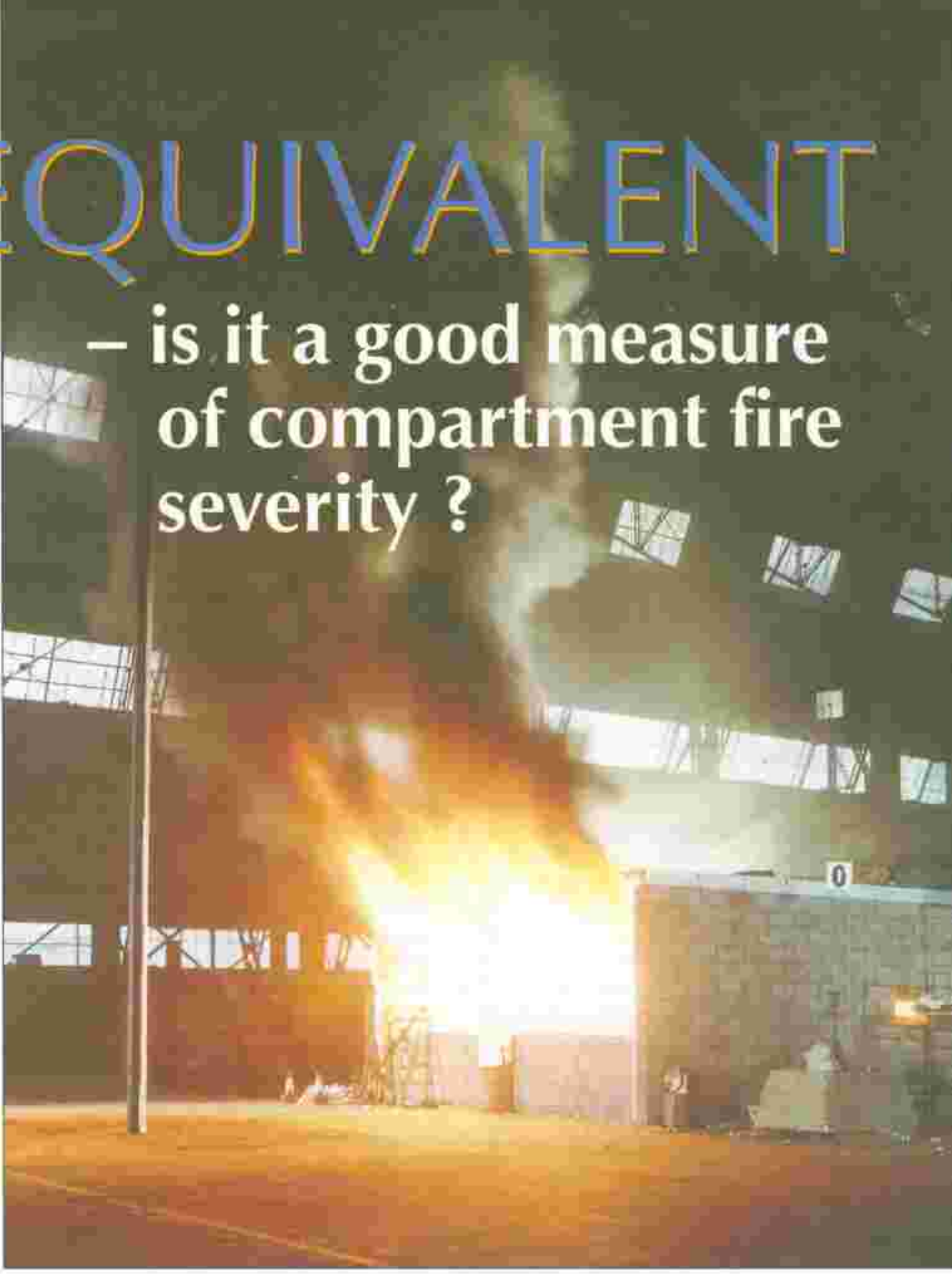
TIME EQUIVALENT

– is it a good measure of compartment fire severity ?



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This article deals with the severity of fully developed fires in a deep compartment. The concept of time equivalent as a measure of fire severity is introduced before reviewing some fire tests in full size compartments. Measured values of time equivalent are reported and shown to have large variations in a deep, well insulated compartment. Care should be taken in using measured results when validating calculations of time equivalent for the purpose of deriving the fire resistance needed to survive a burn-out of the contents.

Fire severity

Intuition tells us that the severity of a fire in an enclosure depends on the temperature of the combustion gases and the duration of the fire. It takes only a small step in our imagination to think that the area under the temperature-time curve might serve as a measure of fire severity. Figure 1 shows a compartment fire and the standard furnace curve BS 476 Part 20 (ISO 834). By inspection we can see that the areas under the two curves are equal at about 22 minutes. We might think that at 22 minutes the severities associated with the two fires are the same and that the real fire has a severity equal to 22 minutes of furnace exposure. However if the responses of identical protected steel columns exposed to these fires are compared it is clear from figure 2 that the responses are markedly different: the real fire corresponds to a furnace exposure of about 45 minutes. The differences are thought to result from differences of heat transfer, there being more radiation in the real fire due to luminous flames. More details of the comparison of compartment fires and furnace test results are given elsewhere.[1]

Time equivalent

We have seen that one way of quantifying the severity of a fire in a compartment is to measure or calculate the maximum temperature attained by an element of building construction (such as a protected steel beam or column) in the compartment and find out how long it would take to achieve this temperature in a standard fire resistance test on an identical element, figure 3. This time is called the 'equivalent time of fire exposure' or simply the 'time equivalent', and is usually expressed in minutes. As we shall see later this method has been used to determine the severity of fires resulting from a burn-out of the building contents in full size experiments.

The time equivalent can also be calculated directly from a knowledge of the fire load, the size and shape of the ventilation opening(s), and the thermal properties of the enclosure. Most of these parameters are included in an equation for time equivalent given in the Fire Actions part of the Structural Eurocodes (ENV 1991-2-2 'Actions on structures exposed to fire') which will enable designers

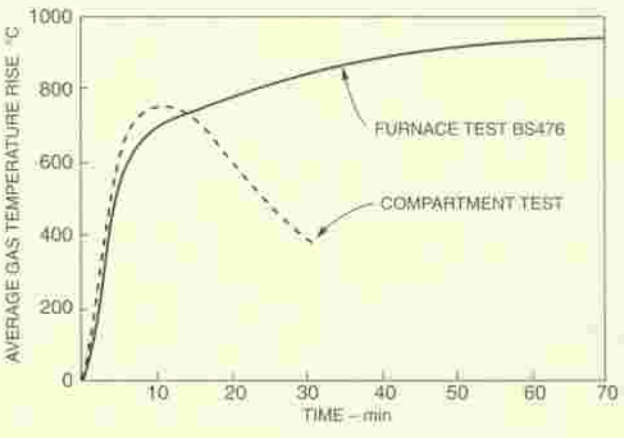


Figure 1. Combustion gas temperatures

to calculate the period of fire resistance needed in the building rather than use the periods given in official guidance such as Approved Document B. However, the purpose of this article is to discuss experimental results not calculation methods.

The connection between time equivalent and fire resistance has not yet been made. Let us assume that in a real fire the maximum temperature attained by a structural steel column is 650°C and, from a standard test on an identical column, a time equivalent of 40 minutes is obtained, corresponding to Point B in figure 4. The ability of the column to resist collapse, hence possess fire resistance, will depend on the load ratio (the ratio of the applied load to the ultimate failure load at room temperature). The lower the load ratio the higher the fire resistance. With a low load ratio of say 0.25 the column buckles and is unable to support the load when it attains a temperature of say 750°C corresponding to Point A. With a high load ratio of say 0.5 the column fails at a temperature of say 550°C corresponding to Point C . It can therefore be seen that the load ratio needs to be considered in making the connection between equivalent time and fire resistance. In this example it would not be valid to claim that the fire resistance was 40 minutes simply because the time equivalent was 40 minutes because if the load ratio was 0.5 the fire resistance would be less than 40 minutes, figure 4. This has implications for the interpretation of the calculated time equivalent which yields only a time.

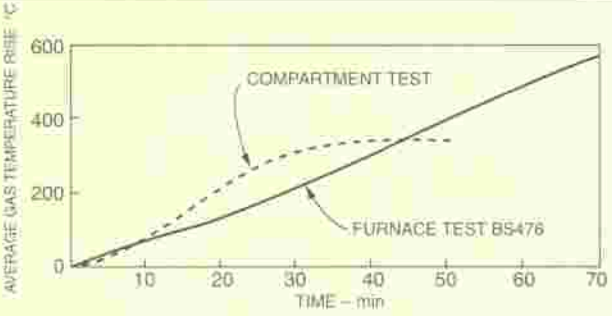


Figure 2. Protected steel column temperatures

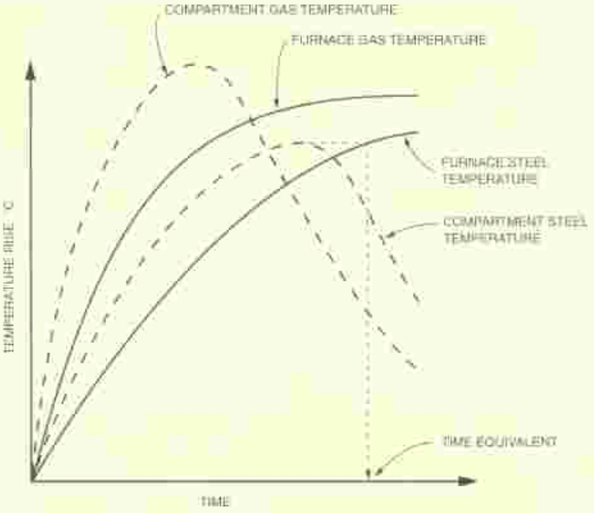


Figure 3. Time equivalent concept

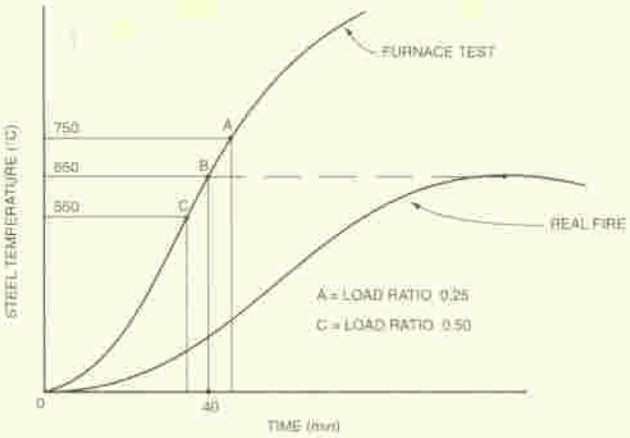


Figure 4. Effect of load ratio

Compartment fire tests

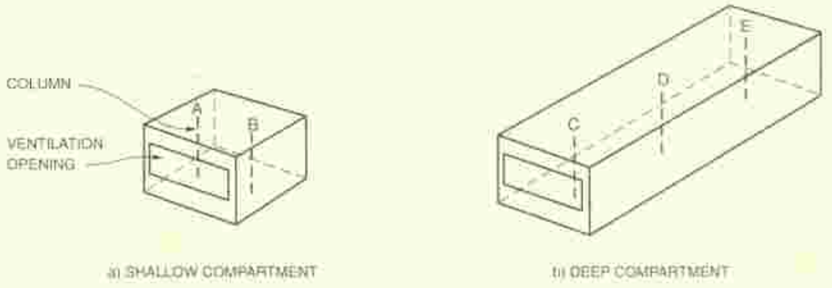
Until the mid-90's most full size fire test compartments used in the UK for the validation of time equivalent equations were about 3m high and roughly square in plan with a floor area not larger than about 60m². Two parameters of practical importance should be mentioned here - the fire load and the ventilation opening. In most of the test work the fire load used was wood sticks arranged as cribs but several tests were performed in which other fuels were used, for instance ordinary domestic furniture. The combustion gas temperature-time curves for the tests using furniture indicated that wood cribs, chosen as a convenient and easily reproducible fire load for test purposes, are also representative of furniture. In a building the ventilation opening is represented by windows when the glazing falls out, by open doors or other areas of low fire resistance which have burnt through, so allowing cold air to enter at the bottom and combustion gases to flow out at the top assuming no through-draft. The behaviour of glazing in fire is notoriously variable and to reduce the number of variables in experimental programmes of research into fire severity it has been common practice to use unglazed openings. Unglazed openings were used in the work described here.

Such research programmes have also been confined to single compartments, whereas in practice a fire in one room or space may spread to another reaching their peak severities at different times. When applying the results of this research these assumptions may be important and need to be considered.

Over the past three decades the steel industry in the UK has been particularly active to show by the application of fire science and engineering that structural steel framed buildings are able to withstand the effects of fire without putting lives at risk or leading to high property losses. British Steel and the BRE Fire Research Station (FRS) and their predecessors have collaborated in several compartment fire test programmes.

These and earlier compartment fire tests are reviewed elsewhere.[2]

In most of the full size tests the fire load was uniformly distributed over the floor area and the ventilation opening was in one wall. In these conditions it is generally true to say that after flashover occurred the combustion gas temperatures were uniform throughout the compartment at any point in time. In these circumstances it would be reasonable to assume that identical specimens in different locations in the compartment would experience the same heating rates and have the same time equivalent



a) SHALLOW COMPARTMENT

b) DEEP COMPARTMENT

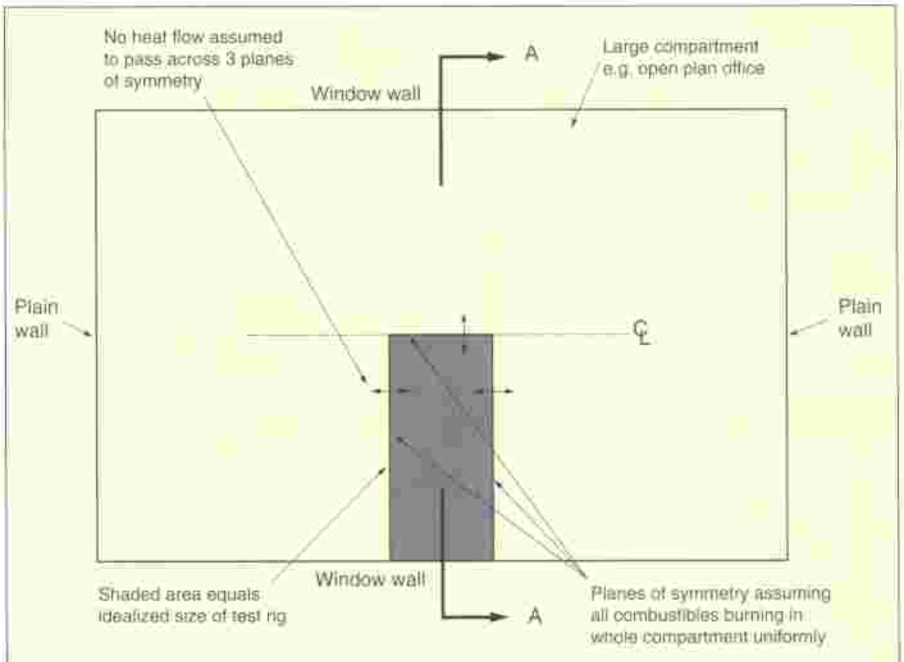
Figure 5. Columns in compartments of different depth

values, assuming that the specimens were receiving the same amount of radiation. In other words the two columns A and B shown in figure 5a would have the same temperature-time profiles, but note that a specimen placed in a corner, which receives less radiation due to the smaller radiation configuration factor, would not. But what if the compartment was deep, figure 5b, and, as in figure 5a, the ventilation opening was only in one of the sides. Would the three columns C, D and E shown in figure 5b have the same time equivalent? What would be the variation ? A programme of tests arranged by the author in 1993 while working at FRS would, as a by-product, answer these questions. These tests are now discussed.

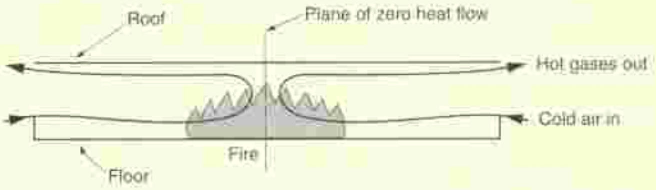
Tests in a deep compartment

Tests in a deep compartment were deemed necessary following the author's observation that the time equivalent equation had only been validated for 'small' compartments (i.e. compartments up to 60m^2 floor area). The Construction Directorate of the Department of the Environment agreed to sponsor some large compartment fire tests with British Steel which was particularly interested in the use of the equation for the fire engineering design of steel structures.

If the equation underestimated the real fire severity this could lead to constructions which were unable to contain the fire - a potentially dangerous situation. The levels of fire resistance stipulated in the technical guidance (Approved Document B) referenced in the Building Regulations for England and Wales are not related to ventilation or thermal properties of the enclosure but do include various factors of safety (increased fire resistance for high rise buildings for example). These two factors are also ignored in technical guidance in Scotland and Northern Ireland. So there was concern that the Eurocode approach might give very different results.



a) Plan view of large compartment and test rig



b) Section A - A

Fig 6. Concept of test rig showing planes of symmetry

The objective was to design a fire compartment that was substantially larger than the 60m^2 compartments previously tested. There were, however, practical constraints on the size of compartment and the external environment. Among other things it would be necessary to :

- ensure that the experiments were unaffected by wind, rain and daily temperature variations – the controlled environment was needed in a location where the materials and instrumentation would be secure, and the experiments were therefore made in the BRE Large Building Test Facility at Cardington
- limit the heat released into the laboratory to prevent damage by the thermal plume
- limit the cost of construction of the test compartment and the cost of the specially prepared fire load

As to the size of test compartment the following question was asked 'Could a very large compartment in a building such as an open-plan office be represented by a smaller portion in which the fire severity could be assumed to be similar?' If it could, then the experimental fire compartment could be made the same size as the portion. It was considered that it could if it was assumed that the open-plan office had window openings along two opposite sides so that after flashover a vertical plane of symmetry existed parallel to the window walls along the centre line of the office across which there was no transfer of heat (assuming no cross wind), as shown in section A-A in figure 6. If it was also assumed that after flashover there was no variation in heat transfer along the length of the large compartment, then two slices could be made from window wall to window wall which could be taken to represent the sides of the fire test compartment. This is shown in the plan view in figure 6. For these assumptions to be valid the walls representing these three slices would have to be highly insulated to satisfy the assumption of zero heat flow through the walls; the use of high temperature resisting low density ceramic fibre lining to enable repeated use of the compartment would satisfy this need. By making the compartment deep (front to back) but narrow with ventilation only in the narrow wall it would be possible to explore the effects, if any, of non-uniform burning of the fire load caused by restricted air supply.

It was decided that the compartment should be nominally 23m deep by 6m wide by 3m high, with a single ventilation opening in one of the 6m by 3m walls

The programme of tests was undertaken by FRS and British Steel Technical and was sponsored by the then Department of Environment and British Steel Sections, Plates and Commercial Steels.

Nine experiments were made to examine the effect of:

- changing the fire load density from 20 40kg/m^2
- varying the size and shape of the ventilation opening in one wall including a simulation of a poorly ventilated basement. Ventilation areas were 100, 50, 25 and 12.5 per cent of one of the 6m by 3m walls
- changing the thermal properties of the walls and ceiling in one test
- changing the size of compartment in one test
- simultaneous ignition of all 33 cribs compared with ignition of three cribs at the rear of the compartment followed by natural fire spread to the others

The concrete walls and roof of the compartment were lined internally with a 50mm layer of highly insulating ceramic fibre so that (a) the compartment would survive repeated tests (b) the thermal properties of the walls and ceiling would not change from

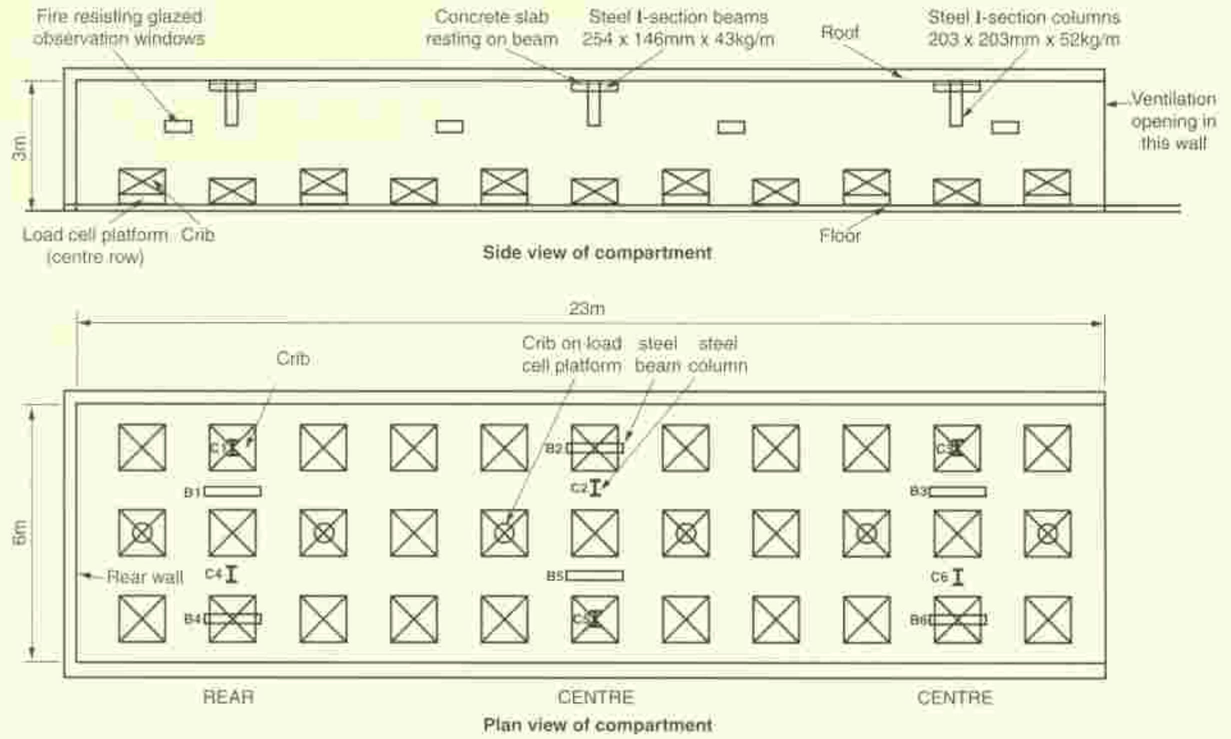


Figure 7. Details of test rig, crib fire load and steel work

test to test and (c) the assumption of near-zero heat flow through the walls was valid. The concrete floor was insulated with 100 mm thick layer of dry sand. Apart from one test the fire load was in the form of 33 cribs each 1m square made from 50mm square kiln-dried Hemlock (a low grade softwood) sticks having a moisture content of 8-10 per cent by weight. The cribs were arranged in 11 rows of 3, figure 7.

Each crib was spaced 1m from its neighbour. Six of the cribs in the central row were supported on load cell platforms so that weight loss could be measured. Twelve thermocoupled 1m long sections of unprotected and protected steel I-sections were suspended below the ceiling so that temperature data could be collected and compared with the temperatures attained by identical sections exposed in the standard fire resistance test. Six were 254 × 146 × 43 kg/m universal beam sections and six were 203 × 203 × 52 kg/m universal column sections. Their positions are shown in figure 7 .

In most of the tests three of the steel beams (B1 .B2 and B3) were protected with 20 mm thick vermiculite board. and three of the steel columns (C1, C2 and C3)were protected with 30 mm vermiculite board ; the other steel beams and columns were intended to be left unprotected but it was clear as the tests progressed that the temperatures attained were too high to be useful and so some of the sections were protected. The report prepared by British Steel Technical (BST)[3] provides data of combustion gas temperatures, steel temperatures and gives the measured and predicted time equivalents for the range of fire load density and ventilation openings used. Other measurements were made by FRS and included combustion gas temperatures, velocity of air flowing in and hot gases out of the compartment, radiation intensity inside and outside the compartment, crib mass loss, and temperatures of flames/hot gases emerging from the opening.[4]

In these tests, except in one test in which all 33 cribs were simultaneously ignited, the row of three cribs at the rear of the 23m deep compartment were 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 flames and hot gases under the ceiling and radiation from the vertical face of the neighboring 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 appeared to stop (from observations made through the fire resisting glazed windows) because the cribs at the front were consuming most of the inflowing air needed for combustion. Full depth burning of each row of cribs thus proceeded from the front to the rear of the compartment. The same phenomenon occurred when all 33 cribs were ignited simultaneously, and this suggests that the mode of combustion of the cribs after flashover (i.e. burning from front to rear) is independent of the numbers and locations of the cribs first ignited. This mode of combustion is reflected in the combustion gas temperatures measured near the front and rear of the compartment and may help to explain the variations of time equivalent. Such data are shown in figures 8 and 9 for ventilation openings of 25 and 12.5 per cent respectively.

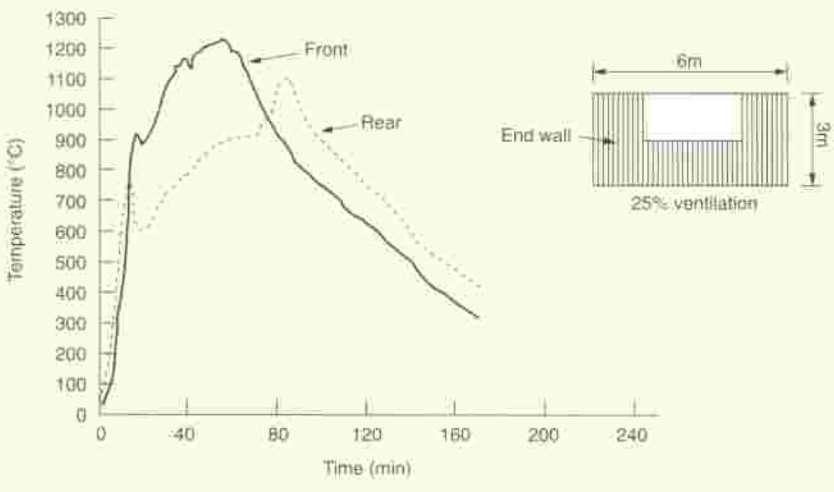


Figure 8. Combustion gas temperature-time profiles

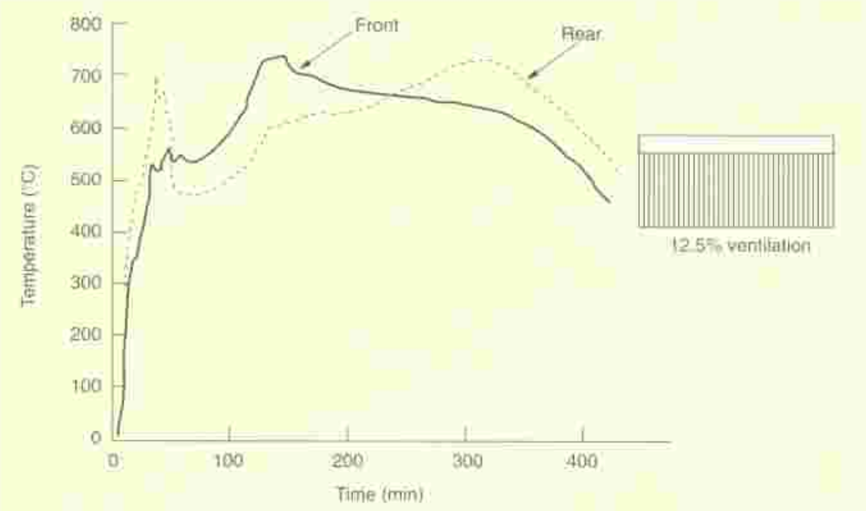


Figure 9. Combustion gas temperature-time profiles

Variation of time equivalent

Here we look at measured individual and average time equivalents for five of the nine tests in which the fire load was constant at 20 kg/m^2, the compartment depth was kept at 23m, the insulation of the compartment enclosure was kept the same but the ventilation varied from 100 to 12.5 per cent of the front wall, as shown in table 1.

The data we shall now examine relate to protected beam or protected column sections. The data are taken from the BST report.[3] The individual time equivalent is defined as the time equivalent for one of the three specimens i.e. a specimen which may be at the rear, or at the centre, or at the front of the compartment. The average time equivalent is defined as the average of the time equivalents for the three beam specimens or the three column specimens.

The way in which the average time equivalents for the protected beam and column sections vary in the growing fires is shown in figure 10. In this comparison the three beams and three columns are protected with 20 mm and 30 mm vermiculite board respectively. This shows that (a) time equivalent increases with a decrease of ventilation - a relation well known from earlier test results but worth mentioning here - and (b) the average time equivalents for the beams and columns are reasonably close, as we might expect them to be.

A comparison of average time equivalents for the two modes of ignition is given in table 2. This shows that the average time equivalent is only slightly affected by the mode of crib ignition.

Figure 11 shows the way in which the three individual time equivalents for the beam specimens vary in the growing fires and how these differ from the average time equivalent. In each test nominal differences of 15 minutes were observed in individual time equivalents and this was so for all four tests. In the tests with 100 per cent and 50 per cent ventilation the largest time equivalent was measured at the centre of the compartment. In the tests with 25 per cent and 12.5 per cent ventilation the individual time equivalents were maximum at the front and rear respectively, and the reasons for the reversal are not immediately obvious.

In two of the tests (tests 4 and 5) we have the opportunity to compare the time equivalents for protected columns C3 and C6 and an unprotected beam B6, all situated at the front of the compartment and therefore exposed to the same fire environment, Table 3.

In both tests the time equivalent varied greatly for the members considered and this suggests that time equivalent depends on the thermal response of the member whereas it should be independent if it is to be a true measure of fire severity. Additionally the maximum temperatures attained by the unprotected steel beams and columns in tests 1, 2, 3, and 5 indicate time equivalents of between two to four hours assuming that in the furnace tests the unprotected steel would attain the combustion gas temperature. Even using this conservative assumption the unprotected steel beams at the centre and rear, B4 and B5, in test 5 had time equivalents greater than four hours.

General remarks

The measured time equivalent appears to depend on the construction being heated. In the large compartment tests reported here the measured time equivalents used to validate calculated values were determined using protected steel members. Using temperature data for the unprotected steel members generally gave far greater measured time

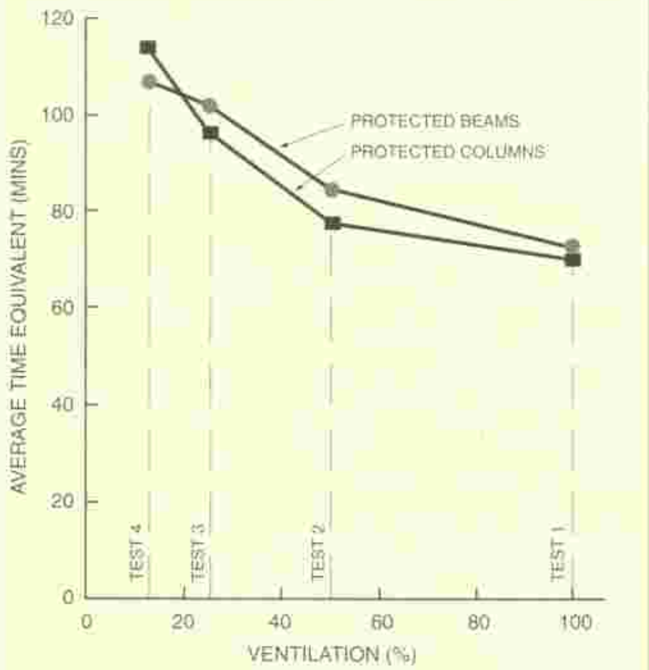


Figure 10. Variation of time equivalent with ventilation

Test number	1	2	3	4	5
Ventilation per cent	100	50	25	12.5	100
Crib ignition	G	G	G	G	S

Note: G = growing fire i.e. 3 cribs ignited at the rear; S = simultaneous ignition of 33 cribs

Table 1. Test parameters

	Test 1 (3 cribs ignited)	Test 5 (33 cribs ignited)
Average time equivalent for protected beams, min	72.3	78
Average time equivalent for protected columns, min	70.6	69.8

Table 2. Effect of mode of ignition

	Time equivalent, min		
	Nil protection Beam B6 at front	30 mm protection Column C3 at front	70 mm protection Column C6 at front
Test 4	32	108	195
Test 5	>120 approx.	61	122

Table 3. Effect of protection thickness

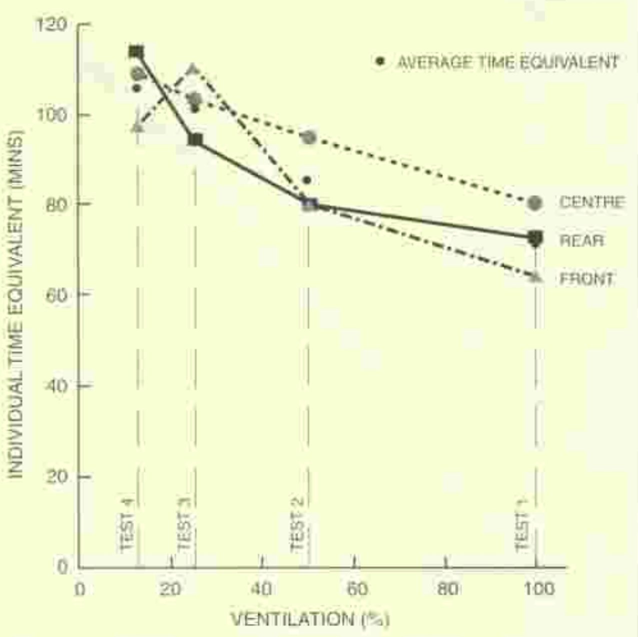


Figure 11. Individual time equivalents for protected beams

equivalents. In two tests the time equivalent doubled when increasing the protection thickness, table 3. To be a true measure of fire severity the time equivalent should be independent of protection thickness.

The large compartment tests have shown, Figure 11, that the individual time equivalents for identical protected steel beams at the front, centre and rear of the compartment can vary by 15 minutes. This is a large variation, e.g. 20 per cent in the test using 100 per cent ventilation.

The use of the average measured time equivalent for validating calculations will lead to underestimates of time equivalent - the difference between the average and maximum values of time equivalent in these tests were as much as ten minutes in the test using 50 per cent ventilation, and more than 5 minutes in the other tests, figure 11.

The time equivalent increases as the ventilation area reduces, figure 10, and the fire duration increases (compare figures 8 and 9). While the tests do not show the amount of ventilation needed to produce the maximum time equivalent, i.e. maximum fire severity, we may surmise that it will be nearer 10 per cent than 0 per cent since with zero ventilation the fire will be starved of oxygen and would never reach flashover.

The test using a ventilation opening of 12.5 per cent, achieved using a horizontal slit at the top of the wall, is probably typical of a fire in a basement of a building where the compartment has little ventilation perhaps in the form of broken pavement lights. After six hours the combustion gas temperatures had only dropped to approximately 500°C, figure 9, and this confirms anecdotal evidence from fire fighters of long duration, hot fires in basements.

The time equivalents presented here are for fires that spread in one direction i.e. from front to back of the compartment. If the test compartment had been as wide as it was deep, i.e. 20m square, and if there had been equal ventilation openings in two adjacent walls, we might expect that a fire ignited in the corner of the compartment furthest away from the window walls would spread in two directions, and the effect of this on the variation and magnitude of time equivalent is a matter of conjecture.

The load ratio needs to be considered in making the connection between equivalent time and fire resistance. This has implications for the interpretation of the calculated time equivalent which yields only a time.

In this article fire severity within the compartment has been considered. The severity of fire outside a compartment (as a result of a fire within) is different and is characterised by different parameters such as flame trajectory, flame length and emmissivity , and temperature of the flame or hot gases. The calculation of time equivalent is empirically based and cannot be used to say anything about the severity of a fire outside the compartment and this is reflected in the calculation methods which are fundamentally different.

REFERENCES

1. Butcher E G and Law Margaret. Comparison between furnace tests and experimental fires, Paper 4. Symposium No 2. Behaviour of structural steel in fire, London, 1968, HMSO.
2. Cooke G M E. A review of compartment fire tests to explore the behaviour of structural steel. Fire, static and dynamic tests of building structures, pub E & F N Spon, London, 1997, pp17-32
3. Kirby BR et al. Natural fires in large scale compartments - A British Steel Technical and Fire Research Station collaborative project, British Steel Technical, Swinden Laboratories, June 1994.
4. Cooke G M E. Tests to determine the behaviour of fully developed natural fires in a large compartment. Fire Note 4, Building Research Establishment, February 1998