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The severity of fire in a large compartment with restricted ventilation

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This paper traces theoretical and experimental work on the severity of fully developed fires in compartments and, by reference to fully developed fire tests recently performed by the Fire Research Station (FRS) and British Steel Technical in a large compartment, shows the effect of reducing the ventilation area on combustion gas temperatures, the severity and duration of fire. It has relevance to fires in ship compartments where ventilation conditions may be poor.

INTRODUCTION

Certain compartments in ships require to have fire resisting boundaries, eg bulkheads, to limit fire spread so as to preserve life, reduce property loss and prevent environmental disasters. The complexity of fire is such that it is not possible to model the heat transfer time profile using basic physics and chemistry. Field models based on computational fluid dynamics, although capable of providing local predictions in three space dimensions and in time, of temperatures, densities, pressures, gas velocities and chemical compositions within the volume of a compartment, are not yet able adequately and routinely to predict fire severity in post-flashover fires in compartments. The approach followed by researchers working on fire severity in buildings has been to conduct tests in small compartments and derive empirical relationships for fire severity from these, and it has been found that the amount of fire resistance needed depends upon the nature and magnitude of the fire load, the amount of ventilation, and the thermal properties of the enclosure.

Too much fire resistance leads to structures and their fire protection systems which are unnecessarily costly, heavy and space consuming – features to avoid in ship construction. Too little fire resistance may mean that the structure is unable to resist a burn-out of the contents so that unlimited fire spread might occur if automatic sprinklers are not installed. Setting the correct level of fire resistance is thus important and requires engineering judgement, often aided by sensitivity analysis, to assess the effect of practical variations in parameters which increase the fire severity. When a fire safety engineering approach is adopted for the design of compartments in buildings, the fire load density (total fire load in compartment divided by floor area) in the design is often taken as the 80% fractile value determined from fire load surveys. But what if the use of the building is such that higher than 80% fractile values are likely to occur? If the strategic importance of the fire compartment or adjacent compartments is high then a safety factor must be applied.

In general, the experimental work has confirmed that the periods of fire resistance prescribed in technical guidance documents accompanying building regulations are approximately correct, although the guidance is not sufficiently refined to allow for changes in ventilation conditions or subtle variations in fire load.

THEORY

Work on the severity of fully developed fires in compartments began with the classic work of Ingberg[1] in the USA in the 1920s. He made experiments in a brick/concrete compartment 4.5m x 8.75m x 2.75m high with shutters in one wall which were adjusted to give the maximum fire severity. Fire load densities were 65 – 270 kg timber/m^2 of floor area using wood and paper. (It should be noted that the combustion of 1 kg timber releases 19 MJ.) Equivalent periods of fire exposure were calculated by comparing the area under the

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Author's biography

Gordon Cooke served an engineering apprenticeship before graduating in mechanical engineering at Cardiff University in 1960. He worked on the use of steel in industrialised housing and behaviour of steel in fire before joining a London firm of Consulting Engineers where he became a Partner. He joined the Fire Research Station in 1975, obtained a PhD in fire engineering and currently works on harmonisation of European fire matters and fire safety engineering.

Table I Ventilation conditions for Tests 1 – 4

Test number	1	2	3	4
Ventilation area as a proportion of front wall area, %	100	50	25	12.5
Ventilation area as a proportion of floor area, %	12	6	3	1.5

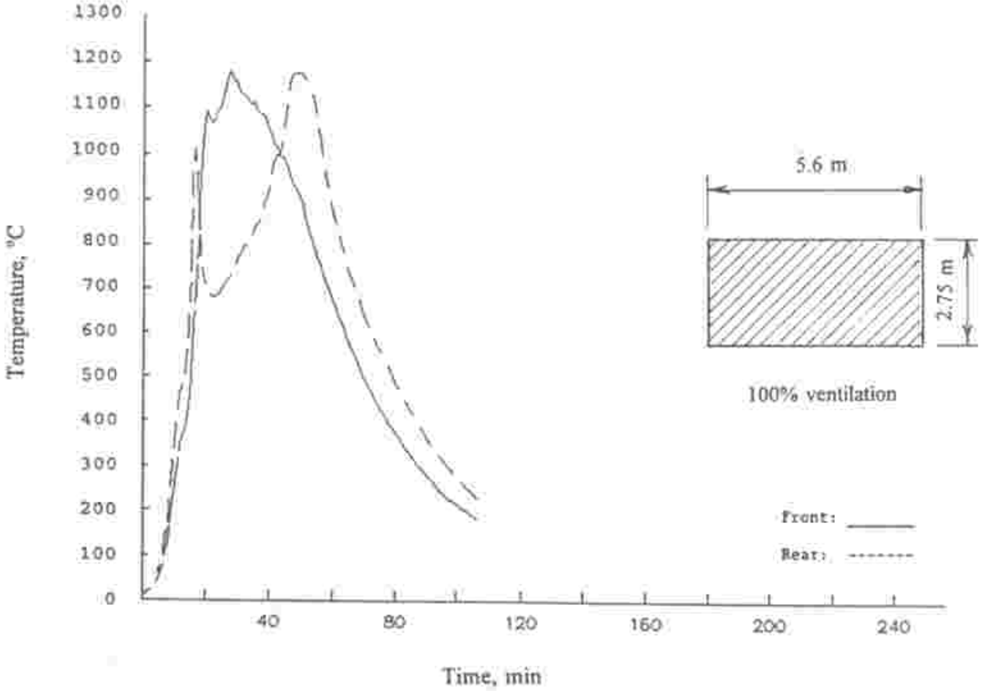

Fig 1 Combustion gas temperature-time profiles, Test 1

combustion gas temperature-time curve for the experimental fire with the area under the standard furnace test curve. Calculated periods of fire resistance were in the range of 2 – 8h.

In the 1960s there was renewed interest in ways of calculating fire resistance. In Sweden tests were made in a small semi-circular tunnel and this resulted in the concept of opening factors used in the Swedish fire engineering approach[2]. At about the same time CIB co-ordinated a programme of 300 model compartment fire tests undertaken by eight international laboratories. The work examined the validity of the relation $R = kA_V H^{1/2}$ where R is rate of burning, k is a constant, A_V is area of ventilation opening and H is height of ventilation opening. This work[3] led to the now well-known time equivalent equation for ventilation controlled fires, t_e:

$$t_e = kL/(A_V A_T)^{1/2} \qquad (1)$$

where k is a constant usually taken as unity, L is total fire load, A_V is area of ventilation opening, and A_T is total area of boundary surfaces.

Further justification for equation (1) came from experiments[4] jointly sponsored by the British Iron and Steel Federation and the Fire Research Station in the early 1960s. This was followed by work jointly sponsored by British Steel Corporation (BSC) and the Fire Research Station in the early 1980s in a compartment 8.6m x 5.8m x 3.9m high, again using timber cribs as a reproducible fire load[5]. None of the work so far mentioned had examined the effect of using a small ventilation area, the subject of this paper.

The next spur to fire severity work in the UK stemmed from the recent (1993) work on European harmonisation of standards. The fire part of the draft Structural Eurocodes includes an empirical equation which enables the amount of fire resistance required to resist a burn-out of the contents of a compartment to be calculated[6]. The equation does not include any factor of safety. The equation, called the equation for equivalent time of exposure, is defined as:

$$t_e = qc'W \qquad (2)$$

where t_e is the equivalent time of exposure (min), q is the fire load density (MJ/m^2), c' is a conversion factor to allow for the thermal properties of the enclosure, and W is a ventilation factor. More details of the equation and a worked example are given in the Appendix.

EXPERIMENTS

Following the author's observation that equation (2) had only been validated experimentally for 'small' compartments (ie compartments of not more than 60m^2 floor area),

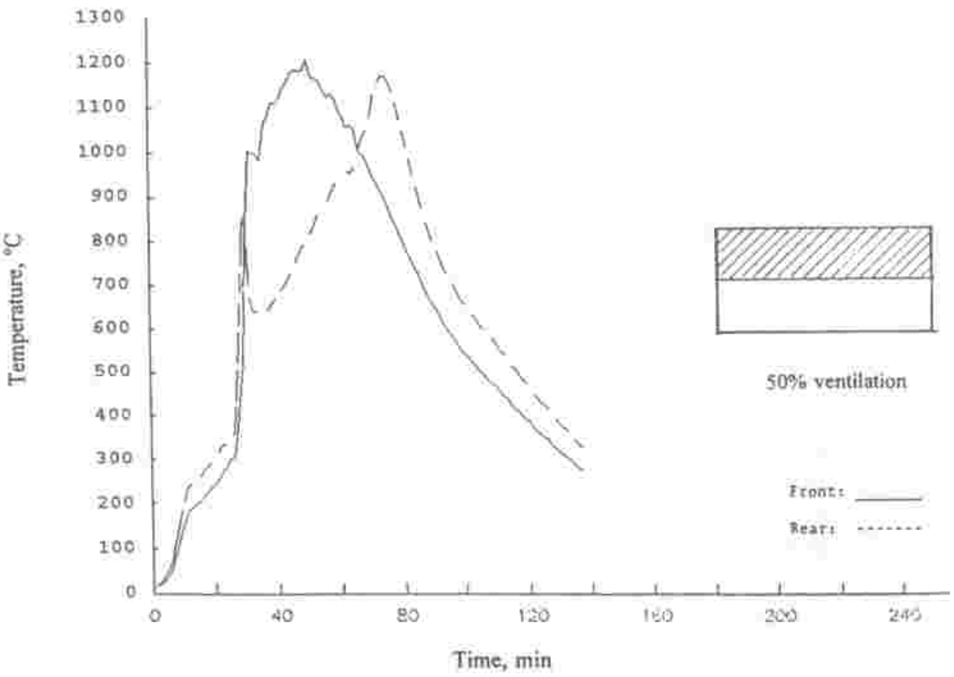

Fig 2 Combustion gas temperature-time profiles, Test 2

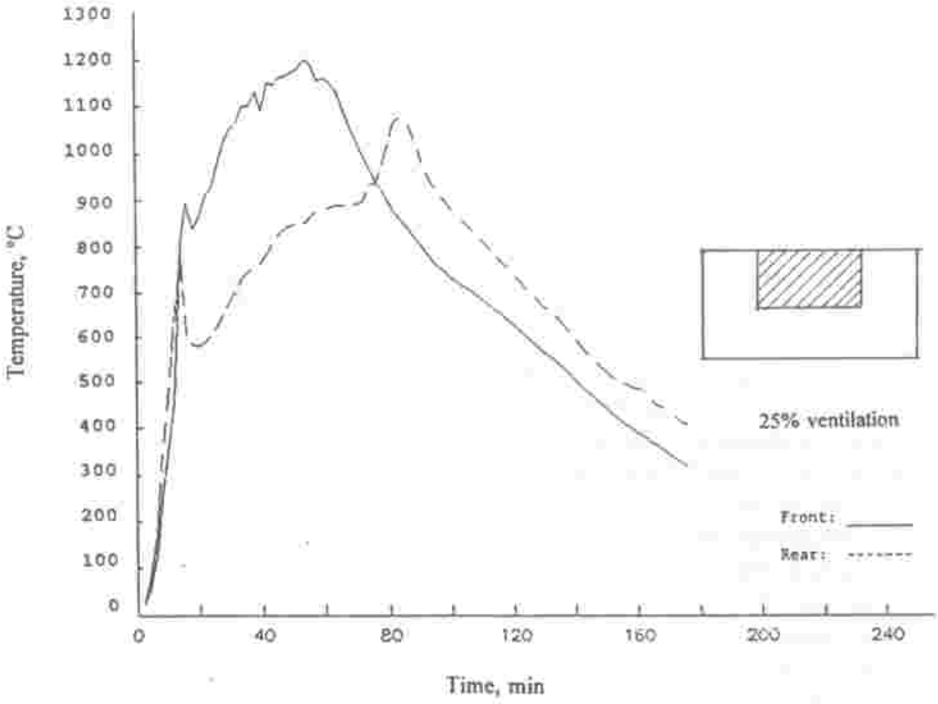

Fig 3 Combustion gas temperature-time profiles, Test 3

the Construction Directorate of the Department of the Environment agreed to sponsor tests in a large compartment. British Steel were also interested in the use of the equation for the fire engineering design of steel structures and became a co-sponsor. British Steel Technical (Swinden Laboratories) and the FRS jointly undertook the experimental work.

The compartment was built in the 245m long by 80m wide by 55m high BRE Cardington laboratory in which protection against wind and rain could be provided. The compartment had concrete block walls, a roof of aerated concrete slabs and was lined throughout with a 50 mm layer of highly insulating ceramic fibre. The internal dimensions were 22.8m x 5.6m x 2.75m high. Ventilation was provided in one of the 5.6m x 2.75m end walls. The concrete floor was insulated with a 100 mm thick layer of dry sand. The fire load was in the form of 33 timber cribs arranged in 11 rows of 3. Each crib was 1m², formed from kiln-dried 50 mm square sticks of hemlock spaced 50 mm apart, and each crib was 900 mm away from its neighbour. Six of the cribs in the central row were supported on load cell platforms so that weight loss

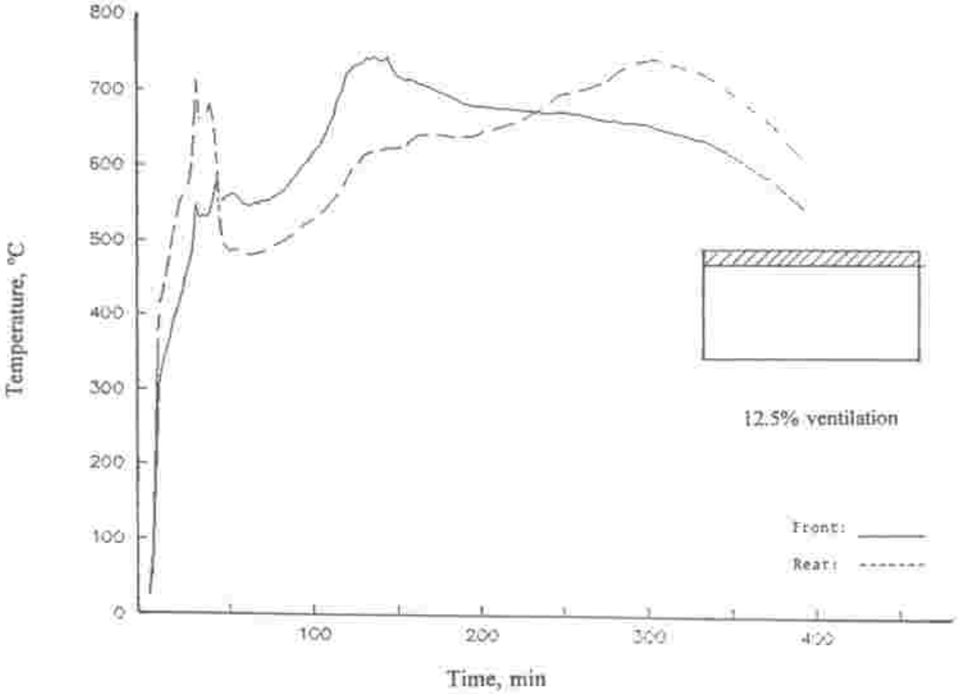

Fig 4 Combustion gas temperature-time profiles, Test 4

Table II Values of t_e determined from the tests

Test number	*1*	*2*	*3*	*4*
t_e determined from test, min	71	80	99	111

could be measured as the fire progressed. For reasons of safety the cribs were ignited from outside the compartment using fuse cord and incendiary devices.

Measurement sensors were installed at different locations within the compartment to record the following while each fire progressed: combustion gas temperatures, steel temperatures, crib mass loss, concentration of CO, CO_2 and oxygen in the combustion gas, and wall temperatures. External measurements were made of intensity of radiation emitted from the ventilation opening and from the flames and plume of hot gases above the ventilation opening.

Nine tests were performed to examine the effect on fire severity of varying the fire load density, ventilation, compartment size, and thermal insulation of the boundaries. The tests were also designed to quantify the effect of a fire which spreads naturally, as in a real fire, through the compartment since most earlier tests had involved simultaneous ignition of all of the fire load.

A recognised way of determining t_e experimentally is to measure the maximum temperature, θ_m, reached by a protected steel member in the experimental fire and find, by reference to a standard fire resistance test report for an identical member, the time when the steel member reached θ_m in the furnace. This time is the equivalent time of fire exposure and was obtained in the present tests using temperature data for a number of 1m long protected steel I-section beams and columns with thermocouples embedded in them, which were suspended immediately below the ceiling of the compartment at three positions along the depth of the compartment. The protection was exfoliated vermiculite board – 20 mm on beams and 30 mm or 75 mm on columns.

Four of the tests are of particular interest in looking at the effect of reducing the ventilation (see Table I). All four tests were in the full size compartment lined with ceramic fibre blanket and all four employed a common fire load density of 20 kg/m^2 (380 MJ/m^2). The only variable was the area of ventilation in one of the 5.6m x 2.75m high walls called the front wall.

More than 50 thermocouples were installed to measure combustion gas temperatures in the compartment. For the comparisons of combustion gas temperatures made in this paper two 3 mm diameter Inconel-sheathed thermocouples were mounted along the centre line of the compartment. Both had their sensors nominally 100 mm below the ceiling. The 'rear' thermocouple was 6m from the rear wall, the 'front' thermocouple was 6m from the front of the compartment, there being a gap of nominally 11m between them. The temperature–time profiles for both thermocouples in Tests 1 – 4 are shown in Figs 1 to 4 respectively.

The measured equivalent times of fire exposure were determined from the test data as described earlier and are given in Table II.

DISCUSSION OF RESULTS

Effect of ventilation on equivalent time of fire exposure

A comparison of Table II and Table III in the Appendix shows that measured and calculated values of t_e agreed well for Tests 2, 3 and 4. In Test 1, however, the measured value was greater than the predicted value by 40% using $c' = 0.09$. However, the Eurocode recommends $c' = 0.06$ where no detailed assessment of the thermal properties of the enclosure is possible and this would result in non-conservative values of t_e for all four tests.

The Eurocode equation for t_e appears inappropriate for long duration, poorly ventilated fires, as in Test 4, which lasted for more than 8h and gave measured t_e values of nominally 2h for a steel column protected with 30 mm of exfoliated vermiculite board and more than 3h for an identical steel column section protected with a 75 mm thick layer of the same protection. Such differences do not occur for shorter duration fires. Nevertheless, some guidance needs to be given for the minimum and maximum thicknesses of protection that can be used as a basis for measured values of t_e so that anomalous results are not obtained.

Taken together Tables I and II show that the effect of progressively reducing the ventilation area is progressively to increase the equivalent time of fire exposure. The increase of t_e with decrease of ventilation is also indicated in Figs 1–3 which feature roughly the same peak combustion gas temperatures (1200°C) but increasing duration. The area under the combustion gas temperature-time curve, which may be regarded as an approximate measure of total heat flux, is seen to increase with decrease of ventilation.

Effect of ventilation on the combustion gas temperature-time profiles

Comparison of the front and rear thermocouple measurements in Figs 1 – 4 show that the combustion gas temperature at any point in time is not uniform throughout the depth of the compartment, unlike earlier tests in smaller compartments which have been characterised by uniform combustion gas temperatures after flashover. Flashover may be assumed to have occurred when the combustion gas temperature exceeds 500°C, which occurred in Tests 1 – 4 within the first 30 min.

An interesting feature of all four tests was that the peak temperature at the front of the compartment always occurred sooner than the peak temperature at the rear, and this can be explained by the mode of fire spread. In all four tests the row of three cribs at the rear of the compartment was ignited and fire was allowed to spread naturally to the other 30 cribs via the tops of the cribs to the row of cribs at the front of the compartment, assisted by radiation from the layer of hot gases under the ceiling and radiation from the vertical face of the neighbouring row of burning cribs. The front row of cribs then burnt downwards and then the next row similarly, while burning in the rear of the compartment stopped because the cribs at the front were consuming most of the inflowing air needed for combustion. This can be seen in Figs 1 – 4 by the sharp drop in temperature recorded by the rear thermocouple within the first 40 min. Full depth burning of each row of cribs then proceeded from the front to the rear of the compartment.

The long duration fire obtained in Test 4 resulted from the low rate of combustion air supply in relation to the large mass of fuel to be burnt. The smallest ratio of ventilation area to floor area was 1:12 for the earlier BSC/FRS tests[5] but was 1:66 for the present 1993 tests for the same fire load density of 20 kg/m², and it therefore follows that the 1993 test duration would be much larger than that for the 1980s tests. This assumes that the rate of air entering the compartment is approximately proportional to the ventilation area and that the total fire load is proportional to the floor area, which it is for a common fire load density. Another reason for the long fire duration in Test 4 is that the heat loss by radiation through the ventilation opening is small.

CONCLUSIONS

1. Within the limits of ventilation used in the four tests reported in this paper, the effect of reducing the ventilation area was to increase the equivalent time of fire exposure determined from the temperature rise of short lengths of steel I-section encased in a fire protecting board material. Increase in the equivalent time of fire exposure was also demonstrated qualitatively by assessing by eye the area under the combustion gas temperature-time curves.

2. The duration of a fully developed fire can be large for a compartment having boundaries of high thermal insulation, a large fire load and restricted ventilation. A duration in excess of 8h was obtained in Test 4.

3. The mode of fire spread through the 23m depth of compartment was interesting. When only the cribs at the rear were ignited the fire subsequently spread to the front via the tops of the other cribs by spontaneous ignition, assisted by radiation from the layer of hot gases under the ceiling. The front row of cribs then burnt downwards and then the next row similarly, while burning in the rear of the compartment stopped because all of the air was being consumed by the cribs at the front of the compartment. Full depth burning of the remaining cribs then proceeded from the front to the rear of the compartment. This mode of fire spread, from the front to the rear, also occurred when all 33 cribs were simultaneously ignited in another test in the same compartment not reported in this paper.

4. The comprehensive data collected in the test programme will be of great use to fire modellers since there is a scarcity of experimental data for fully developed fires in large compartments.

5. The work has practical relevance to safety in large compartments, eg large public spaces in passenger ships, in several ways. The test results provide an accurate indication of the period of fire resistance needed for the enclosing structure of a well-insulated fire compartment which is required to resist a burn-out of the contents. This presupposes: 1 that the nature and amount of fire load represented by the actual contents of a ship's compartment can be determined and; 2 that the area of ventilation opening can be decided. Such data could be of use when reviewing levels of fire resistance in existing codes. Subject to acceptance by the ship approval

authority, the data might also be used to justify a reduction in the required fire resistance of a particular compartment, which could lead to economy in construction.

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APPENDIX

DETAILS OF THE EUROCODE EQUATION FOR EQUIVALENT TIME OF FIRE EXPOSURE

The equivalent time of fire exposure, excluding gamma factors which take account of active fire protection measures, is defined in the 17 September 1992 version of Part 10A (General Principles and Nominal Thermal Actions) of the Actions Eurocode as:

$$t_e = qc'W \tag{1}$$

where:

t_e = equivalent time of fire exposure (min)

q = fire load density (MJ/m^2) = Q_K/A. (See equation (2) below).

c' = conversion factor to allow for the thermal properties of the enclosure, which may be taken as 0.06 where no details are available. Other values may be obtained from a CIB design guide (Design Guide – Structural Fire Safety, Workshop CIB W14, Fire Safety Journal, Vol 10 (1986), pp 73–137) which gives Table III.

Table III CIB design guide

$b = (\lambda r c_p)^{1/2}$ (Wh$^{1/2}$/m^{2}K)	c' (min/(MJ/m^2))
< 12	0.09
12 ... 42	0.07
> 42	0.05

where:

λ = thermal conductivity (W/m°C)

ρ = density (kg/m^3)

c_p = specific heat (J/kg°C)

W = ventilation factor which may be calculated as:

$W = (6.0/H)^{0.3}\,(0.62 + 90(0.4 - \alpha_v)^4/\,(1 + b\,a_h)) = > 0.5$

where:

$\alpha_v = A_v/A_f$ and $\alpha_h = A_h/A_f$

where:

A_v = area of vertical opening

A_f = area of floor

A_h = area of horizontal openings

$b = 12.5\,(1 + 10\,\alpha_v - \alpha_v^2) = > 10.0$

H = is the height of the fire compartment

Fire load density, Q_K/A, may be determined using:

$$A = \text{floor area } (m^2)$$

$$Q_K = SM_{K,i} \,.\, H_{ui} \,.\, (m_i) \,.\, (y_i) \tag{2}$$

where:

$M_{K,i}$ = amount of combustible material (kg) including all combustible building contents and construction elements, including linings and finishings

H_{ui} = net calorific value (MJ/kg)

(m_i) = optional factor describing the combustion behaviour; $M_i = 1.0$ for cellulosic materials (conservative)

(ψ_i) = optional factor for assessing protected fire loads

Worked example

The following worked example is for large compartment Test 1, having a fire load density of 20 kg/m^2 and 100% ventilation in the front wall.

$$t_e = q\,c'W \tag{3}$$

A timber crib fire, load density of 20 kg/m^2, corresponds to 380 MJ/m^2 assuming the net calorific value of timber is 19 MJ/kg. Thus q = 380 MJ/m^2.

c' can be assumed to be 0.09 since the compartment walls and ceiling are insulated with 50 mm ceramic fibre insulation having a low density of 128 kg/m^3 and low thermal conductivity.

$$W = (6/H)^{0.3}\,(0.62 + 90\,(0.4 - a_v)^4/(1 + b\,a_h)) \tag{4}$$

where:

H = 2.75m

A_v = width x height of opening = 5.6 x 2.75 = 15.4m^2

A_f = depth x width = $22.8 \times 5.6 = 127.7\text{m}^2$

A_h = zero (no openings in roof)

Hence

$\alpha_v = 15.4/127.7 = 0.12$

$\alpha_h = 0/127.7 = 0$

Substituting values in equation (1) gives:

$t_e = 380 \times 0.09 \times (6/2.75)^{0.3} (0.62 + 90 (0.4 - 0.12)^4/(1 + 0))$

$$t_e = 50 \text{ min} \qquad (5)$$

The calculation was repeated for Tests 2–4 and the values of t_e obtained shown in Table IV were:

Table IV Values of t_e obtained by calculation from Tests 2 – 4

Test number	1	2	3	4
t_e calculated, min	50	79	100	112