Temporary refuges on offshore installations: Modelling the time taken for heat impairment of workers

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Offshore installations must have a temporary refuge (TR) for use by workers in the event of a major fire or explosion incident. The importance of an effective TR was highlighted by the 1988 Piper Alpha disaster in which 187 workers died. Duty holders must establish suitable TR performance standards to protect workers. HSE Research Report RR1167 describes a model to estimate the time taken for workers in a TR to become impaired due to ingress of smoke or flammable and toxic gases. Another important consideration is effective protection for workers from heat stress. This is to prevent harm to workers and ensure that they can make rational decisions on management of the incident, including evacuation from the platform.

This report describes the development of a model to estimate the time taken for workers in a TR to become impaired due to heat stress in the event of an incident. The model is based on reviews of: heat transfer models; methods for relating heat exposure (thermal load) to heat stress in people; and TR standards and construction methods. The report will be of interest to specialist modellers in industry in the determination of TR performance. The model uses a simple one-dimensional heat transfer calculation to determine the bulk temperature change in the TR, and an existing model for heat stress. This approach is an extensive simplification of a complex three-dimensional scenario. The main benefits of this simple model are that it is straightforward to implement. Therefore, it can be used to give an indication of the effectiveness of changes to a TR design such as extra insulation or reducing the air change rate, as well as to assess the effect of uncertain modelling data.

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Temporary refuges on offshore installations: Modelling the time taken for heat impairment of workers

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KEY MESSAGES

Temporary refuges (TRs) are required on all offshore installations and must have a defined performance standard during a major incident. Protecting people from heat stress is one factor that needs to be considered as the occupants of the TR must remain unimpaired during an incident so that they are able to escape or avoid becoming a fatality.

The aim of this report was to develop an approach for determining the time taken for occupants of a TR to become impaired due to heat stress.

A one-dimensional heat transfer calculation has been used to determine the bulk temperature change in the TR. It requires a complex three-dimensional problem to be extensively simplified, using a number of assumptions. The main benefit of one-dimensional analysis is that it is straightforward to implement and can be run quickly. Therefore, it can be used to give an indication of the impact of changes, such as the effect of adding extra insulation, humidity, reducing the air change rate etc. or to assess the effect of uncertain inputs.

Several approaches are available for relating thermal loads to impairment times. These range from simple correlations used in fire survival analyses to more complicated occupational health models. A version of the latter is the heat stress model defined in ISO 7933. A sensitivity analysis was carried out on the ISO 7933 model and it was found that the input parameters that had the greatest effect on heat stress are the ambient temperature and humidity

It has been shown that the ISO 7933 heat stress model can be coupled to the one-dimensional heat transfer model so that parameters, such as the ambient temperature and humidity, can be computed and input to the heat stress model for the estimation of impairment times in a TR.

EXECUTIVE SUMMARY

Objective

The Cullen Report into the Piper Alpha disaster recommended that a temporary refuge (TR) should be provided on all offshore installations. The TR is required to have a defined performance standard related to its survivability when exposed to a major incident that includes, but is not limited to, the effects of heat stress on the occupants. Current guidance on risk assessment for TRs focuses on the demonstration of TR integrity. This can be interpreted as demonstrating that the occupants of the TR will remain unimpaired for sufficient duration as to allow corrective action and/or evacuation to be planned in the event of an incident.

The objective of this report was to define an approach for determining impairment times due to heat stress, based on reviews of:

- Relevant standards and TR construction methods
- Heat transfer models that are applicable to a simplified TR heat transfer calculation
- Methods for relating thermal loads to impairment times

Main findings

The definition of a TR depends on the installation. They may be stand-alone units, or may form all, or part, of the accommodation module. TR construction standards and material properties have been reviewed to enable an assessment of the heat transfer through typical TR construction elements. A one-dimensional heat transfer calculation has been used to determine the bulk temperature change in the TR. It requires a complex three-dimensional problem to be extensively simplified, using a number of assumptions. One-dimensional methods are applicable where there is uniform heating of panels, such as when the hot fire plume is relatively large compared to the TR, or when a well-mixed interior exchanges heat with the exterior. The accuracy of the approach will diminish when there is localised heating of sections of panels, or when the internal geometry of the TR is particularly complex, such as in multi-room accommodation modules where the assumption of uniform mixing cannot be applied. The main benefit of one-dimensional analysis is that it is straightforward to implement and can be run quickly. Therefore, it can be used to give an indication of the impact of changes, such as the effect of adding extra insulation, humidity, reducing the air change rate etc. or to assess the effect of uncertain inputs.

Predictions of heat transfer could be improved with the use of a more complex two-dimensional or three-dimensional model. However, such methods would also be based on further assumptions and simplifications. Predictions could also be improved by comparing the model to physical test data (validation - if data are available), which would give a more complete understanding of the impact of the one-dimensional assumption. However, given the variation in TR geometry among installations, validation against specific test cases would be of limited use if the geometry of concern is very different from the test cases.

Models for relating ambient temperature to impairment times have also been reviewed. These range from simple correlations developed for predicting survival times in fires, to more complex models aimed at predicting heat stress in occupational health settings. The Predicted Heat Strain (PHS) model set out in the ISO 7933 standard was used to relate ambient temperature to impairment time.

The ISO 7933 model is relatively complex and requires values for a number of inputs to estimated. A global sensitivity analysis was carried out on the model, to help identify the most important input parameters and help to set appropriate values for use in a TR impairment analysis. The sensitivity analysis was done using a freely available tool box which includes a number of different methods. A screening test or elementary effects test was firstly carried out to identify important parameters, followed by a variance based analysis to determine the effects of the most important parameters on model output. Ambient temperature and humidity were found to have the most influence on model predictions.

There is a significant difference between impairment times predicted by the simple correlations and those predicted by the ISO 7933 model. This is due to the different drivers for development of the models, where the simple correlations were intended to predict survival times in fires and the ISO 7933 model is designed for occupational health settings. The latter was considered more relevant to the analysis of the impairment of occupants of a TR due to the emphasis on decision making in the event of an incident. Validation of the physiological aspects of the model is reliant on that done by the ISO 7933 model developers; further validation of this part would involve the generation of new test data relevant to TR analyses.

CONTENTS

1 INTRODUCTION

1.1 TEMPORARY REFUGE INTEGRITY

The Cullen Report into the Piper Alpha disaster (Cullen, 1990) recommended that a temporary refuge (TR) should be provided on all offshore installations. TRs are a means of shelter in the event of a major incident such as an explosion, fire or gas leak. The guide to The Offshore Installations (Offshore Safety Directive) (Safety Case etc) Regulations 2015 (HSE, 2015) highlights the requirement that arrangements must be made "for the protection of persons on the installation from hazards, including explosion, fire, heat, smoke, toxic gas or fumes in particular during any period while they may need to remain on the installation following an incident." Provision must be made for "facilities within temporary refuge for the monitoring and control of the incident and for organising evacuation." The criteria for TR design are therefore to not only provide an environment in which the occupants can survive, but to allow rational decisions to be made in terms of managing an incident and, potentially, evacuation from the platform (Tam *et al*., 1996). Consideration of these requirements forms the first stage in setting performance standards and impairment criteria for the TR (HSE, 1994).

Initially, Temporary Refuge Impairment Frequency (TRIF) was established as a surrogate for societal risk offshore, where the focus was on the frequency that impairment would occur. Recently, the emphasis has changed and integrity demonstration is now driven by consequence analysis, i.e. the TR must be shown to work for a specific duration. HSE Offshore Information Sheet 3/2006 states "Previously, the first edition guidance to SCR92 set a quantitative criterion for Temporary Refuge Impairment Frequency (TRIF) and this implied the need for QRA. This has now been better aligned with HSE thinking on risk tolerability and the more focused criterion of Temporary Refuge Integrity (TRI) has been established."

Temporary Refuge Integrity is "a determination of the survivability of the TR in terms of its ability to protect the occupants for a specific time period in such a way that they will remain unimpaired until such a time that they determine a need to evacuate the installation or recover following a hazardous event." (HSE Offshore Information Sheet 3/2006). The term "impairment" can therefore be viewed as a degradation of the atmosphere in the TR such that personnel are unable to carry out safety related functions. The length of time the TR must remain unimpaired is dependent on the installation and this is recognised in the regulations.

1.2 APPLICABLE REGULATIONS

The regulations covering TR integrity were revised in 2015 and are currently:

- The Health and Safety at Work Act 1974 – general duties of employers to their employees
- The Offshore Installations (Offshore Safety Directive) (Safety Case etc) Regulations 2015 - covering oil and gas operations in external waters subject to certain transitional arrangements
- The Offshore Installations (Safety Case) Regulations 2005 - covering oil and gas operations in internal waters
- Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) Regulations 1995

The requirement for a temporary refuge is explicitly stated in the Offshore Installations (Safety Case) Regulations 2005, Schedules 2 and 3 and The Offshore Installations (Offshore Safety Directive) (Safety Case etc) Regulations 2015, Schedules 6 and 7:

"A description of the measures taken or to be taken or the arrangements made or to be made for the protection of persons on the installation from hazards of explosion, fire, heat, smoke, toxic gas or fumes during any period while they may need to remain on the installation following an incident which is beyond immediate control and for enabling such persons to be evacuated from the installation where necessary, including provision for –
(a) temporary refuge;…"

The Prevention of Fire, Explosion and Emergency Response Regulations 1995 (PFEER) contain a number of individual regulations relevant to the provision, assessment, management and maintenance of TRs (HSE, 2016):

- Regulation 4 requires a dutyholder to take appropriate measures to protect persons on the installation from fire and explosion
- Regulation 5 requires a dutyholder to assess major accident hazards arising from fire and explosion and events which may require evacuation, escape and rescue, and identify appropriate arrangements for dealing with them
- Regulation 13 requires a dutyholder to take appropriate measures to mitigate the effects of fire and explosion. It also requires these measures to remain effective in an emergency
- Regulation 14 requires the dutyholder to make provision for personnel on the installation to assemble safely while the emergency is assessed and control action taken
- Regulation 19 requires that plant is maintained in an efficient state, in efficient working order and in good repair

1.3 IMPAIRMENT SOURCES

The dominant sources of heat impairment arise from fires caused by leaks of flammable substances and these are extensively documented in risk assessment guides such as Spouge (1999) and currently HSE (2010). Leaks and fires are broadly classified by Spouge (1999) as "hydrocarbon events" arising from the following sources:

- Blowouts – defined as an uncontrolled release of fluid from a well
- Riser/pipeline leaks – leaks in the sections of pipelines leading from the seabed to the installation
- Process leaks – any leak occurring in the production flow not covered in the above categories

Leaks arising outside the production flow are referred to as "non-process" leaks; these typically involve fuels or lubricating oils. Ignition of a leak may result in various fire scenarios such as pool or jet fires and these may either directly impinge on the TR, or produce a hot gas plume which subsequently envelopes the TR. Fires may also arise in electrical apparatus or other machinery such as gas turbines. The risk assessment process will usually identify a range of credible scenarios to be modelled, to give estimates of heat fluxes onto the walls of the TR.

1.4 SCOPE OF REPORT

Previous work by Coldrick (2013) considered TR impairment by smoke or gas ingress. It is an example of one part of the chain of the modelling needed to demonstrate TR integrity. The assumption is made that other parts of the modelling process, such as modelling of leaks, dispersion, combustion and smoke or gas transport have already been carried out so that some estimate of a smoke or gas concentration at the exterior TR has been made. The model set out by Coldrick (2013) determines the infiltration rate of smoke or gas, the interior concentration build-up and the effects on the occupants. The model set out in this report follows a similar format and forms an example of another part of the modelling chain: assessing the effect of heat build-up on the TR occupants. Again, the assumption is made that the necessary modelling has been done to estimate the heat flux at the TR walls for the required fire scenarios. In addition, the current modelling approach allows for the possibility that the occupants of the TR may themselves contribute to the heat impairment, in the absence of an external heat source. However, impairment due to fires internal to the TR is not included.

1.5 REPORT LAYOUT

The remainder of the report is structured as follows:

- Section 2 of this report reviews relevant standards and TR construction methods
- Section 3 reviews generalised heat transfer models that are applicable to a simplified TR heat transfer calculation
- Section 4 reviews methods for relating thermal loads to impairment times
- Section 5 describes a model to determine the evolution of temperature with time in a TR, based on the review stages
- Section 6 describes the application of a systematic sensitivity analysis to determine the relative importance of the various input factors to the model
- Section 7 describes application of the modelling approach to two example cases

2 TEMPORARY REFUGE CONSTRUCTION

2.1 DEFINITION OF THE TEMPORARY REFUGE

The temporary refuge may be a stand-alone unit, or it may form all, or part, of the accommodation module. If the TR is designated as part of the accommodation module, then it may be quite large, possibly extending over a number of floors. TRs are usually constructed from steel, commonly from prefabricated panels consisting of an outer skin which is filled with an insulating material such as glass or ceramic fibre, depending on the level of fire resistance required. The TR may also be bounded by parts of the primary structure. The TR should be defined and described in the safety case, bearing in mind that the relevant boundaries and operational extent may change throughout the life of the unit (HSE, HID Inspection Guide Offshore - Inspection of Temporary Refuge Integrity (TRI)).

2.2 STANDARDS

There are a number of standards covering the specification of TRs and these follow the format of the regulations in that they are “goal setting” rather than prescriptive:

- BS EN ISO 19901-3:2010 Petroleum and natural gas industries — Specific requirements for offshore structures Part 3: Topsides structure:
  “The main load-bearing primary structure, which is one of the SCE [Safety-Critical Elements] and is fundamental to the support of the temporary refuge, the life boats and other components essential to the safety of the personnel shall be designed to retain sufficient integrity during accidental situations and to maintain sufficient integrity to provide protection to personnel for a duration sufficient to effect their evacuation…”

- BS EN ISO 13702:2015 Petroleum and natural gas industries — Control and mitigation of fires and explosions on offshore production installations — Requirements and guidelines:
  “In developing the layout of the installation, consideration shall be given to maximizing, as far as reasonable, the separation by distance of the temporary refuge (TR), accommodation and evacuation, escape and rescue (EER) facilities from areas containing equipment handling hydrocarbons.”
  “Either separation by distance or the use of barriers (floors and walls) can prevent the escalation of fire or explosion to another area. The provision of such barriers influences ventilation, access/escape routes, ESD/EDP system design, explosion resistance, and firewater demands. The interdependency of safety systems shall be considered during the design of the installation. Any penetration of a barrier provided to prevent escalation of a fire or explosion shall not jeopardize the integrity of the barrier.”
  “Passive fire protection (PFP) shall be provided in accordance with the requirements of the FES which shall consider application of PFP to:
  protect personnel in the TR(s) until safe evacuation can take place”

- BS EN ISO 15138:2007 Petroleum and natural gas industries - Offshore production installations - Heating, ventilation and air-conditioning:
  “The following additional requirements apply to specific areas in the installation to ensure their safety goals are met: – maintain the survivability in the TR by preventing ingress of potentially flammable gas-air mixtures through appropriate siting, isolation, pressurization, provision of multiple air-intake locations, sufficient number of air changes, gas detection and emergency power supply;”

> *"The requirement for space cooling depends on the rate of temperature rise due to electrical/electronic equipment heat. Emergency-powered cooling shall be provided only when maximum operating-space temperatures or the permissible "heat stress" is exceeded within the required emergency operating period."*

Although the specification of the TR may differ from one installation to the next, the general principle is that there are enclosed spaces bounded by "divisions". Divisions form the protective barrier between the enclosed space and envisaged fire hazards. Performance specifications apply to these elements whether they are walls, floors, windows or ceilings and whether or not they form part of the primary structure. A commonly used construction method is modular components such as pre-fabricated panels which are sold as having a particular level of fire resistance. Resistance can also be achieved through the application of passive fire protection (PFP) materials. Divisions are given a fire-rating according to their resistance. These ratings have their origins in the International Convention for the Safety of Life at Sea (SOLAS) and have been adopted and extended for offshore use. The main groupings are A, B and C class divisions which are as follows:

"A" class divisions

- Divisions formed by bulkheads and decks:
  - Constructed of steel or equivalent.
  - Suitably supported.
  - Constructed to prevent ingress of smoke/flame to the end of the one-hour standard fire test.
  - Insulated with additional materials, so that if either face is exposed, the average temperature on the other side will not rise more than 140°C above original temperature. In addition, the temperature will not rise in any one area ("hotspots", joins etc.) more than 180°C above the original temperature within time limits:

Class	**Minutes**
A60	60
A30	30
A15	15
A0	0

"B" class divisions

- Divisions formed by bulkhead, decks, ceiling or linings:
  - Constructed to be capable of prevented ingress of flame to the end of 30 mins of standard fire test.
  - Have an insulation value so that if either face is exposed, the average temperature of the unexposed side will not rise more than 140°C above the original temperature. In addition the temperature at any one point ("hotspots", joins) will not rise more than 225°C above the original temperature, within the following time limits:

Class	**Minutes**
B15	15
B0	0

"C" class divisions

- Divisions constructed of approved non-combustible materials:
  - They do not meet requirements relative to the passage of smoke and flame and are therefore not suitable for TR construction.

Class A, B and C divisions are rated against cellulosic fires (timber, paper or cotton) and the temperature limits involved are intended to protect against the spread of fire from one compartment to another. On a typical process plant, the hazard is more likely to arise from hydrocarbons spilled or released under pressure. A hydrocarbon fire will also exhibit much more rapid growth than a cellulosic fire (Section 2.3). These factors led to the introduction of a hydrocarbon “H” rating e.g. DNV-OS-D301 (DNV, 2008), which is derived from furnace tests of samples where the test furnace temperature curve corresponds approximately to a hydrocarbon time-temperature curve.

“H” Class Divisions

- Divisions formed by decks and bulkheads that comply with the following:
  - Constructed of steel or equivalent.
  - Suitably supported.
  - Constructed to prevent ingress of smoke and flame after 120 minutes exposure to a hydrocarbon fire test.
  - Structures intended to be load bearing should be tested under representative conditions of loading and restraint.
  - Have insulation so that if either face is exposed, the average temperature of the unexposed side will not rise more than 140°C above the original temperature. In addition the temperature at any one point (“hotspots”, joins) will not rise more than 180°C above the original temperature, within the following time limits:

Class	**Minutes**
H120	120
H60	60
H0	0

In addition to the A, B, C and H ratings, a jet fire “J” rating has also evolved, based on the idea that hydrocarbon or cellulosic fires do not exhibit the same levels of heat flux and erosion as a full scale jet fire. The jet fire testing originally undertaken was not intended to be used to confer a jet fire rating, (Roberts and Willoughby, 2004) and there is uncertainty in the applicability of the rating. At the time of writing, the jet fire resistance test is under review. Few existing TRs are jet fire rated (being A rated only). However, most passive fire protection coatings used on installations have passed jet fire tests. BS EN ISO 13702:2015 follows a slightly different convention in defining fire resistance, but notes that its nomenclature does not follow any existing conventions with respect to the rating or classification of fire barriers. BS EN ISO 13702:2015 suggests typical integrity requirements of load bearing structures such as the TR and accommodation blocks in the event of a fire, where the fire types are classified as cellulosic, hydrocarbon pool or jet.

2.3 FIRE RESISTANCE TESTING

Fire resistance is usually determined using standardised furnace tests where one face of the sample is exposed to a predetermined heating curve and the temperature of the unexposed face is monitored. The form of the curve is specified in standards, where ISO 834-1:1999 is the international standard and BS EN 1363-1:2012 and BS 476-20:1987 are the European and British equivalents. The heating curve specified in these standards is intended to represent a typical cellulosic fire, generally applicable to building use. As mentioned previously, hydrocarbon fires that may occur in offshore installations are characterised by a steeper growth rate and higher overall temperatures. A heating curve more representative of a typical hydrocarbon fire is given in Appendix D of BS 476-20:1987 and a slightly different one in BS EN 1363-2:1999. The standard curves are shown in Figure 1, alongside an indicative curve for a jet fire test.

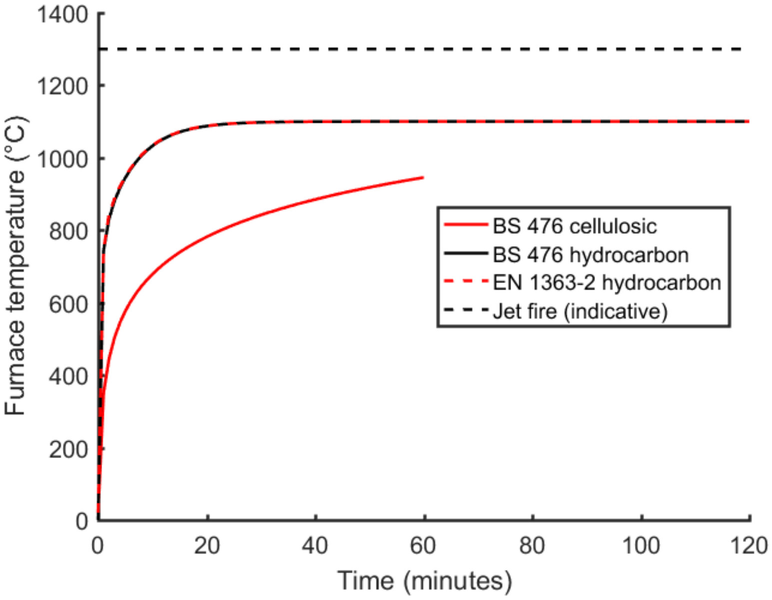

Figure 1 Comparison of standard fire test curves (the hydrocarbon curves are overlaid). The jet fire curve is indicative and taken from Roberts and Willoughby (2004)

BS 476-20:1987 defines failure criteria as either an average unexposed face temperature rise exceeding 140 °C, a spot temperature rise exceeding 180 °C, or mechanical failure. It is likely that the resistance criteria in the classifications described in Section 2.2 have their origins in these standards. BS ISO 22899-1:2007 differs from the other fire resistance standard as it specifies parameters for the jet fire, rather than the temperature curve. This standard also states that the critical temperature rise be defined, in advance of the test. This should be according to the protection criteria for the equipment, assembly or structure being protected, making reference to the 140 °C specified in the other standards. Heat loads from jet fires are not well defined. According to Cowley and Johnson (1992), a peak flux value of 300 kW/m^2 was derived from early experiments and became widely used as a "single value" to characterise jet flames but the value used in hazard assessment should be case specific. DNV (2001) specifies that critical items must survive a jet fire of 250 kW/m^2 for 30 minutes. Where the living quarters are exposed to a heat load below 100 kW/m^2 a passive fire protection rating of A60 is considered sufficient for the surface facing the source of the heat load. However, for heat loads above 100 kW/m^2, H-rated protection shall be used.

2.4 OBTAINING MATERIAL PROPERTIES

Compliance with a standard or a particular test specification does not usually allow material thermal properties to be inferred. A product may be listed as having met a particular test specification e.g. A60, but in some cases, the complete range of thermal properties needed for modelling are not given. Different products meeting the same fire resistance specification can have different thermal properties (Cowley and Johnson, 1992), or the thermal properties may not have been determined. Where complete manufacturer data are not available, it is necessary to rely on generic test data for the component parts of fire divisions, such as steel sheet and mineral wool. Various sources including ASHRAE (2001) provide tabulated thermal property data for a range of common building and insulating materials and this can be used to approximate composite materials. An illustrative example of the heat transfer solution for a composite panel is given in Section 5.2.

3 MODELLING HEAT TRANSFER

3.1 INTRODUCTION

This Section reviews some commonly used approaches to modelling heat transfer. It focuses on basic one-dimensional methods that can be readily implemented in a spreadsheet and can be used to represent a wide range of geometries and fire scenarios. More involved two- or three-dimensional methods can be implemented using the same principles, but it is possible that the additional information yielded by these approaches is outweighed by the uncertainties in many of the input parameters. If in-depth modelling of a particular scenario is of interest, it may well be appropriate, and justifiable, to resort to a more complex modelling approach. In these cases, it may be more efficient to use a conjugate heat transfer model available in many computational fluid dynamics (CFD) packages. One-dimensional approaches can be used to model insulated sandwich panels and laminates. They have also been applied to PFP which uses intumescent coatings that respond to being heated. Modelling intumescent coatings is reviewed by Coldrick *et al.* (2010) but not included in the scope of this report.

3.2 HEAT TRANSFER IN SOLIDS

The transfer of heat energy in a solid is described by the heat-conduction equation. In one spatial dimension, the time-varying temperature distribution is given by:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) = \rho C\frac{\partial T}{\partial t} \tag{1}$$

where *x* is the dimension, *k* is the thermal conductivity, *T* is the temperature, *ρ* is the density, *C* is the heat capacity and *t* is time. Referring to Figure 2, for a small element of length *δx*, the left-hand side of Equation 1 represents the change in heat flux into and out of the element over its length and the right-hand side represents the accumulation of heat in the mass of the element.

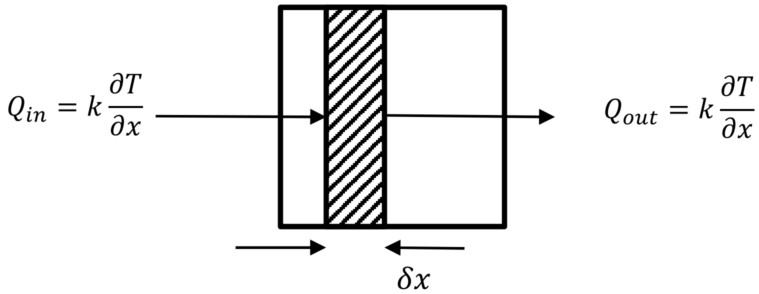

Figure 2 One dimensional heat conduction in a solid

The heat flux, *Q*, (per unit area) is proportional to the temperature gradient multiplied by the thermal conductivity, *k*, of the material. In a steady state, the right hand side of Equation 1 becomes zero and the therefore the heat flux through the element is given by:

$$Q = kA\frac{\partial T}{\partial x} \tag{2}$$

where *A* is the area. Equation 2 may be integrated to give:

$$Q = kA\frac{\Delta T}{\Delta x} \tag{3}$$

for finite values of *T* and *x*. For an element of known thickness, the thermal conductivity, *k*, and length, *Δx*, can be combined to give a heat transfer coefficient, *h*, given by:

$$h = \frac{k}{\Delta x} \tag{4}$$

and therefore Equation 3 becomes:

$$Q = hA\Delta T \tag{5}$$

Thermal properties of construction materials are often given in terms of *h* when the thickness is specified.

3.3 HEAT TRANSFER IN GASES

The modes of heat transfer from a solid surface into a gas are convection and radiation. Both of these modes occur simultaneously and in varying proportions depending on a number of factors. Heat transfer from a solid wall into a gas is shown schematically in Figure 3.

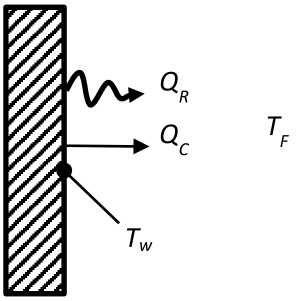

Figure 3 Heat transfer into a fluid at temperature T_F from a wall at temperature T_W

Convective heat transfer from the wall at T_W to a fluid at T_F is governed by a number of factors such as fluid properties, the angle of the wall and the nature of the flow near the wall, i.e. whether the convection is "natural" or "forced". For this reason, the convective heat transfer, Q_C, into the fluid is often approximated by an expression similar to Equation 5 above:

$$Q_C = h_C A(T_W - T_F) \tag{6}$$

where the convective heat transfer coefficient, h_C, is an all-encompassing number that is often empirically derived. As with convective heat transfer, radiative heat transfer is highly complex and is often reduced to a simple expression:

$$Q_R = \epsilon\sigma A(T_W^4 - T_F^4) \tag{7}$$

where σ is the Stefan-Boltzmann constant and ϵ is the emissivity. The Stefan-Boltzmann constant is the constant of proportionality between the heat transmitted and the fourth power of temperature for a perfect thermal radiator, or blackbody. The emissivity is the relationship between the actual emitting surface and the ideal blackbody. Equations 6 and 7, rather than being accurate descriptors, aim to quantify orders-of-magnitude effects of the different heat transfer mechanisms.

3.4 SOLVING THE HEAT TRANSFER EQUATIONS

When a more complete analysis of the heat transfer into a space is required, Equation 2 may be solved using a suitable technique, e.g. finite differences, or analytical solutions to determine the spatial and temporal heat distribution. In other cases, a simplified approach can be justified and this may involve the solution of Equations 5 to 7 to yield temperatures or heat fluxes. A commonly used approach, particularly in thermal analysis of building structures, is the "thermal resistance" concept (McQuiston and Parker, 2000). In this method, the thermal resistance, *R*, is given by:

$$R = \frac{\Delta x}{k} \tag{8}$$

Thermal resistance is analogous to electrical resistance. Therefore, the heat transfer through building components such as multi-layer walls can be determined by summing the resistances of each part:

$$R_{Total} = R_1 + R_2 \cdots \tag{9}$$

This approach makes use of tabulated material properties and is useful for steady state heat transfer analyses. Material properties are sometimes specified in terms of a U-value, which is the reciprocal of the thermal resistance value.

In some scenarios involving conductive and convective heat transfer, the resistance to heat transfer of the solid is much lower than the resistance to convective heat transfer. In these cases, the solid is considered to be "thermally thin"; an example being convective heat transfer from a steel sheet into air. The temperature gradient across the steel sheet would be relatively low and the sheet could be considered to be at a uniform temperature. Whether or not a solid can be considered to be thermally thin is guided by the Biot number, *Bi*, given by:

$$Bi = \frac{h_C \Delta x}{k} = \frac{R_{Cond}}{R_{Conv}} \tag{10}$$

Where R_{Cond} and R_{Conv} are the conductive and convective resistances. Small values of *Bi* indicate that the convective resistance dominates and the solid may be considered thermally thin. Large values of *Bi* indicate that conductive resistance dominates and that the heat transfer within the solid needs to be modelled. The lumped heat capacity method (Holman, 2002) is one approach that can be used to model heat transfer across thermally thin solids. Figure 4 shows heat transfer from a fluid at T_{F1}, through a thin wall, to a fluid at T_{F2}.

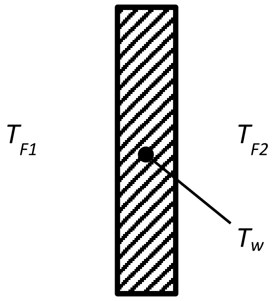

Figure 4 Lumped heat capacity method for a thermally "thin" wall

The convective heat fluxes into and out of the thin wall are balanced by the temperature change in the wall with time (heat capacity), assuming a uniform temperature in the wall.

$$\rho C \frac{dT_W}{dt} = h_C(T_{F1} - T_W) - h_C(T_W - T_{F2}) \tag{11}$$

The lumped heat capacity method may also be used to model heat transfer in solids, by constructing a system of nodes having masses, heat capacities and resistances. Such a system has the appearance of a finite difference method.

4 MODELLING HEAT STRESS

4.1 INTRODUCTION

Exposure to elevated temperatures may result in burns or heat stress. Burns are associated with being a pathological effect (HSE, 2010) arising from short term exposure to high temperatures. Heat stress is termed a physiological effect from relatively long term exposure to lower temperatures, often when combined with physical exertion. Heat stress is an important factor in occupational settings but can be distinguished from thermal comfort which relates to satisfaction with the environment, rather than something that may cause harm. The following Section provides an overview of methods available for relating an elevated ambient temperature to a time associated with some level of physical impairment. The need to determine tolerance times for heat stress arises in a number of areas, particularly in fire engineering and in occupational health. However, the drivers in each area are different and therefore the tolerance criteria will be different. In fire engineering, the emphasis is on survival, whereas in occupational health, the focus is on avoiding ill-health through heat stress in the workplace. As with the effects of toxicity, the nature of heat stress means that there is a large amount of variability and uncertainty and therefore predictions of effects can be at best approximations.

Various methods are available for assessing the direct effects of fire in, for example, an escape situation. These include thermal radiation “doses” or probit functions (HSE, 2010). In a TR impairment analysis, the main concern is of the indirect exposure to the heat from a fire. In such situations, the exposure may be at a relatively low level of thermal radiation, but where the ambient air temperature is the most important factor (HSE, 2010).

4.2 TOLERANCE TIMES

Crane (1978) reports results of tests for time to collapse for “healthy adult males” wearing “business dress” derived from a literature search and these are shown in Table 1.

Table 1 Thermal collapse data from Crane (1978)

Air temperature (°C)	*Time to collapse (min)*
50	300
105	25
120	15
200	2
82	49
93	32
115	20
140	5

ASHRAE (2001) report similar values, which may have been derived from the same tests, noting that exposure to 85 °C is possible in a sauna, because the air is dry and cooling can occur through sweat evaporation. In humid environments, exposure to 50 °C can be intolerable if the dew-point temperature is greater than 25 °C. Purser (2002) also reports data derived from various sources giving “tolerance time” for exposures in dry and humid air, see Table 2. It is noted that above 120 °C, exposure is limited by skin pain whereas below this value, exposure is limited by hyperthermia. HSE (2010) review a number of methods of determining tolerance times and suggest that, for temperatures below 70 °C, the situation inside a compartment will be uncomfortable but not fatal.

Table 2 Tolerance times from Purser (2002)

Air Temperature (°C)	*Tolerance time (min)*
110	25
180	3
205	4
126	7
32 (100% humidity)	32
140	5

The values in Tables 1 and 2 would need to be considered as indicative, because the test conditions are not known, there are few data points and the criterion of "collapse" is a severe level of impairment beyond a reduced ability to make decisions in an emergency.

Crane (1978) fitted a function to the test data, to derive an expression for the time to collapse (t_c) in minutes, as a function of temperature (T), in °C:

$$t_c = \frac{4.1 \times 10^8}{T^{3.61}} \tag{12}$$

The above formula would then give time to collapse for exposures to constant temperatures. Crane viewed the constant of proportionality of 4.1×10^8 as being related to the total amount of heat energy the body could absorb before collapse. Therefore, an assessment could be made for exposure to time varying temperature by carrying out a time integration of the temperature, so that t_c is reached when:

$$\int_0^t T^{3.61} dt = 4.1 \times 10^8 \tag{13}$$

Various other curve fits have been proposed:

Spieth et al. (1982):

$$t_c = \frac{5.33 \times 10^8}{T^{3.66}} \tag{14}$$

Purser (2002):

$$t_c = \frac{5 \times 10^7}{T^{3.4}} \tag{15}$$

Purser (1989):

$$t_c = e^{5.1849 - 0.0273T} \tag{16}$$

Curve fits such as these are limited by the range of data used to fit the curve and should only be applied within that range. However, the original data sources and test conditions are not readily available and factors such as humidity and clothing, which are known to have an effect, are not specified.

4.3 PHYSICALLY BASED MODELS

Physically based models for predicting heat stress have been developed for numerous applications. Among these are occupational situations, for example foundry workers performing strenuous tasks in high ambient temperatures, where there are clear health implications of exposure to heat. These models aim to be able to investigate extremes of human tolerance without running into ethical problems (Haslam, 1989). A physically based model, in contrast with the simple curve fits described previously, gives the potential to make predictions for conditions outside the range of data used to fit the model. However, there may be constraints in the way the model makes use of the test data and therefore it is still necessary to observe the range of validity specified by the model developers. Physically based models are based on an energy balance for a person, which describes how the body exchanges energy with the environment leading to changes in the core temperature. In practice, determining these energy exchanges is complicated by the many factors that need to be taken into account, coupled with inherent variability. Therefore, these models contain many constants derived from fits to test data which are subject to uncertainty, and also require a large number of inputs, each of which is also subject to uncertainty.

Haslam (1989) presents an overview of the energy balance model, using the following expression:

$$S = M - W - C - K - R - E \quad (\text{W/m}^2) \tag{17}$$

where S is the storage, M is the metabolic rate, W is the rate of mechanical work and C, K, R and E are the heat transfer by convection, conduction, radiation and evaporation, respectively.

The rates are given as a function of body area (W/m^2) where the body area is estimated. If the metabolic rate is not balanced by heat loss through the various mechanisms e.g. sweating, then there is net energy storage and core temperature will rise. Significant deviations from the "normal" core temperature may lead to a decrease in performance, illness or collapse. The model in Equation 17 treats the body as having a single compartment which loses or gains heat. Other more complex models divide the body into several compartments, exchanging energy with each other and the environment. ASHRAE (2001) present a model having two compartments; a skin compartment and a core compartment. More complex models have been developed having more compartments.

Haslam (1989) reviewed several models including a version of the ISO standard 7933, which is a model that calculates a required sweat rate to maintain a core temperature within a range. A later version of this standard "Analytical Determination and Interpretation of Thermal stress using Calculation of the Required Sweat Rate" was produced in 1989 (ISO 7933:1989) and widely criticised (Malchaire *et al.*, 2001). It was also reviewed for use in industry (Bethea and Parsons, 2002) and found, in common with other models, to:

- Lack relevance to industrial situations, for example the type of protective clothing typically worn
- Be of questionably validity in terms of its predictions
- Have limited usability in the industrial context – the methods presented were seen as impractical, leading to poor usability and therefore potentially erroneous predictions

The model in ISO 7933 was revised and updated, being renamed the Predicted Heat Strain (PHS) model to reflect a number of fundamental changes (Malchaire *et al.*, 2001) and reissued (BS EN ISO 7933:2004). Subsequent references in this report are to this updated 2004 version. One of the advantages of physically based models is that they can take into account factors which are thought to be important in estimating heat stress, among which the following are relevant to TR impairment analysis:

Ambient humidity – the ambient humidity has a significant effect on impairment time. The higher the moisture content of the air in the TR, the lower the cooling effect of sweat evaporation. However, the length of time and rate of sweating are limited and cooling is also limited because sweat is absorbed by clothing. ASHRAE (2001) suggest a typical level of cooling is 350 W/m^2, which equates to a sweat rate of about 1 L/h.

Clothing – the type and thickness of clothing greatly affect the heat transfer to and from the body. Clothing offers protection against convected and radiated heat, but also reduces the cooling capacity. The clothing worn in a temporary refuge may vary from an immersion suit, to fire retardant overalls, or lighter casual clothing.

Physical activity – the level of physical activity in the TR affects the metabolic rate, as well as the surface area available for heat transfer. Standing can increase the metabolic rate by a small amount, but also increase the area for heat transfer by about 10% (BS EN ISO 7933:2004).

Physiological state on arrival – if individuals have run, climbed stairs or been performing strenuous tasks prior to arrival in the TR, this can increase core temperature and therefore heat stress when in the TR.

Availability of fluid – if fluids can be replenished, cooling by sweating can continue to a greater degree than if fluids are not available.

The relative importance of these effects in the context of the ISO 7933 model, will be examined in Section 6.

4.3.1 Impairment criteria for the ISO 7933 model

The increased complexity of physically based models means that impairment can be more specifically defined than it can by the simple temperature based correlations, which only consider a limiting time or heat dose. ISO 7933 defines impairment based on two "stresses" which are the body's response to heat load and two "strains" which result from those stresses. The stresses are two factors that contribute to cooling which are a maximum value of skin wettedness and maximum sweat rate. The strains are a level of dehydration and a rectal (core) temperature rise. The values that these take depend on whether the subject is heat acclimatised, whether fluids are available and the section of population the subject is drawn from, i.e. the mean (50%) or susceptible (95%). These impairment criteria are summarised in Tables 3 and 4. It is worth noting that ISO 7933 makes the recommendation that special precautionary measures need to be taken if the work environment results in impairment times less than 30 minutes.

Table 3 ISO 7933 impairment criteria - stresses

Stress	*Non-acclimatised*	*Acclimatised*
Max skin wettedness (-)	0.85	1
Sweat rate (g/h)	650-1000	+25%

Table 4 ISO 7933 impairment criteria - strains

Strain	*50% population*	*95% population*
Water loss with drink (% body mass)	7.5	5
Water loss without drink (% body mass)	3	3
Core temperature (°C)	38	38

4.4 COMBINING HEAT STRESS AND SMOKE IMPAIRMENT

In a TR impairment analysis, the effects of infiltration by smoke or gas may need to be considered in addition to those from heat. One approach that has been used to combine several different effects is the "Fractional Effective Dose" model (Hartzell and Emmons, 1988), which is commonly applied to assess the effect of simultaneous exposure to different toxic substances. In this model, the dose of each substance is calculated as a fraction of the limiting dose for that substance. Incapacitation is assumed to occur when the sum of these fractional doses, or FED, reaches a value of one, i.e:

$$FED = \sum_{i=1}^{n} \frac{D_i}{Dlim_i}, FED \leq 1 \tag{18}$$

where there are n substances, each having a dose, D_i, and a limiting dose, $Dlim_i$. The FED model has been widely used (Purser, 1989; Purser, 2002), possibly because it is a convenient mathematical treatment of a complex physiological problem. HSE (2010) warns that the approach is only usually considered valid if the harmful agents considered bring about the same end point, attack the same organ or have a similar mode of action.

The FED model has been used to combine the effects of radiative and convective heat stress (Purser, 2002) by considering radiative and convective “doses”, where the convective dose is calculated from Equation 15, for example. The FED model has also been applied to the prediction of the combined effects of smoke, gas and heat stress by including the heat dose in the FED calculation; (OGP, 2010a; Speitel, 1996) however, the validity of this approach is unclear. In view of this, an alternative approach is to treat the effects of toxicity and heat separately, following from Purser (2002) “A reasonable model can be used in which asphyxia, sensory irritancy, and the effects of heat and visual obscuration can be treated separately. Interactions may be more important at the behavioural level.”

5 MODEL DEVELOPMENT

5.1 HEAT TRANSFER

This Section presents a model of heat transfer into a space, based on the principles set out in Section 3. A simplified one-dimensional model of heat flow into a space is shown in Figure 5. The model consists of a single room having some of its wall area covered with insulated panels and some constructed from a single steel sheet. The room is ventilated to some degree as a result of leaks (Coldrick, 2013) and this ventilation may add, or remove, heat. There are a number of occupants who add heat to the room. In the model, the insulated panels represent fire resistant panels and are of a sandwich construction. The outer surface of the sandwich panel is exposed to a heat flux. Heat can be transmitted from the inner surface of the sandwich panel into the room by radiation and convection, and heat is transmitted out of the room through contact with the other walls. The time evolution of temperature at a number of nodes can be calculated by applying an overall heat balance to the model, based on the equations set out in Section 3. It is assumed that there is no separate decorative interior cladding.

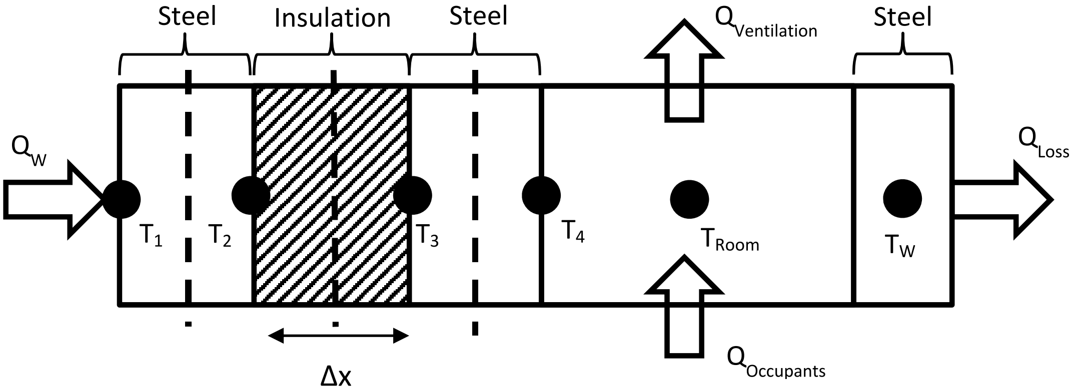

Figure 5 One-dimensional heat transfer into a space bounded by an insulated wall and a non-insulated “thermally thin” wall. The space is heated by occupants and has a ventilation air flow. Temperature calculation points are marked by black nodes

For internal nodes in the sandwich panel, a finite difference approximation of Equation 1 can be solved, where the temperature at each node is given by:

$$\frac{\rho C \Delta x \Delta T_i}{\Delta t} = k\frac{T_{i-1} - T_i}{\Delta x} - k\frac{T_i - T_{i+1}}{\Delta x} \tag{19}$$

For the internal nodes two and three in Figure 5, the control volumes (denoted by the dashed lines) are composed of two different materials and therefore the heat capacity term is the average of those of the two materials. For the boundary node one, one of the conduction terms on the right hand side is replaced by the applied heat flux Q_W, which is the sum of that from the fire source, Q_{Fire} and that which is re-radiated from the heated panel:

$$Q_W = Q_{Fire} - \epsilon\sigma A\left(T_1^4 - T_{air}^4\right) \tag{20}$$

It is necessary to include this re-radiated portion to prevent unphysical temperature rise in the exposed panel. However, this does entail further assumptions on the emissivity and air temperature.

Boundary node four, which interfaces with the room, exchanges heat with the room by convection and radiation:

$$Q_C = h_C A(T_4 - T_{Room}) \tag{21}$$

$$Q_R = \epsilon\sigma A(T_4^4 - T_{Room}^4) \tag{22}$$

The other, uninsulated walls are assumed to be thermally thin and the temperature is given by:

$$\rho C \frac{\Delta T_W}{\Delta t} = h_C(T_{Room} - T_{Wall}) - h_C(T_{Wall} - T_{Air}) \tag{23}$$

Finally, the room temperature rise is the net result of the various heat addition and subtraction:

$$\rho C \frac{\Delta T_{Room}}{\Delta t} = Q_C + Q_R + Q_{Occupants} - \ h_C A(T_{Room} - T_{Wall}) - Q_{Ventilation} \tag{24}$$

Where the heat loss, or gain from ventilation is given by:

$$Q_{Ventilation} = \rho C \dot{V}(T_{Room} - T_{Air}) \tag{25}$$

Where $\dot{V}$ is the leakage ventilation flow rate into the room.
The system of Equations 19 to 25 can be solved numerically, starting from initial conditions at time *t = 0* and marching forward with a timestep, *Δt*, where the solution at a new time level can be computed using only the values at the old time level. This explicit method has the advantage of simplicity, but will become numerically unstable if the timestep is too large. The timestep must be selected so that:

$$0 < \frac{k\Delta t}{\rho C \Delta x^2} < 0.5 \tag{26}$$

A spreadsheet may be used to solve the system of equations, but for the current work, they were solved using MATLAB 2016b.

5.1.1 Verification

Verification is checking that the computer implementation of a model is consistent with its mathematical basis. Verification may include comparing the model against an analytical solution, or simple tests such as conservation of energy. Two tests were carried out on the heat transfer model. The first is shown in Figure 6. In this test, the insulation in the left hand wall was replaced with steel, such that the wall being modelled with the finite difference method was composed of three elements having a total thickness of 3 mm. The right hand wall was also set at 3 mm and adiabatic boundary conditions were specified on the outer faces of the wall. The heat addition from occupants was set to zero and the ventilation flow also set to zero. The interior room was set in the initial conditions at an elevated temperature relative to the walls. Starting from these initial conditions, the system reaches an equilibrium temperature given by Equation 27 and shown in Figure 7. When the system is reduced to a single wall, cooling from an elevated temperature to ambient, the time dependent solution follows the form of $T = e^{-kt}$, where *k* is a constant and *t* is the time. This is shown in Figure 8.

$$T_{End} = \frac{\rho_{Air} C_{Air} A_{Wall} \Delta x_{Room} T_{Room} + \rho_{Steel} C_{Steel} A_{Wall} \Delta x_{Wall} T_{Wall}}{\rho_{Air} C_{Air} A_{Wall} \Delta x_{Room} + \rho_{Steel} C_{Steel} A_{Wall} \Delta x_{Wall}} \tag{27}$$

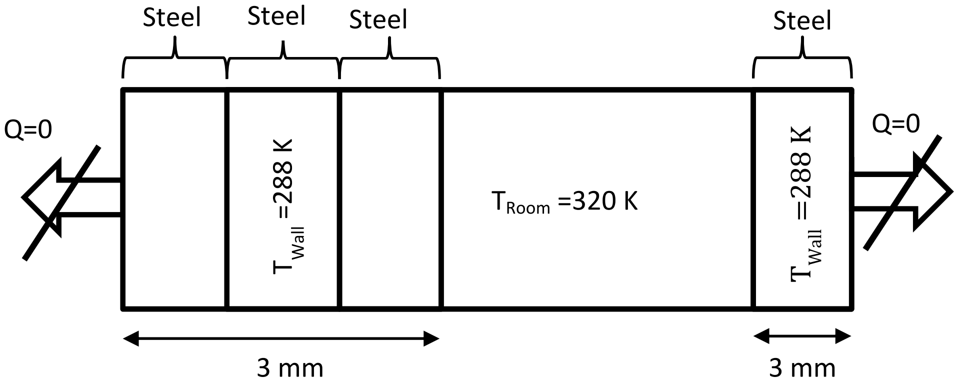

Figure 6 Verification case for a room at elevated temperature having steel walls at a lower temperature

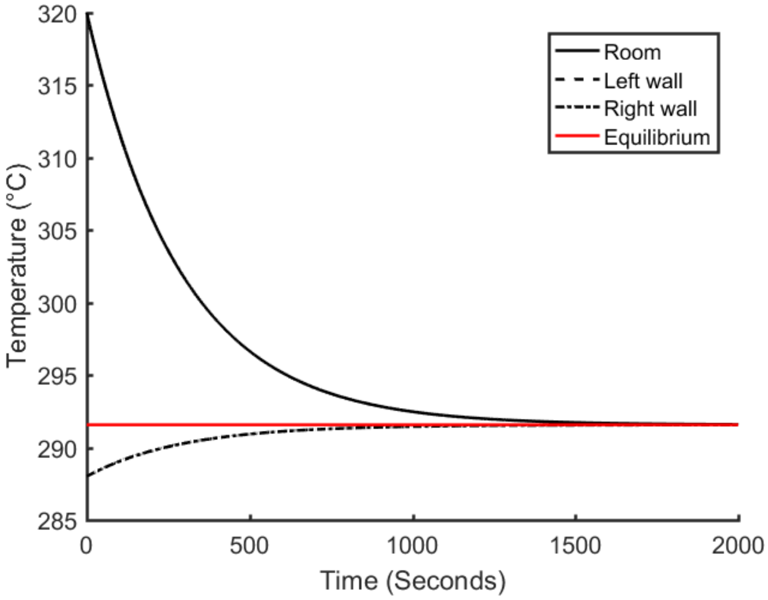

Figure 7 Plot of temperature versus time for the case in Figure 7 above. Profiles for the left and right walls are overlaid

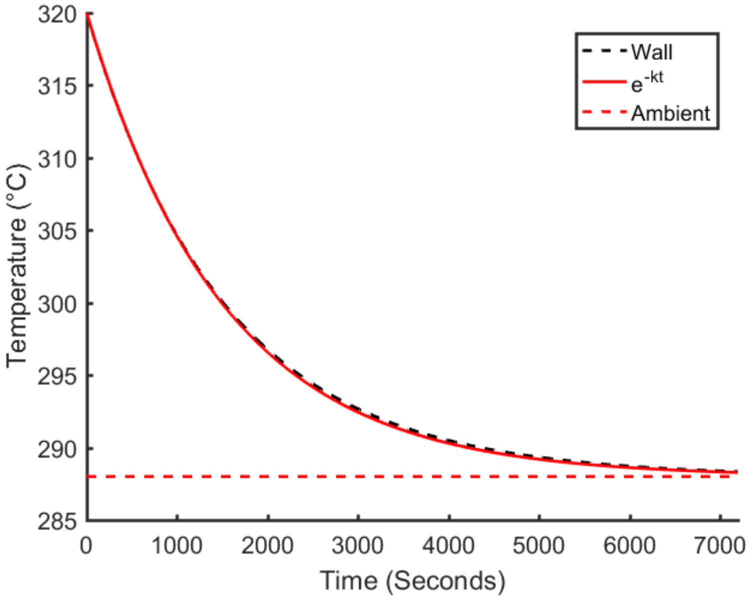

Figure 8 Cooling of a single wall from an elevated temperature to ambient temperature

The second test was to check overall conservation of energy within the model. To do this, the same geometry was used as in the previous example, but a 30 kW heat flux was supplied to the left hand face and 4 kW into the room, as shown in Figure 9. A nominal ventilation air flow rate was applied to the room and the model was run for 7200 seconds. The supplied energy and the energy lost through ventilation and from the right wall were integrated over this period. Figure 10 shows that the sum of the energy accumulated in the model is equal to the supplied energy minus the losses through ventilation and from the right wall.

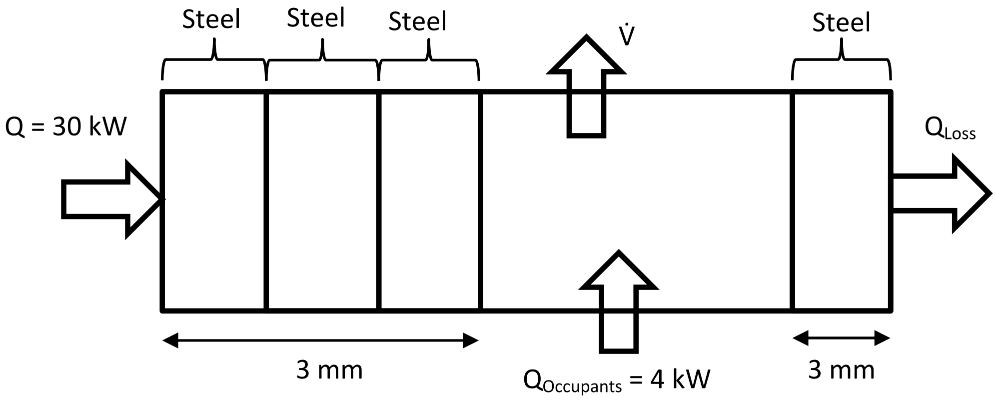

Figure 9 Verification test case for conservation of energy for a constant heat flux applied to the left wall and a heat addition from occupants applied to the room

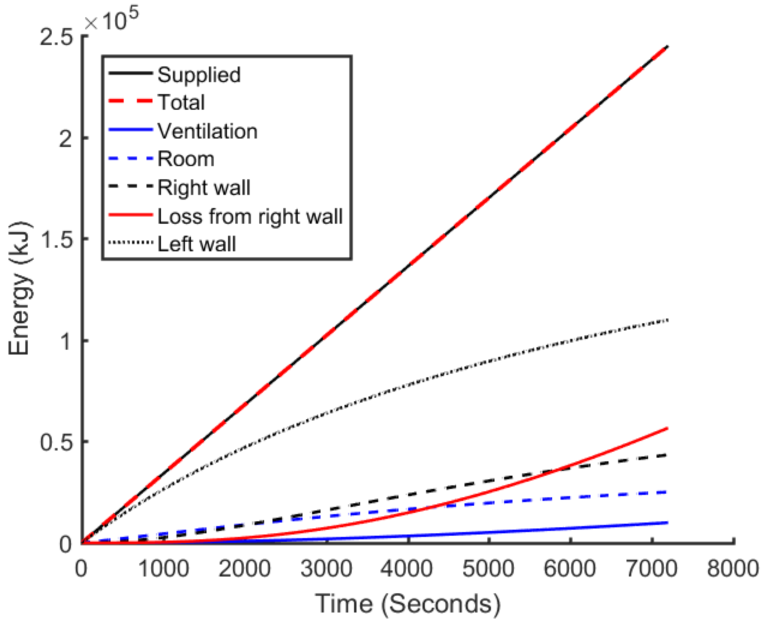

Figure 10 Overall energy balance for the case shown in Figure 10. The energy supplied to the system balances with the total gains in the individual components

5.2 SOLUTION FOR A COMPOSITE PANEL

Prefabricated composite insulating panels are commercially available and will undergo testing to determine compliance with the requirements of standards. As set out in Section 2.4, compliance with standards does not necessarily allow the thermal properties needed for modelling to be inferred and these will need to be obtained either from the manufacturer or by estimation based on the composition of the insulating panels. Properties for an example three-layer panel shown in Figure 11 are given in Table 5, where the overall values for the panel have been determined from the R-values of the individual components.

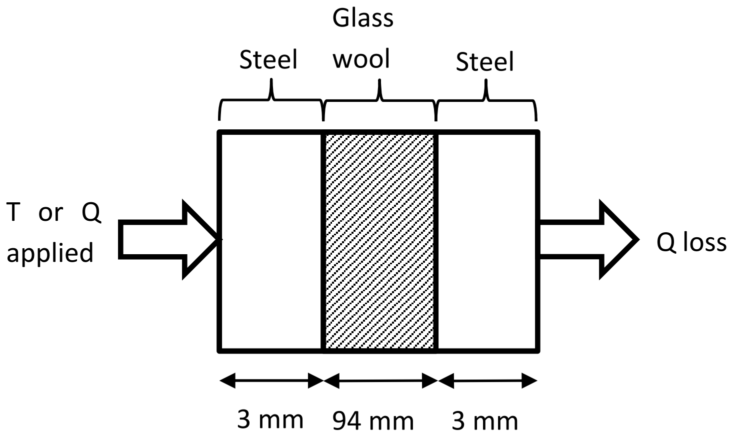

Figure 11 Example insulated composite panel subject to heating on one face

Table 5 Properties for a composite panel

Property	***Glass wool***	***Steel***	***Panel***
Thermal conductivity (W/(mK))	0.038[1]	45.3[1]	0.04[2]
Specific heat (J/(kgK))	657[1]	500[1]	-
Density (kg/m^3)	52[1]	7830[1]	-
Thickness (m)	0.094	0.003	0.1
Resistance (K/W)	2.47	6.62E-05	2.47[2]
Area (m^2)	1	1	1
U (W/(m^{2}K))	0.4	15100	0.4[2]

[1]obtained from ASHRAE (2001)
[2]obtained from R-value (Equation 8)

The properties for the panel given in Table 5 are comparable with data for typical commercial products (SCI, 1992) and the thermal specification in BS 3958-5:1986 for relatively low ambient temperature conditions. However, the thermal conductivity of glass or mineral wool products is not constant, but increases with temperature. This is because these materials are porous and the assumption of heat transfer solely by conduction does not accurately describe the full mechanism of heat transfer within the voids in these materials. The variation in conductivity with temperature of insulating materials is illustrated in BS 3958-5:1986, where the data have been plotted in Figure 12. Detailed modelling of the complete heat transfer processes in insulating materials has not been attempted in the current work. Instead, single representative values of thermal conductivity have been used to cover the temperature range, based on available data. Choosing a value at the upper end of the temperature range will result in conservative heat transfer predictions. Variable thermal conductivity could be accommodated in the heat transfer modelling, but would depend on the availability of data.

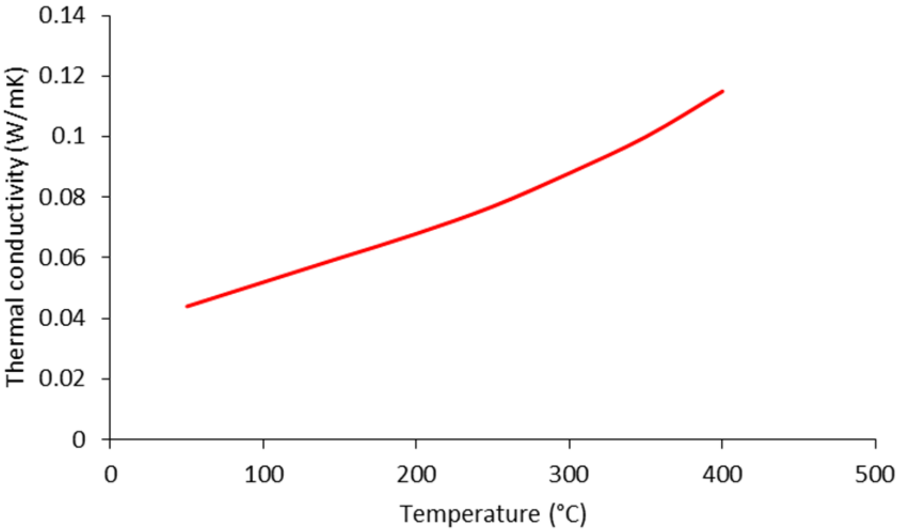

Figure 12 Variation in thermal conductivity with temperature of bonded man-made mineral fibre slabs (data taken from BS 3958-5:1986)

Based on Table 5, a lower estimate of thermal conductivity for an A60 panel is 0.04 W/(mK). Data for higher temperatures are not readily available, but a value of 0.2 W/(mK) has been used. To model the panel exposed to the standard furnace tests, the exposed “furnace” end sheet of the panel was assumed to follow the fire growth curves for the cellulosic curve and the hydrocarbon curve given in

BS 476-20:1987. The “unexposed” end was assigned a surface emissivity of 0.96 and a heat transfer coefficient of 4.5 W/(m^{2}K) to represent exposure to ambient conditions. Assuming that the end face temperature follows the furnace temperature profile will mean that the end face temperature will be slightly overestimated. Results for the cellulosic curve are shown in Figure 13, for the two values of thermal conductivity of the insulating material. In both cases, the unexposed face of the panel does not reach either the 140 °C or 180 °C limiting temperature rise. Results for the hydrocarbon curve are shown in Figure 14 which shows that the unexposed face reaches a temperature rise of 140 °C after approximately 40 minutes for a thermal conductivity of 0.2 W/(mK). For both temperature curves, the lower value of thermal conductivity does not result in a 140 °C temperature rise.

The panel was also modelled with the exposed face subject to a range of heat fluxes between 20 kW/m^2 and 300 kW/m^2. The same boundary conditions used previously were applied to the unexposed face and an emissivity of 0.96 was specified on the exposed face. Figure 15 shows the maximum temperature rise of the exposed and unexposed faces for 60 minute exposure to the different heat fluxes. Assuming a thermal conductivity of 0.04 W/(mK) means that the unexposed face does not reach a temperature of 140 °C in a 60 minute exposure to any of the heat fluxes. For a thermal conductivity of 0.2 W/(mK), a heat flux of 200 kW/m^2 results in the unexposed face reaching 140 °C. The potential for temperature variation of the thermal conductivity of insulating materials therefore needs to be taken into account if exposure to very high temperatures or heat fluxes is possible.

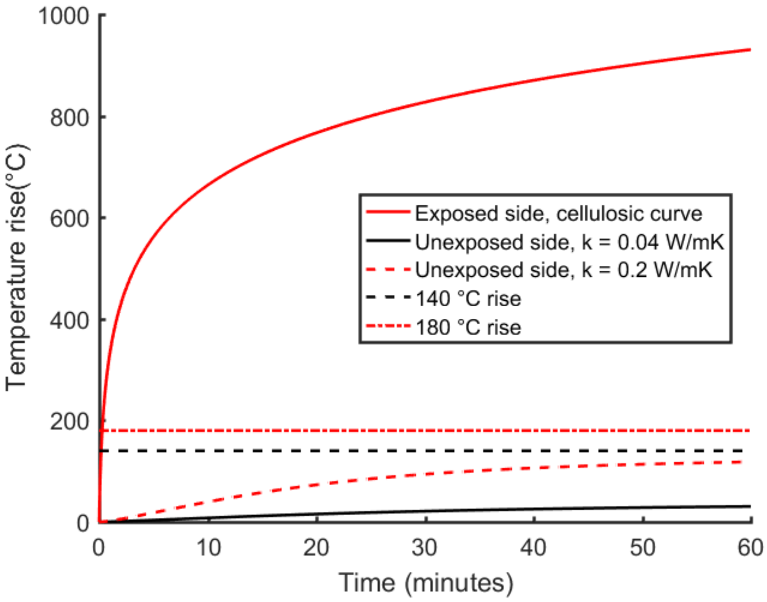

Figure 13 Application of cellulosic fire curve to a composite panel for two values of thermal conductivity of the insulation

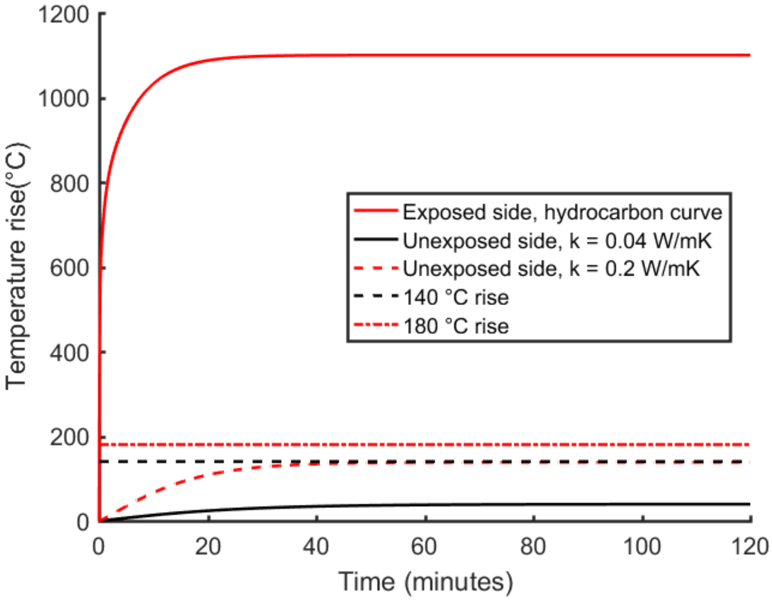

Figure 14 Application of a hydrocarbon fire curve to a composite panel for two values of thermal conductivity of the insulation

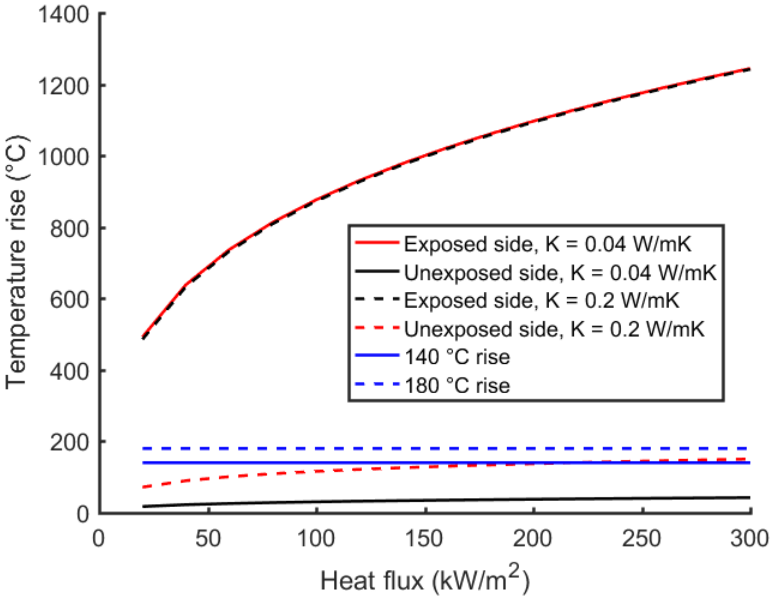

Figure 15 Application of a range of heat fluxes to a composite panel for two values of thermal conductivity of the insulation. The temperatures shown are the maximum values after 60 minute exposures

5.3 INTERFACING WITH HEAT STRESS MODELS

The heat transfer model described in the previous Sections predicts the temperature rise in an enclosed space with ventilation and heat input from a number of occupants. Simple heat stress models, such as those described in Equations 12 to 16, require only the internal temperature as input and they assume the occupants do not interact with the environment in any other way. The heat produced by the occupants must therefore be estimated, based on an assumed activity level within the TR. ASHRAE (2001) provide tabulated heat outputs for people doing various activities, primarily for the purpose of determining air conditioning cooling loads for workplaces. Typical values are 100 W when seated, 130 W for light work and over 400 W for heavy work. It is likely that heat output would increase when in a state of panic, but relevant data are not readily available.

The ISO 7933 heat stress model accounts for occupant interaction with the environment in three ways; through the ambient temperature and humidity level and the amount of heat supplied by the occupants. The ISO 7933 model, as given in the standard, runs for a specified duration in loops of one minute. Each minute, the core temperature and water loss are determined. The limiting time is that which corresponds to either excessive water loss or core temperature rise. The duration over which the model is run is therefore an independent variable and may be shorter than, or exceed the limiting time. The heat transfer model described in the previous Sections was coupled to the heat stress model by solving for the heat transfer within the time loops of the ISO 7933 heat stress model. Each minute, the heat produced by the occupants was updated. The overall framework for running the models is shown in Figure 16.

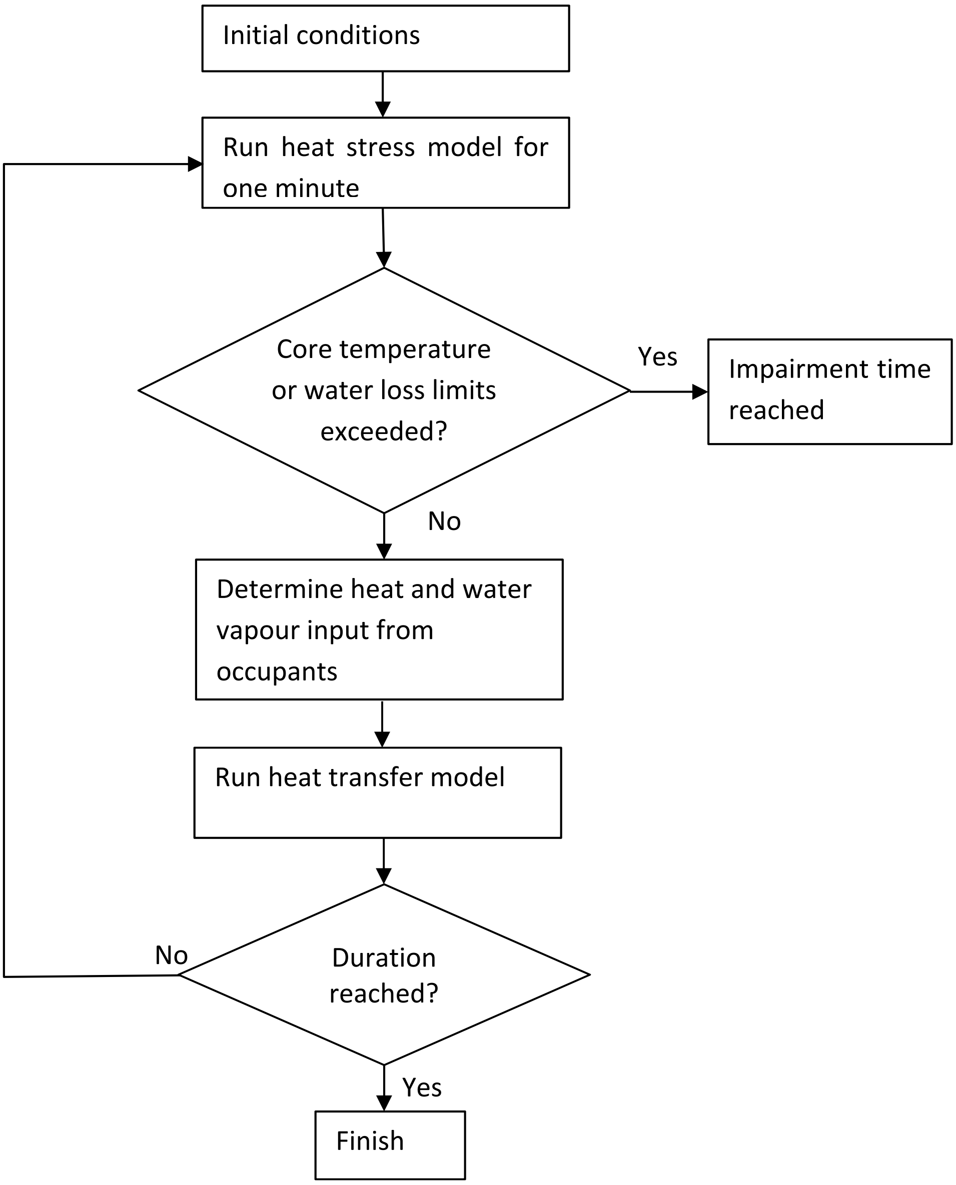

Figure 16 Framework for running the combined heat transfer and heat stress models

Ambient humidity is an input to the ISO 7933 model in the form of a partial pressure of water vapour. However, care is needed using ISO 7933 because the ambient temperature and partial pressure are supplied independently and it is possible to provide incompatible values, i.e. a partial pressure exceeding the saturation value at a given temperature. In the current work, the partial pressure was calculated based on a relative humidity in the TR and a relative humidity of the ventilation flow through the TR, if present. The water vapour partial pressure, $P_{W,}$ is given by:

$$P_W = \phi P_{WSat} \tag{28}$$

Where ϕ is the relative humidity and P_{WSat} is the saturation pressure of water at a given temperature. The mass of water, M_W, in the TR is:

$$M_W = \frac{P_W V W}{R_U T_{Room}} \tag{29}$$

Where V is the TR room volume, W is the molecular mass of water, R_U is the universal gas constant and T_{Room} is the temperature in the TR at a given time. In the case of there being a ventilation flow, the mass of water in the TR may be added to, or reduced, by the ventilation flow. The mass of water in the TR will also be increased by the amount given off by the occupants by respiration and by sweating. However, the exact contribution of these effects is unclear. It seems reasonable to assume that the ambient humidity will increase as a result of the occupants, but may be unrealistic to allow all of the moisture produced to enter the atmosphere in the TR. However, in the absence of further information, this would lead to a conservative result. The effect on model predictions is shown in Section 7.

The range of input parameters to the ISO 7933 model is shown in Table 6. These are taken from the standard which also gives the ranges of validity for a subset of the inputs. Appropriate values for parameters need to be set for those which are not specified by the conditions in the TR. Some guidance on setting appropriate values can be obtained from a sensitivity analysis, which is described in Section 6. Parameters such as body height and weight can be estimated based on typical values, alongside expected values for clothing insulation. The level of activity during mustering in the TR is given by the metabolic rate, which can be estimated from tables in ISO 7933 or ASHRAE (2001). The range of validity of the metabolic rate is given in the standard as having units of Watts. However, it is supplied to the model on a per-unit-area basis (W/m^2) where the area is the DuBois surface area, which is 1.8 m^2 for an average adult (ASHRAE, 2001). ASHRAE (2001) also provide guidance on the effects of heat acclimatisation, suggesting that there can be a degree of heat acclimatisation over a period of days in elevated temperatures, but that this effect diminishes over a two to three week period.

Table 6 Input parameters and validity range for the ISO 7933 model

Input parameter	***Description***	***Range of validity***
Weight (kg)	Body weight	-
Height (m)	Body height	-
Metabolic rate (W)	Level of physical activity	100-450
Posture (-)	Seated, standing or crouching	-
Clothing insulation (-)	Level of clothing insulation	0.1-1
Ambient temperature (°C)	Ambient air temperature	15-50
Radiant temperature (°C)	Radiant temperature	Max. 60 °C above ambient
Ambient humidity (kPa)	Absolute humidity	0-4.5
Air velocity (m/s)	Indoor air velocity	0-3
Walking (-)	Walking speed if moving	-
Acclimatisation (-)	Whether heat acclimatised	-
Drink (-)	Availability of fluid	-
Permeability (-)	Moisture permeability	0.38 (default)
Emissivity (-)	Emissivity of (reflective) clothing	0.97 (default)
Reflective area (-)	Area covered by (reflective) clothing	0.54 (default)

6 HEAT STRESS MODELS: SENSITIVITY AND UNCERTAINTY ANALYSIS

6.1 INTRODUCTION

Sensitivity and uncertainty analyses are used to examine how the output of a model varies in response to changes in the inputs. Sensitivity analysis gives an indication of the relative importance of the various input factors while uncertainty analysis quantifies output variability resulting from variations in inputs. Sensitivity and uncertainty analysis are important aspects of predictive modelling for a number of reasons. They can help to identify which input parameters are important, such that resources can be directed at those parameters and others can be assigned nominal values. The analysis may also involve running a model through its full range of input parameters which can provide useful insight into the characteristics of a model. Errors in the model or its programming may also be identified if the model does not conform to expected characteristics. Sensitivity analysis was used by Coldrick (2013) to identify important parameters in the use of a model for smoke and gas impairment of TRs.

Sensitivity analysis methods can be broadly classified into local and global methods (Campolongo *et al.,* 2011). Local methods often involve defining a “base case” where all the input parameters are given fixed values and varied one-at-a-time from this base case to see what effect this has on the output. Despite being widely used, local methods are not necessarily good practice (Campolongo *et al.,* 2011) and may give misleading results in some circumstances. This is because they do not take into account the possibility that some model inputs may interact with each other and have a larger effect on output than any in isolation. Global sensitivity analysis involves varying all the input parameters simultaneously and computing indices that describe how the variation in output is accounted for by the individual parameters as well as interactions between parameters. The main disadvantage of global methods is that they are resource intensive to carry out because they can involve running a model many times with inputs sampled from a parameter space. In Monte Carlo methods, the inputs are simultaneously sampled at random for each model run and enough samples need to be made to give sufficient coverage of the input parameter space. For complex or slow models, the computational cost can be prohibitive. Effort has been directed at devising more efficient techniques for global sensitivity analysis that make more efficient use of the available model runs.

One way to increase the efficiency of a sensitivity analysis is to use a screening tool to identify important input parameters such that the sensitivity analysis is carried out on a smaller set of input parameters (Saltelli *et al.*, 2004). Tools used for screening analysis may qualitatively rank the model input factors in order of relative importance, rather than providing quantitative information. An example of a screening tool is the Elementary Effects (EE) method or Morris test (Morris, 1991).

In the current work, rather than applying techniques from scratch, use has been made of the “SAFE” global sensitivity analysis toolbox (Pianosi *et al*., 2015). This implements several established methods in Matlab code, which can be used to run the model elements.

It is worth noting that global approaches in which the model inputs are simultaneously varied do not necessarily create combinations of input values that have any physical meaning. Inputs will be defined that are within acceptable ranges, but values for any particular model run may not bear any resemblance to reality.

The model implementation shown in Figure 16 consists of two distinct elements; a heat transfer calculation and a heat stress model consisting of either ISO 7933 or a simpler relationship defined in Equations 12 to 16. The heat transfer and heat stress models are nested, but perform distinct functions. For this reason, the elements were considered separately in the sensitivity analysis. The heat transfer calculation was not included in the sensitivity analysis because it is heavily dependent on the geometry and therefore would not produce meaningful results.

6.2 ELEMENTARY EFFECTS TEST

The elementary effects test was first proposed by Morris (1991) and a refined version is described by Campolongo *et al.* (2011). It is described as a variation on one-at-a-time designs but offers an improvement, for little additional computational expense. The method computes the Elementary Effect (*EE*) for each input parameter, which is defined as the ratio between the variation in model output, *Y*, and the variation in a particular model input parameter, x_i, (Campolongo *et al.,* 2011) for a step change, Δ_i in value of that parameter:

$$EE_i = \frac{Y\left(x_1, \dots, x_i + \Delta_i, \dots, x_p\right) - Y(x)}{\Delta_i} \tag{30}$$

where there are *p* model inputs. The method differs from simple one-at-a-time designs because it involves making the step changes from randomly sampled points in the whole input parameter space, rather than making changes about a single base-case and returning to that base-case each time. The elementary effects are averaged to produce a global measure to describe the effect of each individual input parameter as well as to give an indication of the level of interaction of the parameters. The mean, μ, of *n* elementary effects gives the relative importance of the *i*-th input parameter to the model:

$$\mu_i = \frac{\sum_{j=1}^{n} \left| EE_i^j \right|}{n} \tag{31}$$

where EE_i^j is the elementary effect. The standard deviation, σ, gives a measure of the effects of interactions of each input parameter:

$$\sigma = \frac{\sum_{j=1}^{n} \left(EE_i^j - \mu_i^j \right)^2}{n} \tag{32}$$

A high value of σ for a particular input parameter indicates that it has a relatively high level of interaction with the values that other input parameters are set at. Conversely, a low value of σ indicates that the variability in output obtained from that parameter is largely uninfluenced by the values that the other input parameters are set at. The elementary effects test is implemented in the SAFE toolbox and was applied to the ISO 7933 model with the input parameter ranges shown in Table 7. The input parameters were based on the validity ranges supplied in the standard and given in Table 6; however, some values were altered to be more representative of the conditions in a TR. The range of metabolic rates was set to be between “resting” (70 W/m^2) and “moderate to high activity” (175 W/m^2) which is lower than the limit of 230 W/m^2 representing “very intense activity”. The radiant temperature was set equal to the ambient temperature rather than attempting to estimate possible values and the humidity was calculated from a relative value and the ambient temperature (Equation 28). Validity ranges for body height and weight are not given in the standard so representative values were determined using the population generation tool “PopGen” (McNally *et al*., 2014). The model was set to run for a maximum 12 hour period, with the impairment criteria defined in the standard of a limiting core temperature of 38 °C or maximum water loss of 7.5% of body weight, for an average subject. This means that if neither impairment criteria were met, the model would run for 12 hours.

Table 7 Model input parameters and ranges for the elementary effects test

Input parameter	***Range***
Weight (kg)	60-130
Height (m)	1.6-2
Metabolic rate (W/m^2)	70-175
Posture (-)	Seated, standing, crouching
Clothing insulation (-)	0.1-1
Ambient temperature (°C)	15-50
Radiant temperature (°C)	Equal to ambient
Relative humidity (-)	0.25-1
Air velocity (m/s)	0-3
Walking (-)	Stationary
Acclimatised (-)	Yes/No
Drink (-)	0/1
Permeability (-)	0.38 (default)
Emissivity (-)	0.97 (default)
Reflective area (-)	0.54 (default)

Results for the parameter ranges in Table 7 are shown in Figure 17, where the mean of the elementary effects, μ, has been plotted against the standard deviation, σ and the parameters are listed in order of relative importance. Ambient temperature has the greatest effect on the predicted impairment times, followed by humidity and these parameters also have a high degree of interaction with other model parameters. Body weight, height, posture and level of heat acclimatisation have a relatively small influence on model output, and a relatively low degree of interaction with other parameters. The ambient temperature range given in Table 5 includes values which are unlikely to result in heat impairment. Model runs carried out with low ambient temperatures will result in the model reaching the artificially imposed 12 hour limit. The elementary effects test was therefore repeated with a reduced range of temperatures, with values at the higher end of the original range between 30 °C and 50 °C. Results for the reduced range of temperatures are shown in Figure 18. The results show the same pattern, but the temperature has a slightly reduced influence. This is because fewer model runs lead to the 12 hour time limit being reached.

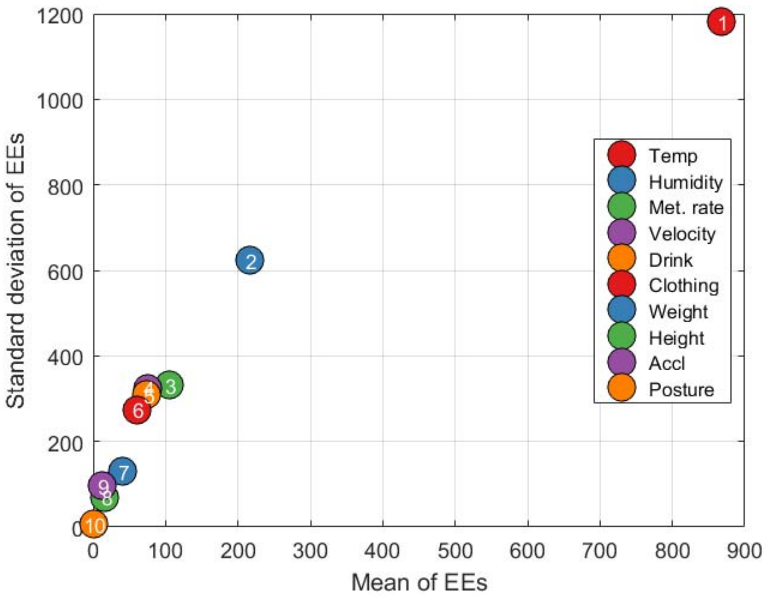

Figure 17 Plot showing the mean and standard deviation of the elementary effects for the model input parameters in Table 5, ranked in order of relative size

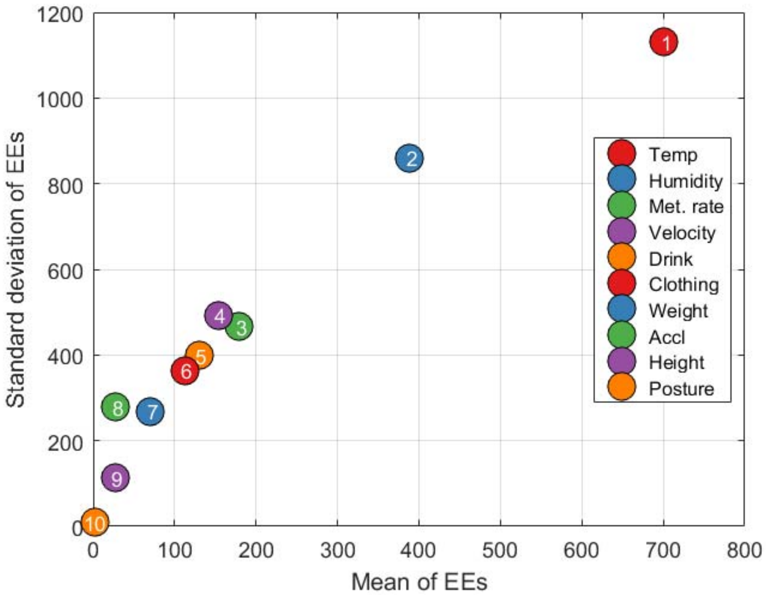

Figure 18 Plot showing the mean and standard deviation of the elementary effects for the model input parameters in Table 5, ranked in order of relative size and for the reduced range of temperatures

6.3 VARIANCE BASED SENSITIVITY ANALYSIS

The elementary effects test described in the previous Section gives an indication of the relative magnitudes of the effects of varying a model's inputs, but it does not allow these effects to be quantified. Variance based sensitivity analysis (VBSA) is a type of global sensitivity analysis which provides a way to quantify these effects, but it requires more computing resource due to the number of model runs that need to be made. The sensitivity analysis method used by Coldrick (2013) was "winding stairs" (Chan *et al.*, 2000) which is a sampling strategy design to make use of relatively few model runs. In this work, a VBSA method implemented in the SAFE toolbox was used, with a reduced set of input parameters informed by the elementary effects test. The metabolic rate, clothing, ambient temperature and relative humidity were varied, with the other parameters given fixed values, as shown in Table 8. The ambient air velocity was found to be relatively important in the elementary effects test, but for the VBSA, was assumed to be zero, given the ambient air in the TR is likely to be stationary. The Drink parameter was not included in the VBSA. Instead, the analysis was run with Drink switched off and repeated with it switched on.

Table 8 Model input parameters and ranges for the VBSA. Parameters that were varied are highlighted in bold

Input parameter	***Value***
Weight (kg)	87
Height (m)	1.77
Metabolic rate (W/m^2)	**70-175**
Posture (-)	Standing
Clothing insulation (-)	**0.1-1**
Ambient temperature (°C)	**30-50**
Radiant temperature (°C)	Equal to ambient
Relative humidity (-)	**0.25-1**
Air velocity (m/s)	0
Walking (-)	Stationary
Acclimatised (-)	No
Drink (-)	**0/1**
Permeability (-)	0.38 (default)
Emissivity (-)	0.97 (default)
Reflective area (-)	0.54 (default)

Results of the VBSA with Drink switched off are shown in Figure 19. The plot shows the relative sensitivity of the model output to variations in the four input parameters. Two sensitivity indices are plotted; the main effect and the total effect, which are analogous to the mean and standard deviation in the elementay effects test. For variation of each input parameter, the main effect shows how much of the variance in model output is attributable to that parameter. However, not all of the variance of the model output is attributable to individual input parameters alone, because there will be some degree of interaction between parameters. The total effect therefore shows how much of the variance in output is accounted for by interactions and will be greater than the main effect. Ambient temperature and humidity have the largest effect and the greatest degree of interaction, followed by metabolic rate. This is because the sweating rate is limited by water loss, which is in turn limited by the availability of water. With the analysis repeated with Drink set to on, the effects of ambient temperature and humidity dominate, but the insulating effect of clothing becomes important (Figure 20).

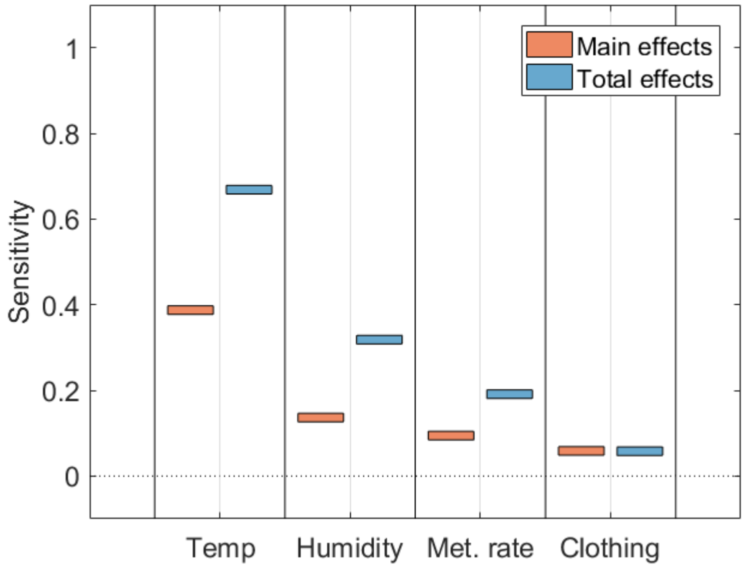

Figure 19 Results of the VBSA with Drink set to off

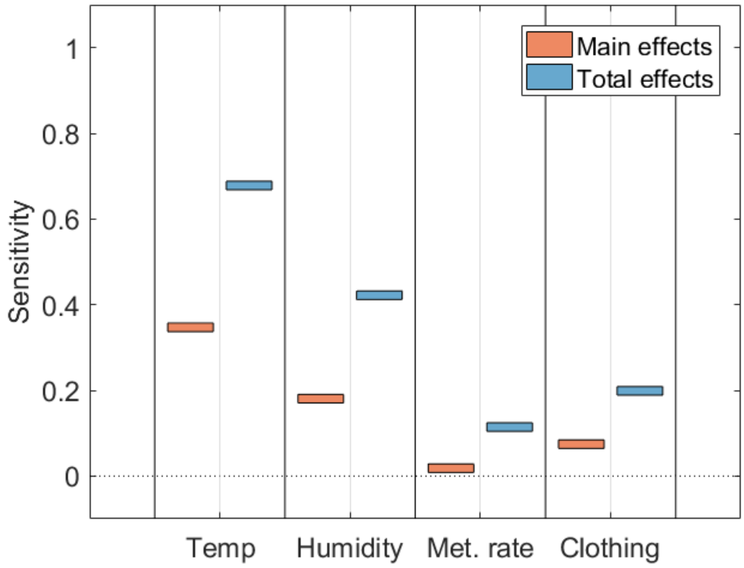

Figure 20 Results of the VBSA with Drink set to on

Using the results of the sensitivity analysis, a set of nominal input values were estimated for running the ISO 7933 model over a range of temperatures and with two values of relative humidity, for comparison with the heat stress models presented in Section 4. The humidity vales used were a lower value of 0.25 and a high value of 0.6. While the humidity has a significant effect on predictions, it is also a highly uncertain quantity. The metabolic rate was set at 100 W/m^2 which represents light activity (BS EN ISO 7933:2004), though the results are less sensitive to the metabolic rate than ambient temperature and humidity. A value of one was assumed for the clothing insulation, corresponding to underclothes and overalls (BS EN ISO 7933:2004). The full set of input values is shown in Table 9. Figure 21 shows the results for the ISO 7933 model when run with the nominal set of inputs, in comparison with those predicted by the simple correlations, for a range of temperatures. A number of individual data points given by Purser (2002) for dry air and humid air are also shown. The range of results in Figure 21 demonstrates the variability in the different approaches and also highlights the effect that ambient humidity can have, particularly in the predictions of the ISO 7933 model.

Table 9 Nominal input values for comparison of impairment times with other models

Input parameter	*Value*
Weight (kg)	87
Height (m)	1.77
Metabolic rate (W/m^2)	100
Posture (-)	Standing
Clothing insulation (-)	1
Ambient temperature (°C)	30-50
Radiant temperature (°C)	Equal to ambient
Relative humidity (-)	0.25, 0.6
Air velocity (m/s)	0
Walking (-)	Stationary
Acclimatised (-)	No
Drink (-)	1
Permeability (-)	0.38 (default)
Emissivity (-)	0.97 (default)
Reflective area (-)	0.54 (default)

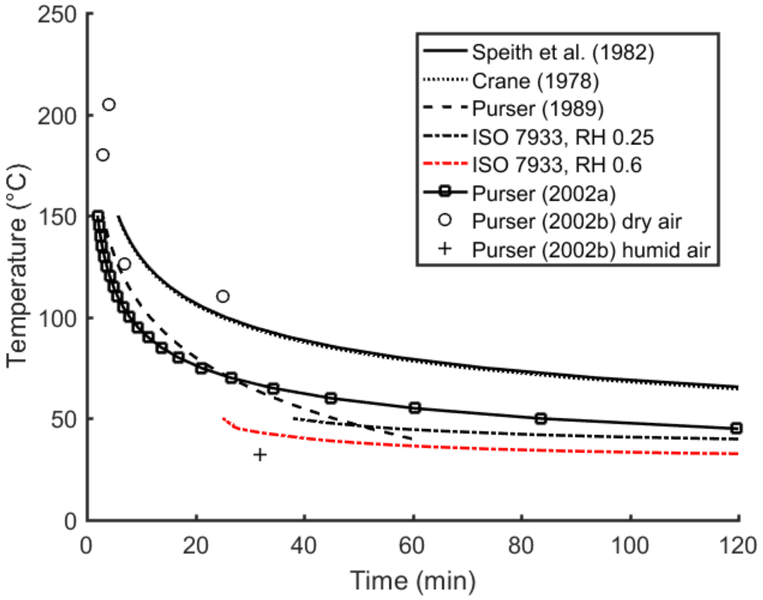

Figure 21 Predicted impairment times by different models for a range of temperatures. Also shown are individual data points from Purser (2002)

6.4 COMMENTS ON HEAT STRESS MODEL RESULTS

Simple models such as those described by Equations 12 to 16, or the temperature limits given in Tables 1 and 2, were intended to provide guidance on survival times for fires. They are therefore applicable to higher temperature ranges than the more complex heat stress models, such as ISO 7933, which have ranges of validity within lower temperature limits. In most circumstances, models developed for occupational health reasons produce shorter impairment times and more conservative results. However, as shown in Figure 21, this is not always the case and there is some overlap in the predictions of the different models. The goal of a TR impairment study is to demonstrate that rational decisions can be made in the event of an emergency and this supports the use of an impairment model predicting heat stress, rather than collapse. A significant benefit of using a physically based heat stress model is that they are based on a larger volume of data than the simpler correlations. Furthermore, despite the shortcomings of such models, the availability of a pre-coded version in the ISO 7933 standard makes it relatively straightforward to use in an impairment analysis.

7 EXAMPLE APPLICATIONS

7.1 TEST CASES

This Section gives example applications of the TR heat impairment model to two hypothetical geometries. In the first example, an external heat source is applied to one face of the TR. In the second, the heat source is from the occupants and equipment in the TR.

7.2 EXAMPLE 1

In this example, the TR is formed from part of another module. For modelling purposes, it is separated from the module by steel divisions and has an A60 division from an external fire source. The properties of the panel have been taken from Table 5, but with the thermal conductivity of the insulating material set as 0.2 W/(mK) (Section 5.2). A fire source of 10 kW/m^2 is applied uniformly over the exposed surface, giving a total heat flux of 500 kW. Input parameters for 100 persons on board (POB) are shown in Table 10, and a schematic of the modelled geometry is shown in Figure 22. The ISO 7933 model was used to determine impairment time in two configurations. In the first, the moisture given off by the occupants was added to the humidity in the TR. In the second, this interaction was removed. Results for the first configuration are shown in Figure 23. The internal temperature rise in the TR is fairly small, but after approximately half an hour, the air becomes saturated. Impairment is predicted to occur in just under two hours. In the second configuration, with no effect on humidity by the occupants, impairment is not predicted to occur in a 12 hour period. Predictions for the first configuration will be conservative as it is unlikely that all the moisture generated by the occupants will enter and remain in the atmosphere in the TR.

Table 10 Input parameters for example 1

Parameter	***Value***
POB	100
Weight (kg)	87
Height (m)	1.77
Metabolic rate (W/m^2)	100
Clothing insulation (-)	1
Posture (-)	Standing
Drink (-)	1
Initial TR temperature (°C)	20
Module temperature (°C)	20
TR air change rate (/hr)	0.35
Initial TR humidity (-)	0.25
Module humidity (-)	0.8

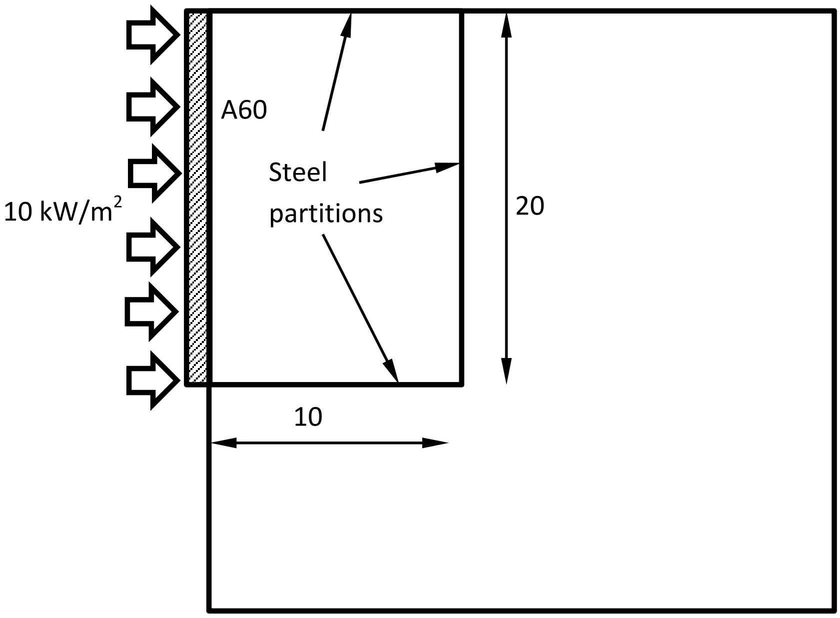

Figure 22 Geometry for example 1. The TR is a subsection of another module and is separated from the hazard by an A60 barrier

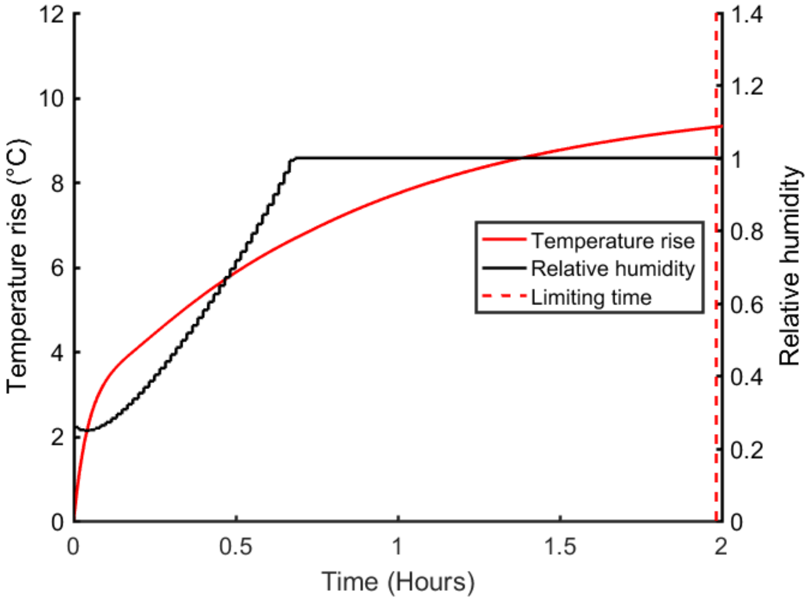

Figure 23 Internal temperature and humidity rise within the TR for example 1 when the humidity generation by the occupants is included. Impairment time is indicated by the dashed line

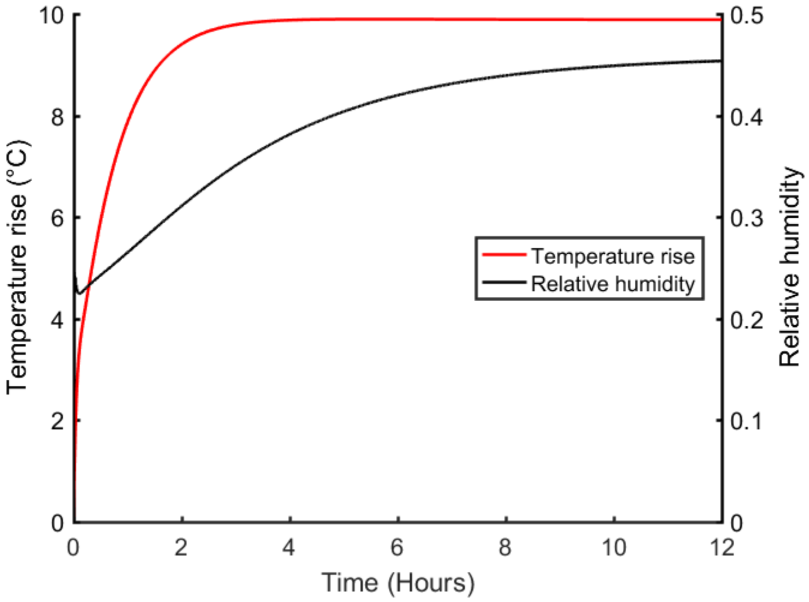

Figure 24 Internal temperature and humidity rise within the TR for example 1 when the humidity generation by the occupants is not included. Impairment is not predicted to occur in the modelled period

7.3 EXAMPLE 2

In this example, the TR is a small, stand-alone unit with walls and roof covered with A60 rated panels. The panels have properties as given in Table 5. There is no external heat input in this case, so that the heat sources are the occupants and equipment in the TR. Input parameters for this example are shown in Table 11 and the modelled geometry in Figure 25. Results for the ISO 7933 model are shown in Figure 26, when moisture given off by the occupants is included in the humidity in the TR. In this case, the heat input from the occupants and equipment causes a modest temperature rise so that heat impairment is not predicted to occur within four hours. Due to the relatively long heat impairment time, a check on impairment by oxygen depletion and carbon dioxide accumulation was made using the model set out in Coldrick (2013). Results for this model are shown in Figure 27, which shows the time variation of oxygen, carbon dioxide and carbon monoxide in the TR, as well as the Fraction Effective Dose (FED) resulting from each component. Impairment occurs when the FED reaches one, which is not predicted in the simulated period.

Table 11 Input parameters for example 2

Parameter	***Value***
POB	10
Weight (kg)	87
Height (m)	1.77
Metabolic rate (W/m^2)	100
Clothing insulation (-)	1
Posture (-)	Standing
Drink (-)	1
Initial TR temperature (°C)	20
Ambient temperature (°C)	15
TR air change rate (/hr)	0.1
Initial TR humidity (-)	0.25
Ambient humidity (-)	0.8
Heat input from equipment (W)	200

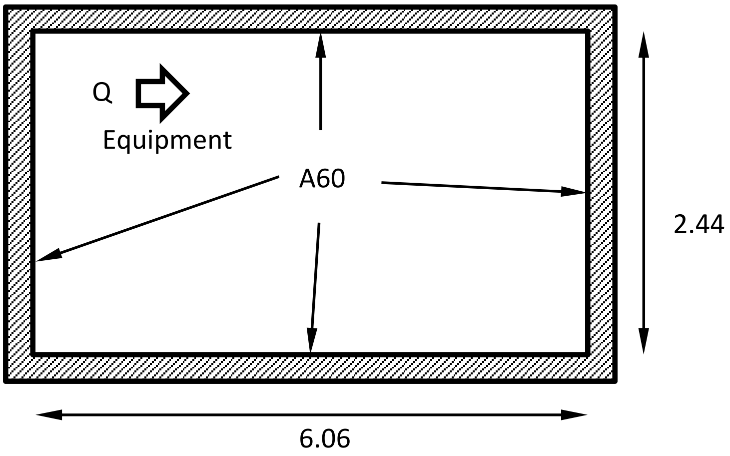

Figure 25 Geometry for example 2. Stand-alone unit, with no external heat source

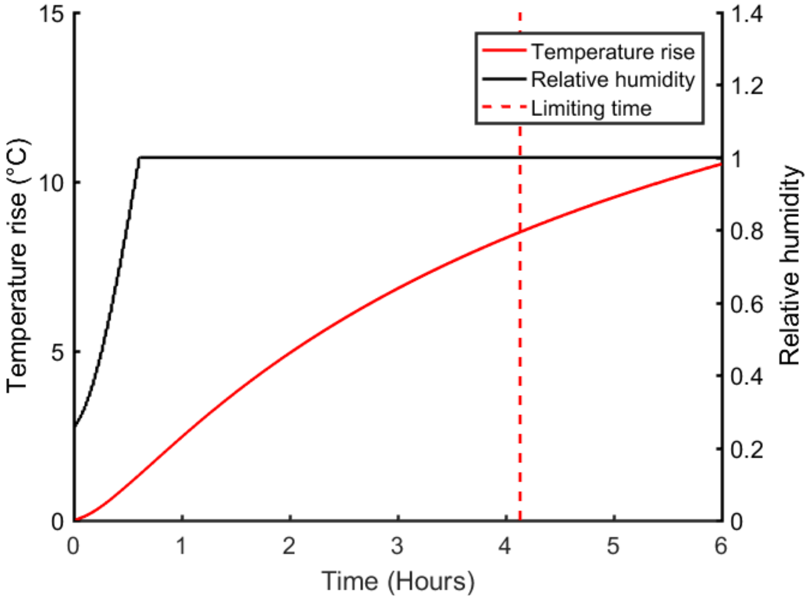

Figure 26 Internal temperature and humidity rise within the TR for example 2 when the humidity generation by the occupants is included. Impairment time is indicated by the dashed line

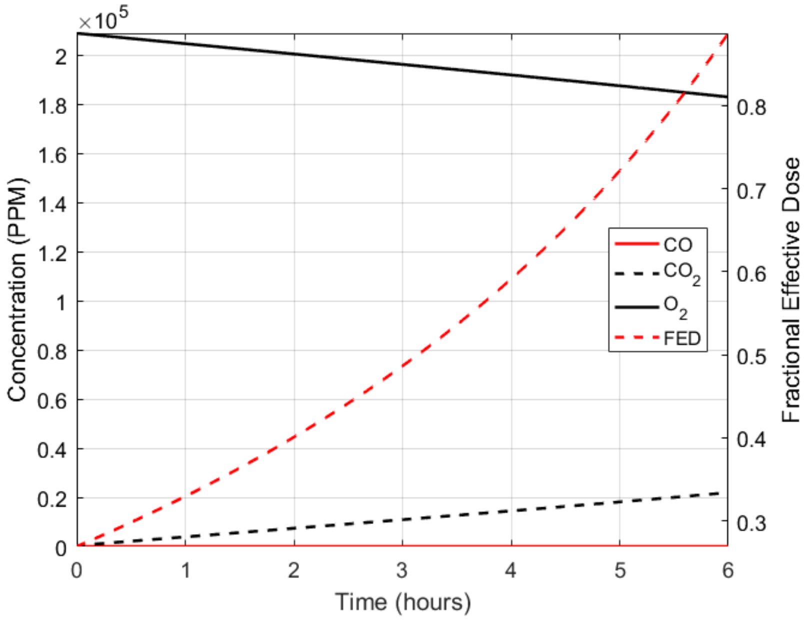

Figure 27 Time varying interior concentrations of carbon monoxide, carbon dioxide and oxygen for the TR in example 2. Impairment occurs when the FED reaches one

8 CONCLUSIONS

Current guidance on risk assessment for offshore temporary refuges focuses on the demonstration of TR integrity rather than the determination of an impairment frequency. TR integrity can be interpreted as demonstrating that the occupants TR will remain unimpaired for sufficient duration as to allow corrective action and/or evacuation to be planned in the event of an incident. Heat stress is an impairment mechanism that may arise as a direct result of the incident, or because the normal mechanisms for heat removal, such as ventilation do not operate.

This report describes an approach for determining impairment times due to heat stress. The approach consists of simplified one-dimensional heat transfer modelling to determine the time variation of temperature in an enclosed space, coupled with a model to predict physiological response to the elevated temperature. TR construction standards and material properties have been reviewed to enable an assessment of the heat transfer through typical TR construction elements. Models for relating ambient temperature to impairment times have also been reviewed. These range from simple correlations developed for predicting survival times in fires, to more complex models aimed at predicting heat stress in occupational health settings. The Predicted Heat Strain (PHS) model set out in the ISO 7933 standard was used to relate ambient temperature to impairment time.

The use of a one-dimensional heat transfer calculation is based on being able to identify the main heat transfer processes to determine the bulk temperature change in the TR. It requires a complex three-dimensional problem to be extensively simplified, using a number of assumptions. One-dimensional methods are applicable where there is uniform heating of panels, such as when the hot fire plume is relatively large compared to the TR, or when a well-mixed interior exchanges heat with the exterior. The accuracy of the approach will diminish when there is localised heating of sections of panels, or when the internal geometry of the TR is particularly complex, such as in multi-room accommodation modules where the assumption of uniform mixing cannot be applied. The main benefit of one-dimensional analysis is that it is straightforward to implement and can be run quickly. Therefore, it can be used to give an indication of the impact of changes, such as the effect of adding extra insulation, humidity, reducing the air change rate etc. or to assess the effect of uncertain inputs.

Predictions of heat transfer could be improved with the use of a more complex two-dimensional or three-dimensional model. However, such methods would also be based on further assumptions and simplifications. Predictions could also be improved by comparing the model to physical test data (validation - if data are available), which would give a more complete understanding of the impact of the one-dimensional assumption. However, given the variation in TR geometry among installations, validation against specific test cases would be of limited use if the geometry of concern is very different from the test cases.

The ISO 7933 model is relatively complex and requires values for a number of inputs to estimated. A global sensitivity analysis was carried out on the model, to help identify the most important input parameters and help to set appropriate values for use in a TR impairment analysis. The sensitivity analysis was done using a freely available tool box, which includes a number of different methods. A screening test or elementary effects test was firstly carried out to identify important parameters, followed by a variance based analysis to determine the effects on model output of the most important parameters. Ambient temperature and humidity were found to have the largest influence on model predictions.

There is a significant difference in impairment times predicted by the simple correlations and those predicted by the ISO 7933 model. This is due to the different drivers for development of the models, where the simple correlations were intended to predict survival times in fires and the ISO 7933 model is designed for occupational health settings. The latter was considered more relevant to TR impairment analysis due to the emphasis on decision making in the event of an incident. Validation of the physiological aspects of the model is reliant on that done by the ISO7933 model developers. Further validation of this part would involve the generation of new test data relevant to TR analyses.

The TR heat impairment model has been applied to two simple examples, to demonstrate the application of the approach.

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Offshore installations must have a temporary refuge (TR) for use by workers in the event of a major fire or explosion incident. The importance of an effective TR was highlighted by the 1988 Piper Alpha disaster in which 187 workers died. Duty holders must establish suitable TR performance standards to protect workers. HSE Research Report RR1167 describes a model to estimate the time taken for workers in a TR to become impaired due to ingress of smoke or flammable and toxic gases. Another important consideration is effective protection for workers from heat stress. This is to prevent harm to workers and ensure that they can make rational decisions on management of the incident, including evacuation from the platform.

This report describes the development of a model to estimate the time taken for workers in a TR to become impaired due to heat stress in the event of an incident. The model is based on reviews of: heat transfer models; methods for relating heat exposure (thermal load) to heat stress in people; and TR standards and construction methods. The report will be of interest to specialist modellers in industry in the determination of TR performance. The model uses a simple one-dimensional heat transfer calculation to determine the bulk temperature change in the TR, and an existing model for heat stress. This approach is an extensive simplification of a complex three-dimensional scenario. The main benefits of this simple model are that it is straightforward to implement. Therefore, it can be used to give an indication of the effectiveness of changes to a TR design such as extra insulation or reducing the air change rate, as well as to assess the effect of uncertain modelling data.

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