realistically represented as some function of the time for which the temperature of the skin remains elevated (i.e. allowing for the time for the heat to be removed), rather than a function of the time for which the skin is exposed to the radiation source.

Possibly the main advantage of the skin burn model is that it can be related to precise burn depths, so that the exact depth to, for example, partial thickness burn can be derived. However, as Lawton & Cooper describe, skin properties vary from person to person and from place to place – so a number of uncertainties remain.

It is concluded that skin depth models, such as that proposed by Lawton and colleagues, have been developed to the point where they can be used to investigate more detailed effects of burn impact than is possible through the use of thermal dose analysis only. However, the models are based on relatively limited experimental data and appear to be dependent on a relatively limited range of dose estimates. More work is required in linking the effects of thermal dose and skin temperature to improve the benefits that can be derived from such models. Temperature effects alone have little practical use since the temperature of a certain depth of skin, at an unspecified distance from a fire event, cannot be determined without knowledge of the heat output of the fire, which is inherently based on radiation intensity and dose.

It is unlikely that temperature, or its related effects, can be used as an alternative to thermal dose units, but future refinements of radiation effects analysis should concentrate on using both thermal dose and skin temperature in tandem. It is likely that thermal dose units will remain the most practical approach to determining radiation effects for use in risk assessments and safety cases, etc., while temperature models can be of benefit in calibrating and enhancing existing models based on dosage.
6. SUMMARY AND CONCLUSIONS

6.1 Overview

The primary conclusion of the assessment is that the existing Dangerous Dose criterion for vulnerable populations of 500 (kW/m²)^45s is reasonable, and is appropriate to both children and the elderly.

In addition to proposing a dangerous dose for vulnerable populations, the validity of using thermal dose units has also been considered. The primary conclusion from this element of the report is that thermal dose units are the most practical form of determining radiation impacts, although models using temperature and skin depth may be used to calibrate and enhance models based on thermal dose units.

6.2 Dangerous dose criteria for vulnerable populations

The following lists the main points and conclusions relating to the determination of a vulnerable populations Dangerous Dose criterion that have been drawn from the reviews and analysis described in Sections 2 to 4 of this report.

Literature and data reviews

1. There are many factors that affect the response to thermal radiation for a given level of dose and burn area. The most significant of these factors (but by no means the only ones) are listed below:
   • age;
   • part of the body that is burned;
   • level of clothing;
   • pre-existing medical conditions;
   • existence of inhalation injury;
   • speed and type of medical treatment received;
   • general health and ‘fortitude’.

2. The primary differences between elderly and ‘average’ populations, in terms of response to a given dose of thermal radiation, are:
   • generally poorer health - the mechanisms of the body which respond to actual burns, as well as the infections, surgery and shock which often accompany burns, are typically weaker in the elderly;
   • pre-existing medical conditions are more common, and have a greater impact on mortality in the elderly;
   • skin is typically thinner, so that the same dose can produce more serious burns in the elderly than it would for younger adults.

All of these factors become more significant with age, so that the very old are at the highest risk. In terms of burn response ‘the elderly’ are taken as being those of 60 years and over, with the ‘average’ age of the elderly assumed to be around 67.5 years of age.

3. The primary differences between children and an ‘average’ population, in terms of response to a given dose of thermal radiation, are:
   • the area of exposed skin is generally greater in children; thus the same dose can produce a greater percentage burn area in children than in adults;
• scars have more impact on children, both in physical and emotional terms;
• in very young children, the mechanisms of the body which respond to actual burns, as well as the infections, surgery and shock which often accompany burns, are typically weaker than in adults.

In other aspects of burn response children can have greater resistance to burns than adults (due to faster healing and higher priority medical treatment) and so the above points apply particularly to very young children. Thus, in terms of burn response, ‘children’ are assumed to be those between 0 and 10 years of age. Note that this is the same age range for which East et al [31] suggest that children are ‘vulnerable’ in terms of escape characteristics.

Mechanisms of burn injury and fatality

4. The actual process of burning can lead to loss of fluid and risk of infection through the wound, but the primary consequences are the risk of fatality through oedema and the resulting fluid loss, which leads to hypovolaemia. Oedema is the swelling of tissues, which can cause fatality in burns around the face, neck and chest, where vital organs can be blocked or affected. Hypovolaemic shock is the primary cause of fatality through burns and is a consequence of fluid loss, which prevents essential nutrients and oxygen from circulating around the body.

5. Hospitals and burns units usually determine burns as being ‘serious’ when intravenous, rather than oral, fluid replacement is required to combat hypovolaemia. This level is defined as a burn area of 15% TBSA for average healthy adults, while 10% TBSA is taken as the threshold for both children and the elderly.

6. In addition to the risk of fatality, burns have serious consequences in terms of scarring, or morbidity. Partial thickness burns usually heal without the need for grafting, although, for deep partial thickness burns, grafting is usually necessary to prevent scarring. All full thickness burns require surgery to repair the skin, and scarring is almost inevitable in these cases. As well as having obvious social and emotional consequences, scars can have substantial impacts due to ‘contracture’. This refers to the effect that scarred skin, which does not stretch like undamaged skin, can have in restricting, or preventing, movement if occurring around limbs. This effect is exacerbated in children, since their bodies will continue to grow around the damaged tissue (i.e. the scar), which will not grow or stretch.

Dangerous Dose criteria for vulnerable populations

7. Using the same basic approach as used for defining the ‘average’ population dangerous dose criterion suggests that the area of skin exposed to burns will be approximately half of the unclothed area, giving up to 10 and 15% TBSA burn areas in the elderly and children respectively.

8. In children, burns of 15% TBSA exceed the 10% limit which is used to define a severe burn by the medical profession. Burns of this level are also much more likely to produce scarring, which is particularly undesirable in children, and even more so in exposed areas such as the face or neck. Thus, it is suggested that the dose limit should be set so that partial thickness burns do not become deep. This should minimise the risk of scarring, and eliminate the chance of full thickness burns and fatalities occurring in all but the most extreme cases.
9. In the elderly, burns of 10% TBSA just meet the 'severe' burn criterion. However, this limit is based on a burn area that is assumed to be predominantly partial thickness, and because of their thinner skin a higher proportion of full thickness burns may occur in the elderly. Also, analysis of incident data suggests that there remains a relatively high mortality rate in the elderly even with only partial thickness burns of around 10% TBSA. It is thus recommended that the dose limit is set such that significant partial thickness burns cannot occur.

10. Hence, for different reasons, the limit of burn severity in both children and the elderly is suggested to be 'mid-range' partial thickness burns. The dose level at which this occurs is estimated at between 500 and 600 (kW/m²)²/s. The lower of these values is recommended, as it is more conservative and also maintains consistency with the existing HSE approach to vulnerable populations.

11. The dose level for 'mid-range' partial thickness burns is primarily based on estimates of the threshold of partial thickness burns, which can range from 240 to 730 (kW/m²)²/s. This range illustrates the uncertainty associated with dose predictions, and the key uncertainties are summarised below.

- Human response is extremely variable and any depth of burn, beyond the most superficial, has the potential to cause fatality in extreme cases.
- Depth of skin varies around the body (and with age), so assumptions about the dose level to produce a certain burn severity may also vary.
- Experimental analysis of the depth of burn caused by certain doses is dependent on the type of skin tested and by the type of radiation source used to simulate a fire. Measurement techniques are also highly variable, since the point at which burns become '2nd degree' is often difficult to determine.
- There is evidence that there is a range of constant damage for second degree burns, where the same depth of burn may occur across the full range of doses.
- The assumption of 20% unclothed area in a normally dressed population is extremely variable (according to weather, fashion, activity, etc.).

12. In mitigation of the above uncertainties, there are several conservative assumptions that have been made in the approach used:

- The 10 and 15% TBSA limits for severe burns are used in hospitals and burns units to determine when intravenous fluid replacement is required to treat serious burns. This limit is inherently conservative to ensure that all patients who might be at risk are covered.
- Both of the above limits, for children and the elderly, are based on partial thickness burns, which should ensure that no full thickness burns are experienced. Although there are risks in extreme cases, due to oedema, inhalation injury and pre-existing conditions, the risk of fatality from small areas of partial thickness burns is very small at all ages, even without medical treatment.
- The basic assumption that half of the unclothed area is burned is conservative. Since the geometry of the body is irregular and rounded, the actual burn area will typically be closer to a quarter of the 'available' skin area.
- Although there is a wide range in the estimates of the dose for partial thickness burns, these refer to the threshold of partial thickness burns and the limits for 'mid-range' partial burns will be higher.

It is possible that several stages of conservatism have been built into the various predictions of the dose criteria that produce certain burn depths, which may have
'lowered' the predicted values. Although the aim is to produce the most realistic dose criteria, it is important to err on the side of caution. Hence, as described above, conservative assumptions have been made where necessary, in light of the uncertainties associated, but it is believed that none are excessively conservative.

13. A number of models based on incident data have been assessed in some detail in Appendix B, with particular respect to variations in the response to thermal radiation with age. The overall conclusions that can be drawn from this data (Section 4.3) produce further support for many of the assumptions that have been used in determining the dangerous dose for vulnerable populations, of 500 \((\text{kW/m}^2)\times\text{s}^2\).

6.3 Thermal dose units equivalency

The following lists the main points and conclusions relating to thermal dose units, and potential equivalents, that have been drawn from the reviews and analysis described in Section 5 of this report.

14. The use of thermal dose units is considered to provide the best correlation between radiation intensity and exposure time, over the typical ranges of fire incidents such as fireballs and pool fires. At extremes of either radiation intensity or exposure, thermal dose units can significantly over-predict the effects that will be experienced. Thus, there is an argument for consideration of simple alternatives, such as simple radiation intensity limits, outside of the normal range. However, this is not considered to be of key significance since it would only apply to extreme circumstances and the use of thermal dose units will remain conservative, if not realistic, in such conditions.

15. Because of the obvious difficulty associated with conducting experiments that involve severe burns, the index of \(n=4/3\) that is used in thermal dose units is accepted as the best that is available. There is, however, a suggestion that it may be less accurate with respect to non-fatal injury effects.

16. Lees [28] proposes a model which makes use of the linear relationship between thermal dose and burn depth (in the dermal layer) to predict injury effects. It is recommended that this approach is developed further, given the variation in skin depth around the body, and the importance of depth of burn with respect to burn severity (which determines the extent of scarring and, ultimately, fatality). The main areas in which the approach requires further consideration are:
   - justification of the linear relationship between burn depth and thermal dose,
   - reducing the uncertainty in predicting the dose levels at which partial and full thickness burns occur - which are used as boundary conditions for the model.

17. Further use of the burn depth is used in models that consider the skin temperature as the primary function of damage, rather than the thermal dose. It is found that such models are still dependent on the use of thermal dose units to represent the actual output of fire incidents and can also be relatively complex. However, more detailed representation of the actual burns can be made through temperature to burn depth assessments, as shown by a recent model developed by Lawton [29]. It is unlikely that temperature, or its related effects, can be used as a practical alternative to thermal dose units, but it is recommended that future refinements of radiation effects analysis should concentrate on using thermal dose and skin temperature in tandem – either for ‘calibration’ or to set thresholds and evaluate damage more accurately.
7. REFERENCES


4. TNO (1992) "A Model for the Determination of Possible Damage", CPR 16E.


34 McIndoe Burn Centre (The Queen Victoria Hospital, East Grinstead) Internet Site (1999): www.queenvic.demon.co.uk/mcinburn.htm.

35 Pinderfields Burn Centre (Pinderfields General Hospital, Wakefield) Internet Site (1999): www.demon.co.uk/pinderfields/wwwburn.html.

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


APPENDIX A:

GLOSSARY OF MEDICAL TERMS

The following terms are used frequently when dealing with the various aspects of thermal radiation effects on humans, i.e. burns. While they are common in the field of medicine, they are briefly explained below for the assistance of readers from an engineering, or non-medical, background. Most of the descriptions given are from the New Collins English Dictionary (1997).

_Atrophy:_ the wasting away of a physical organ or part,

_Haemoglobin:_ protein in red blood cells that carries oxygen from the lungs to the tissues,

_Intubation:_ insertion of tube into (larynx, etc.) to keep it open,

_Morbidity:_ relating to or characterised by disease – typically used in burns references to describe non-fatal physical impacts, particularly scarring.

_Myocardial infarct:_ fatal damage to the muscular substance of the heart, i.e. a 'heart attack'.

_Oedema:_ an abnormal accumulation of fluid in the tissues of the body, causing swelling.

_Pulmonary:_ affecting the lungs,

_Renal:_ of the kidneys,

_Sebum:_ oily substance secreted by the sebaceous glands (which are the small glands in the skin that secrete oil into hair follicles and onto most of the body surface),

_Sepsis:_ poisoning caused by the presence of pus-forming bacteria in the body,

_Septicaemia:_ an infection of the blood which develops in a wound,

_Sterol:_ a natural insoluble alcohol, such as cholesterol or sryosterol,

_Termbosis:_ coagulation of the blood in the heart or a blood vessel, forming a blood clot,

_Tracheotomy:_ the cutting of a hole through the skin of the neck, so that a tube can be used for artificial respiration.
APPENDIX B:
REVIEW OF PROBIT & LOGIT FUNCTIONS DEVELOPED FROM INCIDENT DATA

B.1 General Conclusions

A wide range of statistical analysis based on incident data from hospitals or burn units, using either probit or logit models, is available, which can be compared against basic mortality data given in mortality charts, such as that produced by Lawrence [B1]. These methods are reviewed in some detail by Hockey & Rew [B2] and also summarised in work by Maillette & Birk [B3] and Lees [B4]. A number of overall conclusions that can be made from the review by Hockey & Rew are listed below.

- Rittenbury et al [B5] state that in their review of 1831 patients, only 2% of patients with no full thickness burns died.

- Moores et al [B6] and Pruitt et al [B7] suggest that the extent of full thickness burns is not independent of the total area of burn. Several authors use both full thickness and partial or total thickness burn areas in their correlations.

- Rittenbury et al [B5] also conclude that, “as expected”, complicating factors (i.e. pre-existing medical conditions that can increase mortality for a given severity of burn) are more predominant in elderly patients.

- Moyer [B8] reports that the elderly who die from a burn injury die more rapidly than younger adults suffering from a similar injury. They suggest that this is due to the elderly being less able to tolerate internal changes that are brought about by burns and the related surgery.

- Rittenbury et al [B9], Moores et al and McCoy [B10] all indicate that race and sex can have an effect on the mortality for a given burn. However, the variation is not significant (approximately 10% at 50% mortality levels), and may be related to socio-economic factors as well as physical ones. Given that this study is interested predominantly in the implications of age, it is assumed that any variations caused by sex or race are consistent at each age level.

- Rittenbury et al [B9] also suggest that the wide range of ‘complications’ in burn fatality are significant at the lower levels of fatality, but for more serious burns the number of factors of influence is reduced. At the 1% fatality level they indicate that area of full thickness burn, cerebral complications, post-burn shock, skin colour, pulmonary complications, pre-existing cardiovascular conditions and other factors are all significant influences. In contrast, at the 5% fatality level they conclude that only age and post-burn liver complications (presumably in addition to total burn area) are significant.

Bearing in mind the uncertainties associated with the use of incident data, which are listed in Section 2.2.1 of the report (and reproduced in Section B.2), further analysis of the models can be performed to investigate the extent of the effects listed below, with respect to age. The conclusions that can be drawn from this analysis are discussed in Sections B.3 to B.8.

- Variation of fatality by age and burn area,
- Fatality rates,
• Comparison between partial and full thickness burns in causing fatality,
• Extent of impact of oedema,
• Extent of impact of inhalation injury,
• Dose to produce partial thickness burns.

B.2 Uncertainty Associated with Incident Data

If 'typical' differences between, for example, an 'average' adult and an 'average' child are to be identified it is essential to acknowledge (and, where possible, address) the limitations of the data. The main points that should be considered when looking at incident data from hospitals or burn are discussed briefly below.

• Data is based on patients actually treated, and does not account for fatalities who never reach hospital (and also minor burn victims who may be treated outside of burns wards or units). Clark & Fromm [B11] state that the crude mortality rate is generally higher in burns units than in general hospitals since, even in cases with the same burn size, the more serious injuries will be treated by specialist burns units. Brigham & McLoughlin [B12] state that, of 5500 recorded fire deaths in the US in 1992, only 1400 (25%) occurred in burn centres or hospitals. Similarly, Barillo & Goode [B13] found in their study of fire deaths that 554 out of 705 burn fatalities (79%) occurred before victims could be treated in hospital, and Clark & Fromm estimate that 50% of burn deaths never enter the healthcare system.

• Hospitals rarely differentiate between different causes of burns – since cure is their overriding interest, not cause – and burns data will include contact, chemical, electrical and even sun burns, which are not relevant to thermal radiation from industrial fires as considered here.

• In a similar way, the wide range of burns covered will include house fires and other scenarios where inhalation injury is more likely than in cases where exposure to radiation occurs at a distance (as is most prevalent in the circumstances of interest here).

• Different data sets will adopt different approaches to defining factors such as cause of death and severity of burns. In particular, differentiation between fatality through burns and through inhalation injury is notoriously difficult, nor is determining the area and depth of burns an exact science.

B.3 Variation of Fatality for Different Burn Areas

Probit functions derived by Clark & Fromm [B11], Hymes et al [B14] and East et al [B15] are compared with basic data from Lawrence’s [B1] mortality chart. The variations in fatality with burn area are compared at similar age ranges, relating to children, ‘adults’ and the elderly. These are shown in Figures B.1 to B.3, and are discussed, for each age group separately, after the summaries of each model which are given below.

Clark & Fromm (1987)

Basis: 507 patients assessed.

Logit function: \[ P = 1 + e^{-2} \]
Where:
\[
y = -4.26 + (0.0976 \times \text{full thickness burn area}) - (0.0454 \times \text{age}) + \\
(0.000919 \times \text{age}^2) + (1.43 \times \text{inhalation injury})
\]

Thus, the function relates the full thickness burn area and age to the probability of fatality, \( P \), with the option of allowing for the presence of inhalation injury. The results are shown in Figures B.1 to B.3 for cases with and without inhalation injury. The results without inhalation injury appear to be consistent with the other models, although, in general, they will tend to over-predict fatality relative to the other models, which are based on total burn area (which will typically involve approximately half full thickness and half partial thickness burns).

**Hymes et al (1993)**

**Basis:**
3,421 patients (1971 to 1980).

**Logit function:**
\[
P = \frac{e^y}{1 + e^y}
\]

**Where:**
\[
y = -7.575 + (0.07184 \times \text{age}(+0.5)) + (0.1135 \times \text{total burn area})
\]

**East et al (1988)**

The probit function used by East et al is not defined, but the results are presented in their report for a range of age groups, which are used to produce Figures B.1 to B.3. Their function is believed to have been derived from a very large sample (around 30,000 incidents) recorded by the US National Burn Information Exchange (NBIE), between 1979 and 1984. It is unlikely that this large sample would contain detailed information on victims, so it is likely that the function is based solely on total burn area and age.

It is noted that the results shown in Figures B.1 to B.3 indicate that this function appears to under-predict fatality compared to the other models, particularly in the adult range. It is possible that the 'adult' range is distorted by the fact that the range is from 5 to 34 years. East et al describe this as the range where peak health (and thus burn response) occurs. Most other authors use a more traditional range for adults of between 20 and 60 years of age.

**B.3.1 Average population**

East et al [B15] state that the peak in health and burns response occurs between 5 and 34 years of age. Using the mid-range value of 25 in the other models, the results are shown in Figure B.1. The age range used is clearly not fully representative of an 'average' population, which is usually from 20 to 60 years of age, but should represent the age at which mortality from a given burn will be close to its minimum.

The key points that can be derived from Figure B.1 are listed below.

- As discussed above, the Clark & Fromm [B11] model is based on full thickness burns and will be slightly over-conservative, particularly when inhalation injury is included. The model of East et al appears to be under-conservative in this age range, as discussed above. If both of these data sets are neglected the remaining sample of 3 curves is very small, but appears to show reasonable consistency and is also approximately half way between the two extremes represented by Clark & Fromm and East et al.
• From these sets it may be estimated that the burn size beyond which the majority of adults will die, taken as a '90% fatality' threshold, is approximately 70% TBSA.

• Similarly, the burn size below which the majority of adults will not die, taken as a '90% survival' threshold, is approximately 25% TBSA.

• In adults, the burn area of interest is 15% TBSA, which is used as the point at which burns are classed as severe (i.e. life threatening). It can be seen that, neglecting the Clark & Fromm model with inhalation injury, the survival rate at this burn area is greater than 95%. If the burn area is doubled to 30% TBSA, the survivability reduces to 85%.

![Comparison of fatality plots for 'adult' populations](image)

**Figure B.1** Comparison of fatality plots for ‘adult’ populations

**B.3.2 Elderly populations**

Taking a 'typical' age for the elderly as being 67.5 years old, the comparison between the different models at this age is shown in Figure B.2. Note that this is selected as a reasonably representative age, although the mortality rate (shown by all models) will increase quite significantly beyond this age range.

The key points that can be derived from Figure B.2 are listed below.

• Although the East et al [B15] model is still the least severe in terms of fatality, there is generally good agreement between the different models at this age range. In addition it should be noted that the Clark & Fromm [B11] model with inhalation injury is reasonably consistent with the other models for the elderly (while it was clearly over-conservative in the ‘adult' age range shown in Figure B.1). This suggests that the other models, and certainly the Lawrence [B1] mortality chart, have been influenced by inhalation injury, or other complications, to a much larger degree at the older age groups than for younger burn victims.
- From these sets it may be estimated that the burn size beyond which the majority of the elderly will die, or the '90% fatality' threshold, is approximately 40% TBSA.

- Similarly, the '90% survival' threshold is approximately 10% TBSA, although even this level may include a high proportion of fatalities if inhalation injury is present.

- In the elderly, the burn area of interest is 10% TBSA, which is used as the point at which burns are classed as severe (i.e. life threatening). It can be seen that the basic survival rate will be greater than 70%, (and greater than 80% if the Clark & Fromm model, including inhalation injury and full thickness burns, is neglected). If the burn area is doubled to 20% TBSA, the survivability becomes much more unpredictable, being between 45 and 85%.

![Figure B.2 Comparison of fatality plots for elderly populations](image)

B.3.3 Children

Considering the lower age range in children, 0 to 5 years old, which should represent the most vulnerable of children, the comparison between the different models at this age is shown in Figure B.3. The key points that can be derived from this are listed below.

- Although the East et al [B15] model is still the least severe in terms of fatality, there is generally good agreement between the different models at this age range. Both of the curves obtained from the Clark & Fromm [B11] model, with and without inhalation injury, give significantly higher mortality rates than the other models. There is, in fact, reasonably good agreement between the other models. The 'over-conservatism' (at least with respect to the other models) of the Clark & Fromm data may be simply because the full thickness burn area which is used by this model is more significant at younger ages. However, it should be noted that such analysis is uncertain in a number of respects at the lower end of the age range. For example, because of the relatively high variability with age, the exact age that is analysed is far more important when dealing with young children.
Thus, the following points are derived without consideration of the Clark & Fromm plots which are shown in Figure B.3. (Note that the data points from the Lawrence chart are averaged over two age groups, which, in this case, produces a slightly irregular curve.)

- From these sets it may be estimated that the ‘90% fatality’ threshold, is approximately 80% TBSA.

- Similarly, the ‘90% survival’ threshold, is approximately 40% TBSA.

- In children, a 10% TBSA burn area is used as the point at which burns are classed as severe (i.e. life threatening), although it is likely that body areas of around 30% may be exposed to radiation. It can be seen that the basic survival rate will be almost 100% for burn areas of up to 20%, and greater than 95% for burn areas up to 30% TBSA.

![Figure B.3 Comparison of fatality plots for children](image)

**B.4 Fatality Rates**

**B.4.1 General**

Based on approximations from Figures B.1 to B.3, in addition to values proposed by other authors, burn areas to produce 50% fatality rates at different ages are summarised in Table B.1. Also included are values obtained from the review of Hockey & Rew [B2], which are derived from the work of Pruitt et al [B7], who compare their results with those of Bull & Squire [B16] and Barnes [B17]. Note that the burn areas referred to are total burn area, which is assumed to include a combination of partial and full thickness burns. Values from the probit function developed by Zawacki et al [B18] are added (where the function is given in Section B.3). This is based on full thickness burns, and also includes factors for the presence of an ‘airway oedema’ and ‘abnormal oxygen pressure’.
The results for 10% fatality are shown in Table B.2, although values from Pruitt et al, Bull & Squire and Barnes are not available at this rate. It should be noted that in both tables, the age ranges used to define each age group have some variation, and there are variations in the assumptions used (such as the use of full thickness burn area by Zawacki et al). Also, the different results cover a broad time scale, over which burn mortality is known to have reduced significantly.

However, it can be seen from Table B.1 that there is reasonable agreement between the 50% fatality results, particularly for the elderly. If the average burn area to cause 50% fatality in adults is taken as 55% TBSA, and the equivalent value for the elderly is around 25% TBSA, it can be seen that the burn area to cause 50% mortality is more than doubled in the elderly.

The difference between children and adults is not so clear, and from this data, no real conclusion can be drawn, other than to suggest that the 50% mortality rate is produced by approximately the same area of burn in children and adults.

There is not enough data available at the 10% fatality level (Table B.2) to draw sensible conclusions, although the ratio of approximately 2:1 between burn area for mortality in the elderly and ‘adults’ can be seen again.

<table>
<thead>
<tr>
<th>Source</th>
<th>Burn area required to produce 50% fatality (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Children (Age 0-14)</td>
</tr>
<tr>
<td>Bull &amp; Squire (1954) [B16]</td>
<td>49</td>
</tr>
<tr>
<td>Barnes (1957) [B17]</td>
<td>39</td>
</tr>
<tr>
<td>Pruitt et al (1964) [B7]</td>
<td>49</td>
</tr>
<tr>
<td>Average value from the results of Section B.3.2</td>
<td>50-70 (age 0-5)</td>
</tr>
<tr>
<td>Zawacki et al (1979) [B18]</td>
<td>54-57 (age 5-10)</td>
</tr>
</tbody>
</table>

Table B.1 Comparison of 50% fatality levels between different assessments, from Hockey & Rew [B2]

<table>
<thead>
<tr>
<th>Source</th>
<th>Burn area required to produce 10% fatality (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Children (Age 0-5)</td>
</tr>
<tr>
<td>Average value from the results of Section B.3.2</td>
<td>40-50 (age 0-5)</td>
</tr>
<tr>
<td>Zawacki et al (1979) [B18]</td>
<td>34-38 (age 5-10)</td>
</tr>
</tbody>
</table>

Table B.2 Comparison of 10% fatality levels between different assessments, from Hockey & Rew [B2]

**B.4.2 1% fatality**

There are many factors that can influence mortality in addition to age and burn area, and as discussed by Rittenbury et al [B5], they become more significant at lower fatality rates. Thus, at 1% fatality, which is equivalent to a dangerous dose, there are a large number of potential causes. Hence, many of the probit models suggest that 1% fatality can occur in burns of '0%
TBSA’, due to complications such as smoke inhalation, oedema or pre-existing illnesses. (Note that in these cases, it is assumed that some burn has occurred, but is superficial, or of very shallow partial thickness.) Also, at these levels, fatality is inherently low and involves extreme cases, which are not necessarily well represented by the overall probit or logit function that is used (which will be based on a form of ‘best fit’ analysis). Hence, it is difficult to draw accurate conclusions, by looking at incident data at the 1% level.

However, general trends may be identified, based on the various probit functions reviewed above. Estimates of the burn area required to produce 1% fatality are summarised in Table B.3 and discussed, for each of the age groups, below.

**Adults**

The following basic conclusions can be drawn from Table B.3, using the assumption that a maximum of 20% burns are likely to be sustained by a normally clothed adult.

- The full range of burns to produce 1% fatality from ‘general’ burns (which will typically include a mixture of partial and full thickness burns) is between 5 and 40% TBSA (rows 1 to 6 of Table B.3). Given that row 6 refers to an extreme case, where more than one ‘complication’ occurs, which is much less likely in adults and in radiation burn cases, the range may be reasonably reduced to between 11 and 40% TBSA.

- Note that the range of values involved is not only an indicator of the uncertainty involved in assessing incident data but of the actual range of responses that can occur in the same age group.

- Partial thickness burns will not produce 1% fatality except in extreme cases where additional complications occur (rows 11 & 12).

- Full thickness burns, of almost any area, are generally sufficient to cause at least 1% fatality, even without additional complications (rows 7 to 10).

**The Elderly**

The following basic conclusions for the elderly can be drawn from Table B.3, using the assumption that a maximum of 20% burns are likely to be sustained by a normally clothed elderly person.

- In general 1% fatality from ‘general’ burns (which will typically include a mixture of partial and full thickness burns) occurs at very small burn areas, in the elderly. It is assumed that the ‘general’ functions (rows 1 to 3 of Table B.3) include allowances for complications such as pre-existing conditions or inhalation injury. These conditions are highly likely in the elderly and should not be discounted, although row 4 indicates that over 10% burn area would be required to produce 1% fatality in the absence of any complicating factors.

- Partial thickness burns alone will produce 1% fatality around 15% TBSA, and at all burn areas where additional complications occur (rows 11 & 12).

- Full thickness burns, of almost any area, are generally sufficient to cause at least 1% fatality, even without additional complications (rows 7 to 10).
The basic conclusion is that, because of the prevalence of pre-existing conditions and generally poorer health in the elderly, fatality rates of greater than 1% should be assumed in any burn beyond the threshold of partial thickness burns.

**Children**

Estimates of the burn area required to produce 1% fatality in children are summarised in Table B.3. Note that, although several authors, as well as medical experts and basic intuition, suggest that burns can be more severe to young children, most of the probit functions developed from incident data suggest reduced fatality at lower ages. The two main explanations for this are postulated as:

- **Very young children receive higher priority medical treatment.**
- **The general trend in burn response is for mortality to reduce with age, down to a certain limit, many of the probit functions may be based on data extrapolation which simply extends the mortality reduction down to very young ages.**

The following basic conclusions can be drawn from Table B.3, using the assumption that a maximum of 15 to 30% burns are likely to be sustained by a normally clothed child.

- **The full range of burns to produce 1% fatality from ‘general’ burns (which will typically include a mixture of partial and full thickness burns) is between 25 and 45% TBSA (rows 1 to 6 of Table B.3). This indicates that, from incident data, in children receiving burns to half of their unclothed areas (which would be typically 30% TBSA) the fatality rate would be below 1%.**

- **Note that the range of values involved is not only an indicator of the uncertainty involved in assessing incident data but of the actual range of responses that ‘typically’ occur. Also, as discussed above, this incident data may represent the actual survival rates but the proportion of children who receive life-threatening burns may be far greater.**

- **Partial thickness burns alone should not produce 1% fatality at burns less than 30% TBSA, even where additional complications occur (rows 11 & 12).**

- **The values in Table B.3 indicate considerable uncertainty in the area of full thickness burns required for 1% fatality. It is reasonable to assume that full thickness burns will produce fatality of more than 1% at burn areas below the ‘typical’ exposed area of 15% TBSA (rows 7 to 10).**

**B.4.3 Fatality at ‘severe’ burn area**

A similar analysis can be performed by considering the data presented in Figures B.1 to B.3, and in other assessments, such as Zawacki et al [B18], at specific burn areas. Estimates of the fatality at burn areas that are likely to produce ‘severe’ burns are summarised in Table B.4 and discussed, for each of the age groups, below.

**Adults**

A ‘normally clothed’ adult is assumed to have 20% TBSA unclothed, of which approximately half is likely to be burned by exposure to thermal radiation. Similarly, the burn area (predominantly partial thickness, but allowing for some full thickness burns) which is
defined in the medical profession as a severe burn is 15 to 20% TBSA. Table B.4 shows the fatality rates estimated from various functions at these burn areas.

- Although the results from Hymes et al [B13], shown in row 1 of Table B.4, suggest that fatality rates of greater than 1% can occur between 10 and 20% burn areas, the other analyses suggest that 10 to 20% TBSA burns can be tolerated in an 'average' population for general burns (rows 1 to 6).

- Similarly, with partial thickness burns only (rows 11 & 12), the fatality should not exceed 1%. There is risk associated with oedema and other complications, which should not be discounted, although generally the incidence of such complications should be low in adults and in radiation burns.

- It can be seen (from rows 7 to 11) that full thickness burns of 10% or greater are likely to produce fatality rates of greater than 1%, even in the absence of 'complications'.

**The Elderly**

A 'normally clothed' adult (which, in this respect, includes the elderly) is assumed to have 20% TBSA unclothed, of which approximately half is likely to be burned by exposure to thermal radiation. Similarly, the burn area (predominantly partial thickness, but allowing for some full thickness burns) which is defined in the medical profession as a severe burn for the elderly is around 10% TBSA. Table B.4 shows the fatality rates estimated from various functions at 10 and 20% burn areas.

- Any burns beyond the threshold of partial thickness burns are likely to exceed 1% fatality in the elderly for areas of 10% TBSA or greater.

- Even with partial thickness burns only, without any 'complications' row 11 of Table B.4 indicates that the fatality approaches 1% for 10% burn areas and will almost certainly exceed 1% as the burn area increases beyond this level.

**Children**

A 'normally clothed' child is assumed to have up to 30% TBSA unclothed, of which approximately half is likely to be burned by exposure to thermal radiation. Similarly, the burn area (predominantly partial thickness, but allowing for some full thickness burns) which is defined in the medical profession as a severe burn for children is around 10% TBSA. Table B.4 shows the fatality rates estimated from various functions at 10 and 20% burn areas.

- The analyses suggest that 10 to 20% TBSA burns can be tolerated by children for general burns (rows 1 to 6 of Table B.4).

- Similarly, the incident data indicates that with partial thickness burns only (rows 11 & 12), the fatality should not exceed 1%, even in the presence of 'complications'.

- There is greater variation in the predicted impacts of full thickness burns in children given by the two models assessed (rows 7 to 11). Given that incident data generally indicates similar fatality rates for children and 'healthy' adults, it is reasonable to assume that full thickness burns of 10% or greater are likely to produce fatality rates of greater than 1%, even in the absence of 'complications'.

B-10
<table>
<thead>
<tr>
<th>Row</th>
<th>Model</th>
<th>Type of burn</th>
<th>Complicating factors</th>
<th>Burn area to produce 1% fatality (% TBSA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average Population</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Age</td>
</tr>
<tr>
<td>1</td>
<td>Hynes et al (1983) [B13]</td>
<td>General</td>
<td>General</td>
<td>5 - 34</td>
</tr>
<tr>
<td>3</td>
<td>Lawrence (1991) [B1]</td>
<td>General</td>
<td>General</td>
<td>5 - 34</td>
</tr>
<tr>
<td>4</td>
<td>Zawacki (1979) [B18]</td>
<td>50:50 full-partial thickness</td>
<td>None</td>
<td>20 - 40</td>
</tr>
<tr>
<td>5</td>
<td>Zawacki (1979)</td>
<td>With oedema</td>
<td>20 - 40</td>
<td>15 - 28</td>
</tr>
<tr>
<td>6</td>
<td>Zawacki (1979)</td>
<td>With oedema and abnormal oxygen pressure</td>
<td>20 - 40</td>
<td>5 - 18</td>
</tr>
<tr>
<td>7</td>
<td>Clark &amp; Fromm (1979) [B11]</td>
<td>Full thickness only</td>
<td>General</td>
<td>5 - 34</td>
</tr>
<tr>
<td>8</td>
<td>Zawacki (1979)</td>
<td>Full thickness only</td>
<td>None</td>
<td>20 - 40</td>
</tr>
<tr>
<td>9</td>
<td>Clark &amp; Fromm (1979)</td>
<td>With inhalation injury</td>
<td>5 - 34</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>Zawacki (1979)</td>
<td>With oedema and abnormal oxygen pressure</td>
<td>20 - 40</td>
<td>3 - 15</td>
</tr>
<tr>
<td>11</td>
<td>Zawacki (1979)</td>
<td>Partial thickness only</td>
<td>None</td>
<td>20 - 40</td>
</tr>
<tr>
<td>12</td>
<td>Zawacki (1979)</td>
<td>With oedema and abnormal oxygen pressure</td>
<td>20 - 40</td>
<td>6 - 25</td>
</tr>
</tbody>
</table>

Note 1: 'General' type of burn refers to Total Burn Area which is an unspecified mixture of full and partial thickness burns – assumed to be predominantly partial thickness.

Note 2: 'General' complicating factors refer to functions which are based on incident data that will inherently include complications such as inhalation injury, oedema, etc, but are not explicitly included in the function itself.

Table B.3 Estimates of burn area to cause 1% fatality
<table>
<thead>
<tr>
<th>Row</th>
<th>Model</th>
<th>Type of burn</th>
<th>Complicating factors</th>
<th>Fatality at 'severe' burn areas (%)</th>
<th>Average Population</th>
<th>The Elderly</th>
<th>Children</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Age</td>
<td>10% Burn Area</td>
<td>20% Burn Area</td>
<td>Age</td>
</tr>
<tr>
<td>1</td>
<td>Hymes et al (1993) [B13]</td>
<td>General</td>
<td>General (2)</td>
<td>5 - 34</td>
<td>1</td>
<td>3</td>
<td>60 - 74</td>
</tr>
<tr>
<td>2</td>
<td>East et al (1988) [B15]</td>
<td>General</td>
<td>General</td>
<td>5 - 34</td>
<td>0</td>
<td>0</td>
<td>60 - 74</td>
</tr>
<tr>
<td>3</td>
<td>Lawrence (1991) [B1]</td>
<td>General</td>
<td>General</td>
<td>5 - 34</td>
<td>0</td>
<td>0</td>
<td>60 - 74</td>
</tr>
<tr>
<td>4</td>
<td>Zawacki (1979) [B18]</td>
<td>50:50 full:partial thickness</td>
<td>None</td>
<td>20 - 40</td>
<td>0</td>
<td>0-0.5</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>Zawacki (1979)</td>
<td>With oedema and abnormal oxygen pressure</td>
<td>20 - 40</td>
<td>0-0.5</td>
<td>0-2</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Clark &amp; Fromm (1979) [B11]</td>
<td>Full thickness only</td>
<td>General</td>
<td>5 - 34</td>
<td>2</td>
<td>5.5</td>
<td>60 - 74</td>
</tr>
<tr>
<td>7</td>
<td>Zawacki (1979)</td>
<td>None</td>
<td>None</td>
<td>20 - 40</td>
<td>0</td>
<td>1-6</td>
<td>60</td>
</tr>
<tr>
<td>8</td>
<td>Clark &amp; Fromm (1979)</td>
<td>With inhalation injury</td>
<td>5 - 34</td>
<td>8</td>
<td>20</td>
<td>60 - 74</td>
<td>32</td>
</tr>
<tr>
<td>9</td>
<td>Zawacki (1979)</td>
<td>With oedema and abnormal oxygen pressure</td>
<td>20 - 40</td>
<td>0.5-3</td>
<td>3-12</td>
<td>60</td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td>Zawacki (1979)</td>
<td>Partial thickness only</td>
<td>None</td>
<td>20 - 40</td>
<td>0</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>11</td>
<td>Zawacki (1979)</td>
<td>With oedema and abnormal oxygen pressure</td>
<td>20 - 40</td>
<td>0-2</td>
<td>0.5-4</td>
<td>60</td>
<td>8</td>
</tr>
</tbody>
</table>

Note 1: 'General' type of burn refers to Total Burn Area which is an unspecified mixture of full and partial thickness burns – assumed to be predominantly partial thickness.

Note 2: 'General' complicating factors refer to functions which are based on incident data that will inherently include complications such as inhalation injury, oedema, etc, but are not explicitly included in the function itself.

Table B.4 Estimates of fatality in 'severe' burn area region
B.5 Comparison between partial and full thickness burns in causing fatality

The probit function produced by Zawacki et al [B18], includes factors for both the total and full thickness burn areas, as shown below. It is assumed that by setting the full thickness burn area as the same as the total area, that the variation in fatality with full thickness burn can be evaluated. If the full thickness burn area is set to zero, it is assumed that the burn is purely partial thickness, or second degree. These two probit functions can then be compared to assess the fatality levels produced by each type of burn. (Note that, generally, total burn area is a combination of both partial and full thickness burns.)

Basis: 1535 patients assessed. Hymes et al [B13] suggest that the results do not differ significantly from more recent data.

Probit function:

Probit indicator of probability of fatality, Y

Where:

\[ Y = (0.036 \times \text{age}) + (0.037 \times \text{total burn area}) + 0.56 \text{ (if airway oedema)} + 0.52 \text{ (if abnormal oxygen pressure)} + (0.028 \times \text{full thickness burn area}) \]

Note that the original model also includes a factor for "prior bronchopulmonary disease", which is not used here since it is a fairly specific form of pre-existing condition.

The burn areas required to produce different fatality levels for each age group, for the two burn severities, are summarised in Table B.5. It can be seen that, in the elderly, a burn area as low as 16% can cause 1% fatality even with only partial thickness burns. In general, the table illustrates the fact that partial thickness burns must cover a considerably greater proportion of the body to produce fatality rates equivalent to third degree burns. Note that the presence of oedema and abnormal oxygen pressure is assumed not to occur, in all of the values presented in this table.

<table>
<thead>
<tr>
<th>Mortality rate (%)</th>
<th>Burn area required to produce fatality for 'partial thickness only' (PT) and 'full thickness only' (FT) burns (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Children (Age 5-10)</td>
</tr>
<tr>
<td></td>
<td>PT</td>
</tr>
<tr>
<td>1% fatality</td>
<td>75</td>
</tr>
<tr>
<td>10% fatality</td>
<td>90-95</td>
</tr>
<tr>
<td>50% fatality</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table B.5 Comparison of fatality levels between full thickness and partial thickness burn areas, based on probit function of Zawacki et al [B18]

B.6 Extent of impact of oedema

Oedema is produced by all burns, but can be a significant cause of fatality in burns to the face, neck or chest, if not treated. Little information is available from which to determine
what extent of burn is required to produce oedema to the extent that a burn victim’s life is threatened.

The effect of an airway oedema is included in the probit function produced by Zawacki et al [B18], and certain conclusions can be drawn from this by using the function with and without the oedema presence. A plot showing the survivability of patients with an airway oedema as a percentage of the survivability of patients without oedema, for different ages and burn areas, is given in Figure B.4, and a selection of key values at different age groups is given in Table B.6. The broad conclusions that can be made from this assessment are listed below.

- For small areas of total burn (from 10 to 20% TBSA), survivability is not affected by the presence of airway oedema.

- The impact that airway oedema has on survivability becomes much more significant with burn area and age. At 50% TBSA, the presence of oedema can reduce the survivability of adults (20-40 years old) to 80-90% of the ‘non-oedema’ survivability. The corresponding value for the elderly can be as much as 50% of the non-oedema survivability (in 80 year olds).

- Reduction in the survival rate due to oedema is almost linear in the elderly, whereas in younger adults, the increase in mortality only becomes significant in burns of 50% TBSA or more.

- The probit function of Zawacki et al assumes that mortality decreases with age even in the very young and so the effect of oedema is, in this case, even lower in children than in adults of an ‘average’ age.

![Figure B.4 Impact of airway oedema on survivability, based on Zawacki et al’s [B18] probit](image)

(Note that data points are shown only to distinguish between each age group, the curves are plotted from continuous equations rather than directly from experimental data)
<table>
<thead>
<tr>
<th>Total Burn Area (% TBSA)</th>
<th>Probability of survival with oedema as a percentage of probability of survival without oedema (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Children (Age 10)</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>50</td>
<td>95</td>
</tr>
<tr>
<td>80</td>
<td>70</td>
</tr>
</tbody>
</table>

Table B.6 Impact of airway oedema on survivability, based on probit function of Zawacki et al [B18]

B.7 Extent of impact of inhalation injury

The extent and severity of inhalation injury is very difficult to determine, so any attempts to quantify its effect must be treated with caution. Nevertheless, it is useful to analyse any incident data that is available to gain an indication of the effect that it may have, particularly with respect to age.

The effect of inhalation injury is included in the logit function produced by Clark & Fromm [B11], and certain conclusions can be drawn from this by using the function with and without the allowance for inhalation injury. A plot showing the survivability of patients with inhalation injury as a percentage of the survivability of patients without, for different ages and burn areas, is given in Figure B.5, and a selection of key values at different age groups is given in Table B.7. The broad conclusions that can be made from this assessment are listed below.

- Inhalation injury has some impact on survivability even at very small burn areas.
- Its impact becomes more significant as burn size increases up to a limit of around 70% TBSA full thickness burn area. Beyond this level of burn size, which has a very low probability of survival even without inhalation injury occurring, the survivability with inhalation is constant at 24% of the 'non-inhalation' survivability.
- Inhalation injury is more significant to elderly patients, even for small burn areas, up to full thickness burn areas of around 60% TBSA.
- Inhalation injury can also be seen to be more significant to children than adults, although the difference is relatively small compared to the difference between adults and the elderly, as can be seen in Table B.7 and Figure B.5.
- Note that the logit function of Clark & Fromm is based on full thickness burn area – which is typically around 50% of the total burn area. (Hence the burn area values in Table B.7 are half of those used in, for example, Table B.6, so that some comparison can be made.)
Figure B.5 Impact of inhalation injury on survivability, based on logit function of Clark & Fromm [B11]

(Note that data points are shown only to distinguish between each age group, the curves are plotted from continuous equations rather than directly from experimental data)

<table>
<thead>
<tr>
<th>Full thickness Burn Area (% BSA)</th>
<th>Probability of survival with inhalation injury as a percentage of probability of survival without inhalation injury (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Children (Age 5)</td>
</tr>
<tr>
<td></td>
<td>Adults (Age 20-40)</td>
</tr>
<tr>
<td></td>
<td>Elderly (Age 60)</td>
</tr>
<tr>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>10</td>
<td>91</td>
</tr>
<tr>
<td>15</td>
<td>87</td>
</tr>
<tr>
<td>25</td>
<td>73</td>
</tr>
<tr>
<td>40</td>
<td>46</td>
</tr>
</tbody>
</table>

Table B.7 Impact of inhalation injury on survivability, based on logit function of Clark & Fromm [B11]

B.8 Dose to Produce Partial Thickness Burns

In addition to the incident data presented in the previous sections, probit models are available which can be used to relate thermal dose to severity of burn, rather than using severity of burn to derive fatality levels. The TNO ‘Green Book’ [B19] gives a probit function which relates the dose, in thermal dose units, to the probability of 2nd degree burns occurring.
Taking the 0.1 to 0.9 probability range as being a realistic dose range at which 2nd degree burns are ‘very likely’, the function gives a range of between 550 and 1300 (kW/m²)⁴/s. The 0.5 probability level occurs at a dose of 850 (kW/m²)⁴/s.

The function is shown in Figure B.6, which also shows the Tsao & Perry [B20] probit function for predicting thermal injury.

![Probit function for prediction of 2nd degree, or partial thickness, burn by TNO [B19]](image)

**REFERENCES – APPENDIX B**


B11 Clark WR & Fromm BS (1987) "Burn Mortality - Experience at a Regional Burn Unit, Literature Review", State University of New York.


B19 TNO (1992) "A Model for the Determination of Possible Damage", CPR 16E.

APPENDIX C:
EVACUATION CHARACTERISTICS

The duration of fireballs and flash fires is normally very short and it is assumed that exposed persons will not have time to escape and that the exposure duration is simply equal to the fire duration. In these incidents, vulnerable populations will be exposed for the same time as ‘normal’ populations, regardless of the relative mobility of each. For longer duration pool and jet fires it is the time taken for persons to escape to a position of safety that will determine the duration of exposure, rather than the fire duration. Thus, for these types of fire, the ability of an exposed person to escape will significantly affect their chance of survival and so a ‘vulnerable’ population (generally less mobile than a ‘normal’ population) will receive longer exposure to the radiation.

The time of exposure is accounted for by the incident dose criterion, which is a function of time \( D=I^{1/2}t \) and so the exposure, or evacuation time, is not required when determining a dose criterion. It is, however, one of the main factors that separate vulnerable from normal populations in their survival of such incidents. Thus, it is complimentary to the work presented here to briefly consider the variation in escape characteristics of different age groups. The following section discusses existing methods of determining escape times, the factors affecting escape time from radiation sources, and attempts to quantify the difference between escape times for different populations.

C.1 Evacuation literature

A great deal of research has taken place on ‘evacuation from buildings’, including the development of a number of models for estimating evacuation times in particular scenarios. Much of this work is summarised in the SFPE Handbook [C1], and the key evacuation studies are also summarised by Thompson [C2] and Holmberg [C3].

The evacuation scenarios covered by the broad area of research which the above references are part of (referred to hereafter as ‘traditional evacuation’) may be categorised by the following points.

- Almost all of this work concentrates on the evacuation of a large number of people from a building.
- While attempting to model the characteristics of people in an emergency evacuation, the escape speed is quoted as a ‘walking velocity’. That is, even allowing for panic situations, the large number of people, combined with the various obstacles that must be negotiated in leaving a building (doorways, stairs, etc.), result in a relatively low speed of escape. (Values of this escape speed are discussed later in this section.)
- The evacuations considered always refer to people exiting a building in order to avoid being involved in a fire (or other such emergency) rather than those who may have been directly affected by a fire. In other words, ‘traditional evacuation’ refers to people who are essentially evacuating because they have been told to, and do not have the urgency of people who can see, or feel, an immediate threat.

C.2 Escape from radiation sources

The study here is interested in the effect that large industrial fire incidents may have on the general public, and the evacuation conditions that apply may differ significantly from those
presented above for the traditional evacuation analysis. These differences are discussed (in a different order to the points presented in the previous section) below.

- Because it is the direct radiation effects of fires that are of interest in this case, it is the time taken for persons caught in the initial radiation range of a fire to escape to a position of safety that is the effective 'evacuation time'. In such an incident, exposed people will be in visual range of the fire, and probably within the pain threshold, so there will be considerably greater urgency in the form of evacuation, as opposed to evacuation from buildings initiated by alarms or verbal commands. It should, however, be noted that the increased urgency may be countered in some instances by the debilitating physical effects of radiation from the fire, as well as the impacts of panic.

- In general, members of the public exposed to an industrial fire will be outdoors. Large industrial fires may well affect other buildings but, generally, building occupants will be shielded from the radiation effects that are of concern here. (Note that people standing in windows or doorways will be exposed to radiation from the fire but their escape characteristics - i.e. stepping away from the window - will be somewhat different to those of someone caught in the thermal radiation range outside.) Thus, the escape scenario of interest is the converse of the traditional evacuation study - people outdoors exposed to a large fire escaping either to a safe distance or to the nearest position of shelter (i.e. outdoors to indoors, rather then the reverse).

- It is reasonable to assume that the density of people outdoors will be substantially lower than in the traditional evacuation cases considered, and that evacuees may be considered as individuals, unaffected by the movement of other people, or obstacles.

So the extensive, and often complex, methods of analysing evacuation times from buildings that have been developed are of little benefit in determining the escape time from the radiation from an industrial fire. In developing models and equations, various authors have estimated the basic speed of evacuation, as well as other factors such as detection and response times. Again, as discussed above, these factors will not be representative of a person escaping from the radiation range of a pool or jet fire.

However, the escape speeds and times can be used to draw conclusions about the speed of escape in an industrial outdoor incident and can give an indication of the lower bound on escape times, or be used to quantify the difference in escape characteristics between vulnerable and normal populations. The following section presents some of the values of escape parameters and proposes values that can be used in the treatment of radiation cases.

C.3 Escape speeds

The Simulex evacuation software package, described by Thompson et al [C4], uses a walking velocity, beyond the “interference threshold”, of 1.7 m/s. This refers to the basic speed a person travels at before the proximity of other people begins to reduce the speed of travel (the point at which this occurs is the interference threshold). The same approach is used by a variety of other authors, including another evacuation model [C5], Exodus, where the quoted base velocities, or ranges, are consistent with that used by Simulex. Some examples are given in Table C.1.

The upper values given in Table C.1 are assumed to be escape speeds for a normal, healthy population, and the lower values would be for younger or older (i.e. less mobile) populations.

These evacuation speeds are no greater than the normal, unimpeded walking speeds identified in analysis of normal commuting behaviour by Ando et al [C6]. This analysis compared the walking speeds of people of different ages, and also of males and females. The
basic conclusion was that males have consistently higher walking speeds than females, and that the elderly and very young walk at speeds that are 40-50% less than for young adults. It is from this work by Ando et al that the values used by Simulex are derived. Thompson & Marchant [C7] state that Simulex randomly assigns an unimpeded walking velocity of between 0.8 and 1.7 m/s to each person in a population, where the range is chosen to represent an even distribution of males and females between the ages of 12 and 55 years of age. (The upper value of 1.7 m/s is for a 20 year old male, and the lower value of 0.8 m/s is for a female at either end of the age range.)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Escape speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulex [C4]</td>
<td>0.8 to 1.7</td>
</tr>
<tr>
<td>Exodus [C5] #</td>
<td>1.2 to 1.5</td>
</tr>
<tr>
<td>Predtechenskii &amp; Milinskii (1969) *</td>
<td>0.9 to 1.2</td>
</tr>
<tr>
<td>Hankin &amp; Wright (1958) *</td>
<td>1.6</td>
</tr>
<tr>
<td>Weston &amp; Marshall (1972) *</td>
<td>1.25 to 1.5</td>
</tr>
</tbody>
</table>

# default settings - wider range may be used
*
values given in review by Thompson [C2]

Table C.1 Unimpeded escape speeds

This work by Ando et al [C6] appears to be alone in attempting to evaluate the difference in escape speeds for different ages, and the following points apply.

- While it is generally acknowledged that the average male will be able to escape more quickly than the average female, the difference should not be great. The significant difference between male and female walking speeds given by Ando et al may be due to a combination of the fact that the study was of commuters and that cultural differences exist in Japan, where the study took place. Thus, no distinction between evacuation of males and females is assumed here.

- It seems reasonable to assume that the average difference in walking speed between young and elderly adults will be equivalent to the difference in speeds under more urgent evacuation conditions. Thus, it is assumed that, on average, it will take an elderly population 40-50% longer to evacuate than a normal adult population. (Note that there will be greater variation in the escape speeds of the elderly - some may escape at similar rates to a normal population, while others may have significant disabilities and may be unable to evacuate at all, once affected by radiation.)

- For young children, the range of possible evacuation speeds is greater. Clearly, very young children will be unable to evacuate at all unless carried (around 0-2 years) or assisted (around 2-10 years) by adults. Older children may have greater response times and less effective decision making in a fire situation, but their actual escape speeds are assumed to be similar to those of adults. Analysis of the American National Burn Information Exchange data by East et al [C7] found that in burn cases where children are classed as "innocent bystanders" the number of incidents reduces significantly for children over the age of 10. This implies strongly that it is at around 10 years old that children begin to evacuate effectively.

- This is also assumed by the TNO 'Green Book' [C8] which suggests that evacuation is less effective below the age of 10, and also above the age of 65. Based on the population of the Netherlands, this reduced escape ability would apply to 25% of a random population sample.
Although the walking velocity of a normal population is well defined, as discussed above, there is very little data to support estimates of more rushed evacuation. A previous study by Hockley & Rew [C9] which reviewed the relevant radiation literature, found only two papers that give escape speeds from actual fire incidents. Hymes [C10] suggests that escape can occur at up to 6m/s, while the TNO Green Book [C8] gives an escape velocity of 4m/s. These estimates are maximum escape velocities which obviously apply to a fit, or normal, population. The latter reference also acknowledges the lack of available data in this area of evacuation and stresses the need for conservatism. A further example of a maximum escape velocity is given by CSIRO [C11], which states that rescue workers have been estimated to travel at up to 2.6m/s. This refers to tunnel fires specifically, where longer distances may be involved, possibly including more obstacles or difficult terrain, which may counteract the fact that the value applies to trained personnel only.

The variations that occur between the few ‘emergency escape’ speed estimates that are available highlights the uncertainty, and further emphasises the need for conservative estimates. To this end, the escape velocities used in the HSE POOLFIRE6 model, by Rew & Hulbert [C12], which are 2.5m/s for normal or average populations and 1m/s for vulnerable populations, appear to be the most appropriate.

Note that another important issue that must be considered in any detailed assessment is the effect of any exposure to radiation that occurs before or during the process of evacuation. A whole range of radiation-related factors can influence evacuation speed, such as ignition of clothing, pain, behaviour of others, etc.

C.4 Response times

Most of the references given above for ‘traditional evacuation’ consider the delay between an incident occurring and a person actually starting to evacuate, as well as the escape speeds. Heskestad and Meland [C13] present a detailed framework for assessing this time, which includes allowances for perception of the incident, recognition of the need to escape and reaction time. They give recommended minimum times for each stage and suggest further negative time factors which are added in particular circumstances, for example if the person or population has “bad mobility”. As for escape speeds, discussed in the previous sections, all of these sources refer to evacuation from buildings to avoid contact with a fire (or other incident). The response times of interest here are for people that are exposed to radiation from a fire and so perception of the incident can be taken as being instantaneous. Recognition of the need for escape will depend on the level of thermal dose that is involved. It is assumed here that in fire incidents that produce dose levels which approach the dangerous dose criterion, either sufficient pain will be experienced, or the size and proximity of the fire will be large enough, such that recognition of the need to escape will also be almost immediate, taking only a few seconds. Similarly to escape speeds, the actual reaction time for people exposed to radiation (who will see, and probably feel, the effects immediately) will be significantly quicker than the times given in ‘traditional evacuation’ analysis.

There is little data available concerning the response time between exposure to a fire incident occurring and the start of evacuation. Both Hymes [C10] and TNO [C8] suggest a 5s delay, which applies to normal populations. It seems reasonable to assume that this time will be approximately doubled for an elderly population. As for escape speeds, it may be longer, or even infinite, for young children unless they are assisted by adults.
C.5 Disabled populations

In considering children and the elderly as vulnerable populations, no consideration of the presence of disabled people has been made. Taylor & Donegan [C14] state that up to 14% of adults have some form of disability that will limit their ability to escape. For simplicity, Kose [C15], and other authors, assume that ‘disabled’ persons will be unable to escape once exposed to radiation. However, in general, most of the population classed as disabled are elderly (Taylor & Donegan give a value of around 40%) so the simplified assumption here is that the escape characteristics of the disabled population are the same as those of the elderly population, and so are not considered further.

REFERENCES – APPENDIX C


C8 TNO (1992) “A Model for the Determination of Possible Damage”, CPR 16E.


APPENDIX D:

SMOKE INHALATION

As Settle [D1] concisely describes it, "the respiratory system of the extensively burned patient is subject to a wide variety of insults". Assessments of incident data by a wide range of authors indicate that the presence of inhalation injuries can significantly reduce the probability of survival of a burn victim. Rue et al [D2] report work by Merrell [D3] and Zawacki [D4] who identified that, in addition to the size and type of burn injury and the age of the victim, the presence of inhalation injuries was significant in predicting death. Both proposed probit analyses which include allowances for the presence of inhalation injury in estimating the probability of fatality. Rue et al also report estimates by other authors of the importance of inhalation injury, as follow.

- Thompson et al [D5] applied strict criteria for determining whether inhalation injury occurs to a sample of 1018 thermally injured patients, and found that those with inhalation injury had a 56% mortality, compared with just 4% for those without.

- Shirani and colleagues [D6] demonstrated that inhalation injury can increase the mortality rate by 20%, and if both pneumonia and inhalation injury occur the risk of death from a burn injury can increase by as much as 60% (which is more consistent with Thompson et al's results).

Hall & Harwood [D7] discuss the relative risk of death caused by smoke inhalation and burns. They acknowledge the large degree of uncertainty in identifying exact causes, since burns and smoke inhalation often occur simultaneously and either can be fatal. They quote a previous study by Berl & Halpin [D8] which estimates that 3/4 of all fire deaths are caused by smoke inhalation. This is supported to some extent by Forjuoh [D9] who states that fire deaths are mostly caused by smoke inhalation. However, the uncertainty in predicting the relative importance of burn or inhalation injury as cause of death is highlighted by Rue et al who are much more conservative in stating that 1 in 3 patients may have associated inhalation injury.

Barillo & Goode [D10] present a study of incident data, in the US, in which the majority of deaths are attributed to both burns and smoke inhalation. Of the deaths where the exact cause can be distinguished, smoke inhalation is far more prominent (178 out of 720 deaths were solely due to smoke inhalation, while only 71 out of 720 were solely attributed to burns.)

Hall & Harwood also state that the available data in the US gives a "fairly clear indication of a 50% reduction (1979-1990) in deaths from burns", while the reduction in deaths due to smoke inhalation is much lower. They suggest that this may, however, be attributable to a US tendency to have much less compartmentation than in other countries such as the UK. Although they do report that deaths from inhalation injury were found to reduce in their study, Rue et al also conclude that the improvement in treatment of inhalation injury is far less significant than the improvement in burn treatment.

The situation of interest in this study is the impact that industrial fires may have on the general public who will be off-site, typically at some distance from the fire source. Previous assessments by Hockley & Rew [D11] and others have not considered smoke inhalation to be significant in this case since affected populations are unlikely to be trapped in an area where smoke inhalation will be a significant factor.
However, when assessing mortality charts and other fatality criteria, it is important to be aware that they may be derived from a range of situations and may include cases where smoke inhalation has increased the rate of mortality. It is possible that the increase in mortality caused by smoke inhalation is proportionately higher in elderly people than for an average person or population.

REFERENCES – APPENDIX D


