A Review of Formulae for T-Equivalent

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ABSTRACT

Formulae for t-equivalent, from Ingberg to Eurocode 1, are reviewed and compared with experimental data for compartment fires. Results for some deep compartment fires suggest that current heat balance models may need re-assessment. It is suggested that t-equivalent is not a useful parameter for design purposes.

KEYWORDS: t-equivalent, compartment fires, fire resistance.

NOTATION

A_F	Floor area	m^2
A_h	Area of horizontal opening	m^2
A_t	Surface area of internal enclosure	m^2
A_v	Area of vertical opening	m^2
b_v	$12.5 (1 + 10\,\alpha_v - \alpha_v^2)$	-
C	thermal capacity of steel element	kJ/K
c	specific heat capacity	kJ/kgK
D	depth of compartment	m
H	compartment height	m
H_N	normalised heat load	$s^{1/2}K$
h	height of vertical opening	m
K	thermal conductivity	kW/m.K
k_f, k_b	factors to take into account insulation of compartment	-
L	fire load expressed in weight of wood	kg
L"	L/A_F	kg/m^2
R	thermal resistance of protective material	K/kW
t_{max}	time in compartment fire when steel element reaches maximum temperature	min
w_f	ventilation factor	$m^{-1/2}$
q_t	fire load expressed in calorific value divided by A_t	MJ/m^2
α_h	A_h/A_F	-
α_v	A_v/A_F	-
δ	the lesser of $0.41\,(H^3/A_v\sqrt{h})^{1/2}$ or 1	-
θ_s	steel temperature	K
θ_f	fire temperature	K

INTRODUCTION

The term t-equivalent is usually taken to be the exposure time in the standard fire resistance test which gives the same heating effect on a structure as a given compartment fire. The compartment fire is characterised by such features as fire load, ventilation and compartment dimensions.

The first person to propose an engineering relationship was Ingberg [1] and the most recent development is given in the Eurocode for Actions [2].

DESCRIPTION OF FORMULAE

Ingberg started fires in rooms with office furniture and allowed all the fire load to burn out, with the ventilation adjusted to give the most severe result. He then compared the areas under the temperature-time curves with areas under the standard temperature-time curve above a threshold temperature. The following relationship was developed:

$$t_e = k_1 L'' \tag{1}$$

where t_e is t-equivalent (min), L'' is fire load (wood) per unit floor area and $k_1 \approx$ unity when L'' is in units of kg m^{-2}. Ingberg's pioneering work has been used as the basis of most fire grading requirements worldwide.

Kawagoe and his colleagues in Japan [3] identified the importance of the ventilation parameter $A_t/A_v\sqrt{h}$ when performing a heat balance to determine temperature, where A_t is the area of the internal envelope (walls, floor, ceiling) , A_v is the area and h is the height of the ventilation opening (window or doorway). They also derived values of t-equivalent by comparing areas under their calculated temperature time curves (assuming a burn out) with area under the standard curve also above a threshold temperature. The values were proportional to L" and were weakly dependent on the ventilation parameter. The following relationship can be derived from their paper:

$$t_e = k_2 L'' (A_t / A_v \sqrt{h})^{0.23} \tag{2}$$

where k_2 is 1. 06 and $5 \leq At/Av\sqrt{h} \leq 30$ (m$^{-½}$).

Work in the UK [4] showed the significance of fire load per unit ventilation area, L/A_v, where L is the fire load in kg of wood. Law [5] then developed a t-equivalent from the results of a CIB experimental research programme of wood crib fires, allowed to burn out, in model compartments 0.5m, 1.0m and 1.5m high [6]. The maximum temperature which would be attained by a protected steel element was chosen for comparison with the heating effect of the standard fire. See Appendix for method. The values of t_e were found to be independent of scale and height of ventilation opening. The best correlation was obtained from the product of (L/A_v) and a term taking into account A_v and the solid surfaces to which heat is lost:

$$t_e = k_3 L'' A_F / [A_v(A_t - A_F - A_v)]^{1/2} \tag{3}$$

where A_F is floor area of compartment (m²). In this correlation, A_F was not included in the evaluation of solid surfaces because the floors were very well insulated. In all the experiments the openings were full compartment height. Law then analysed temperature-time curves for a number of burn-out fires in larger scale brick and concrete compartments (approximately 3m high) [7] and developed:

$$t_e = k_4 L'' A_F / [A_v(A_t - A_v)]^{1/2} \tag{4}$$

where k_4 is 1.0. In this correlation, the floor areas were included in the evaluation of solid surfaces. These data also showed no significant effect of h on t_e.

Magnusson and Thelandersson [8] developed a method to calculate the temperature-time curve of a burn-out compartment fire, with input parameters of an 'opening factor' $A_v\sqrt{h}/A_t$ ($m^{1/2}$) and the fuel load per unit internal envelope area q_t (MJ/m^2). Assuming a calorific value of 18MJ/kg for wood:

$$q_t = 18L''A_F/A_t \tag{5}$$

For ease of comparison, a conversion from MJ to kg of wood will be used in this review. (The data were originally obtained from wood crib fires). The Magnusson and Thelandersson calculations were for a 'standard' brick or concrete compartment. For compartment boundaries with different thermal properties, the input parameters can be multiplied by a factor k_f which ranges from 0.5 (poorly insulated) to 3.0 (well insulated) with 'standard' compartments taking the value 1.0 [9]. Pettersson [10] then adopted the Law approach to t_e but instead of experimental curves, used the family of calculated temperature~time curves for standard compartments to derive:

$$t_e = 1.21L''A_F/(A_v\sqrt{h}A_t)^{1/2} \tag{6}$$

Equation (6) is similar to equation (4) but includes $\sqrt{h}$ because of the input parameters in the method for calculating temperature-time curves. Equation (6) can be modified to take into account the thermal properties of the compartment enclosure by applying the factor k_f to each input parameter. This yields:

$$t_e = 1.21k_f^{1/2}L''A_F/(A_v\sqrt{h}.A_t)^{1/2} \tag{7}$$

Harmathy and Mehaffey [11] developed a normalised heat load H_N ($s^{1/2}K$), for total heat penetrating the compartment boundaries, taking into account $A_v\sqrt{h}$ and the proportion of heat evolution in the compartment, δ. Their purpose was to characterise the potential for fire spread (failure of fire resistance). Based on the results of many experiments, and tests in the DBR/NRC floor test furnace, they give the following relationship for t_e and concrete elements:

$$t_e = 6.6 + 9.6 \times 10^{-4}H_N + 7.8 \times 10^{-9}H_N^2 \quad \text{for} \quad 0 < H_N < 9 \times 10^4 \tag{8}$$

$$\text{where} \quad H_N = 10^6(11.0\delta + 1.6)L''A_F/[A_t(K\rho c)^{1/2} + 1810(A_v\sqrt{h}.L''A_F)^{1/2}] \tag{9}$$

$$\delta = 0.41(H^3/A_v\sqrt{h})^{1/2} \text{ or } 1, \textit{whichever is the less} \tag{10}$$

and H is compartment height (m). $(K\ \rho\ c)^{1/2}$ is the thermal inertia of the compartment boundaries where K, ρ, and c are respectively thermal conductivity, density and specific heat. For concrete, the thermal inertia is 2190 ($Jm^{-2}s^{-1/2}K^{-1}$). Equation (8) is given approximately by:

$$t_e = 0.0016H_N \quad \text{for} \quad H_n \leq 9 \times 10^4 \tag{11}$$

Eurocode 1 [2] for Actions gives the following:

$$t_e = k_b q_t(A_t/A_F)(6.0/H)^{0.3}[0.62 + 90(0.4 - \alpha_v)^4/(1 + b_v\alpha_h)]z \tag{12}$$

where α_v is A_v/A_F, α_h is A_h/A_F, A_h is area of horizontal openings in the roof (m^2), b_v is $12.5(1 + 10\alpha_v - \alpha_v^2)$, k_b depends on the thermal properties of the enclosure and $(6.0/H)[0.62 + 90(0.4 - \alpha_v)^4/(1 + b_v\alpha_h] > 0.5$, $b_v \geq 10.0$, $0.025 \leq \alpha_v \leq 0.25$. This equation is based on work by Schneider et al [12,13]. The element of structure chosen for comparison is a reinforced concrete slab. The calculations of fire behaviour, based on a heat balance, were made using the MRFC (Multi-Room-Fire-Code) computer program developed at the University of Kassel.

For $\alpha_h = 0$, i.e. no horizontal openings, and $k_b = 0.07$, equation (12) may be written:

$$t_e = 1.26 L'' w_f \qquad (13)$$

where w_f is $(6.0/H)^{0.3}$ $[0.62 + 90 (0.4 - A_v/A_F)^4]$.

For $A_F < 100$ m² the following is also given:

$$t_e = k_b q_t (A_v \sqrt{h} / A_t)^{-1/2} \qquad (14)$$

where $0.02 \leq A_v\sqrt{h}/A_t \leq 0.20$. The value of k_b ranges from 0.04 to 0.07 and where no detailed assessment is made a value of 0.07 is recommended. Equation (14) is then virtually the same as the Pettersson equation (6).

EXPERIMENTAL DATA COMPARED WITH FORMULAE

Experimental

The various formulae will now be compared with experimental data from post flashover fires in "full-scale" compartments. Most of the test compartments have been the size of a small room - less than 30 m² in area and some 2.5 to 3m in height. They have had one or more vertical openings but no horizontal ones. The boundary enclosures have normally been brick and/or concrete, occasionally with an internal layer of insulating material. Accordingly these test rooms are described in this review as 'small standard compartments'. Some recent experiments have been carried out in a larger and deeper room, 128 m² in area, with a depth to width ratio of 4:1 and with very well insulated internal surfaces, with one small test room for comparison [14]. Accordingly these test rooms are referred to in this review as a 'deep insulated compartment' or 'small insulated compartment'. The main features of these test rooms are listed in Table 1.

TABLE 1. Main features of well insulated compartments and calculated t-equivalents

Test	H	D	A_F	A_v	h	L"	t_e
1	2.75	22.9	128	15.4	2.75	40	106
2				15.4	2.75	20	55
3				7.7	1.47	20	76
4				7.7	1.47	40	155
5				3.7	1.73	20	113
6				1.95	0.375	20	172
8*				14.4	2.68	20.6	62
9				14.5	2.75	20	61
7+	2.75	5.6	32	3.75	2.75	20	39

* Plasterboard lining added internally
\+ A_v/A_F chosen to be the same as in Test 2

Not many of the experiments included sample test elements for direct comparison with the results of standard fire resistance tests. Accordingly the values of t_e for all the experiments have been derived from the temperature-time curves within the compartments using the procedure adopted by Law as described in the Appendix.

The calculation procedure assumes an efficient furnace, thereby avoiding test house bias, an aspect discussed later. The curves for the small compartments are usually assumed to be representative of a uniform temperature distribution but the assumption of uniformity is known to be more unrealistic for large compartments. This is demonstrated by the results of the deep compartment tests, where the fires burnt progressively from front to back after flashover, regardless of where the ignition source was located. Although the temperature-time curves given for three locations - near the open end (front) at the middle and towards the rear of the deep compartment (back) - were similar in any one test they were displaced in time. Thus, failure would occur first near the ventilation opening, and these are the values of t_e given in Table 1. However, as Table 2 shows, the values of t_e are not sensitive to the locations. The time to reach the maximum steel temperature at the back is about 15% greater than the time at the front.

TABLE 2. Calculated t-equivalent from temperature-time curves reported for the well insulated compartments

Test	t_e - min			t_{max}	Time lag (front to back)
	Front	Middle	Back	min	
1	106	116	109	110	20
2	55	63	61	65	10
3	76	83	78	100	10
4	155	158	151	170	20
5	113	116	104	140	25
6	172	190	194	400	50
8	62	70	61	110	15
9	61	75	70	65	15
7	39	-	-	35	-

Correlation of Data

Figure 1 shows t_e plotted against L". The Ingberg equation (1) is a reasonable average for the small compartment results but there is considerable scatter. The formula is not satisfactory for the deep compartment data.

Figure 2 illustrates that equation (2), derived from Kawagoe and Sekine, is very conservative for small compartments and does not remove much scatter. It is not satisfactory for the deep compartment.

Figure 3 illustrates that the Law equation (4) removes much of the scatter, but a higher value of the slope, 1.75, is needed to correlate the deep compartment results.

Figure 4 illustrates that the Pettersson equation (7) also removes much of the scatter. To correlate the deep compartment results, a curve appears more appropriate than a straight line. This curvature is caused by the incorporation of $\sqrt{h}$ in the formula, an aspect discussed later.

Figure 5 illustrates that the Harmathy and Mehaffey equation (11) gives a reasonable correlation for the small compartment results. As with the earlier formulae, the results for the deep compartment need a line of greater slope, of about 0.0049.

FIG 1: INGBERG CORRELATION

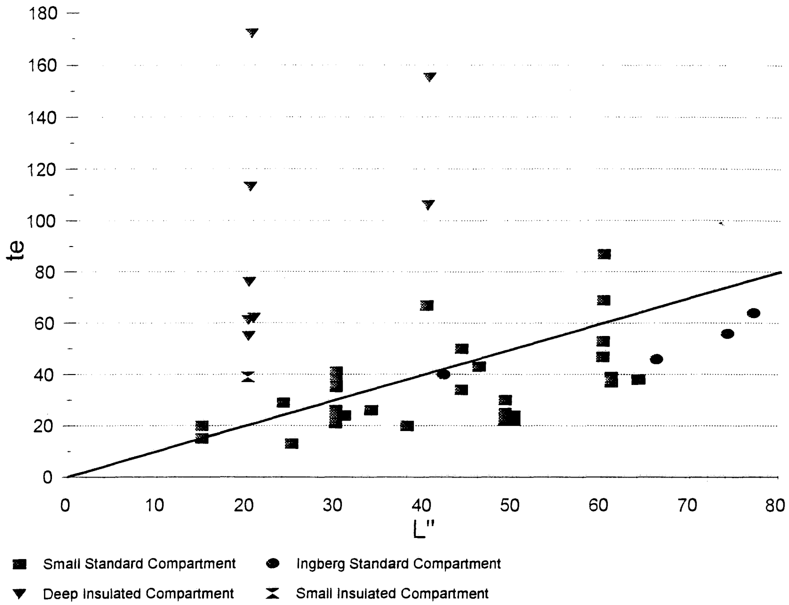


FIG 2: KAWAGOE & SEKINE CORRELATION

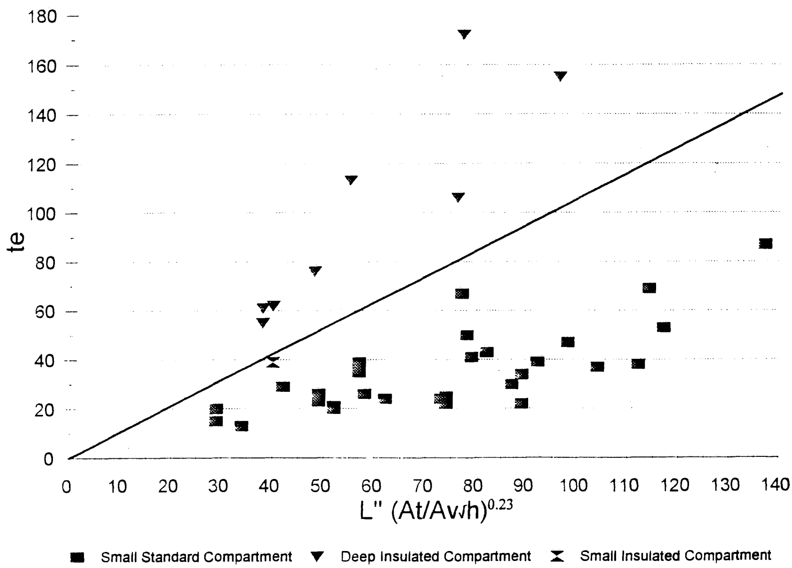


FIG 3: LAW CORRELATION

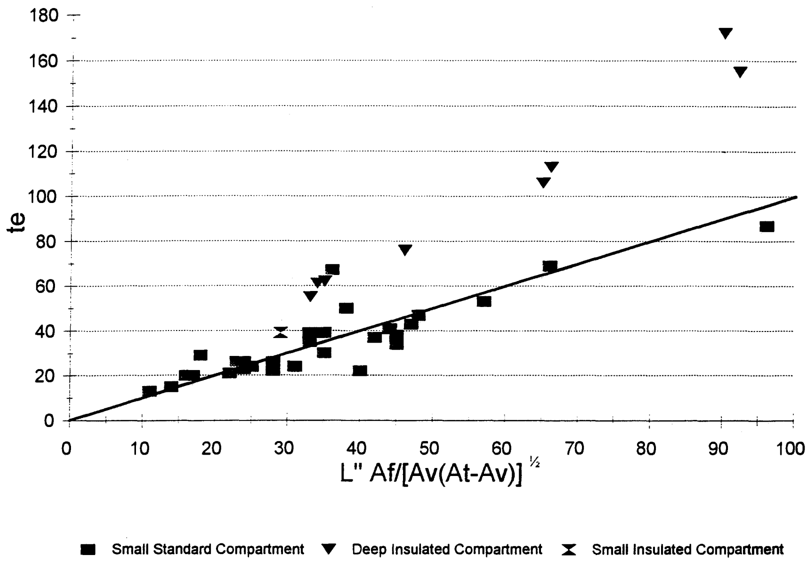


FIG 4: PETTERSSON CORRELATION

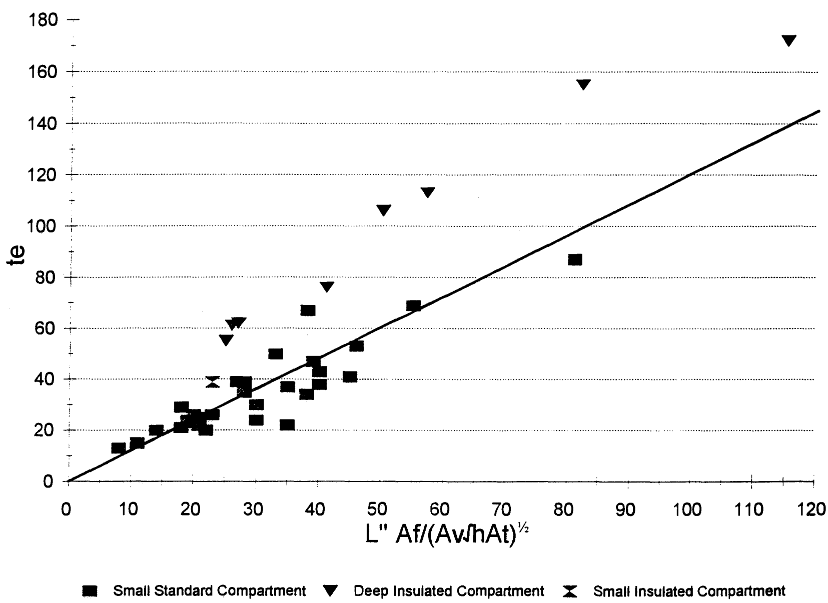
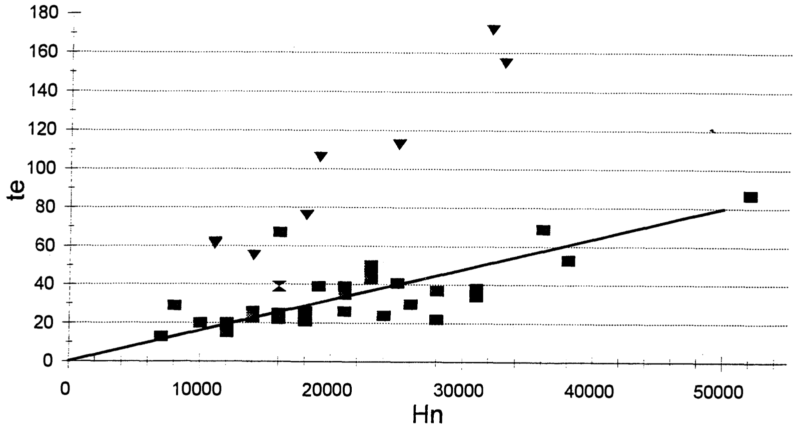
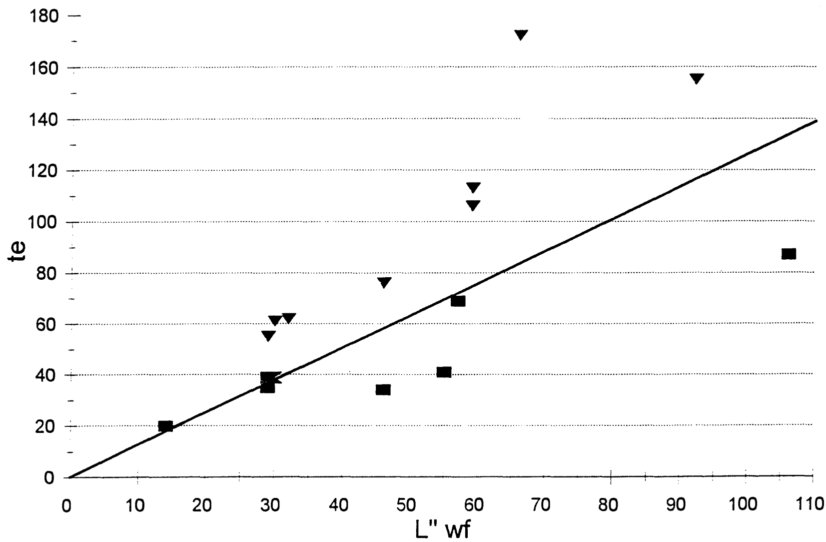


FIG 5: HARMATHY & MEHAFFEY CORRELATION



■ Small Standard Compartment ▼ Deep Insulated Compartment ⧗ Small Insulated Compartment

FIG 6: EUROCODE CORRELATION



■ Small Standard Compartment ▼ Deep Insulated Compartment ⧗ Small Insulated Compartment

Figure (6) illustrates that the Eurocode equation (13), for compartments without horizontal openings, does not give a satisfactory correlation of the results for either small or deep compartments. A straight line correlation does not appear very satisfactory for either set of data. It should be noted that results have not been plotted for those small compartments where A_v/A_F exceeds 0.25, because that is outside the limits of applicability of equation (13).

Of the six correlations described above, the more promising ones are Law, Pettersson and Harmathy and Mehaffey, the third giving an explicit recognition of $(K\rho c)^{1/2}$. However, it is necessary to examine further the deep compartment results.

DEEP WELL-INSULATED COMPARTMENT DATA

Effect of Variables

A regression analysis of the log values of t_e, L'', A_v and h (A_F, A_t and H being constant) shows that L'' and A_v are significant at better than the 0.1% level but h is not significant at the 20% level. The absence of significant h effect was noted by Law in the earlier analysis and appears to be confirmed here. The regressions obtained are:

$$t_e = 14.4(L'')^{0.93}/(A_v)^{0.52} \tag{15}$$

$$t_e/L'' = 11.7/(A_v)^{0.53} \tag{16}$$

The importance of L'' and $\sqrt{A_v}$ are clearly established for these data, as they have been for the small compartments. As the relationships are empirical, there is no obvious theoretical explanation for the lack of h effect. A heat balance study may give an explanation.

Effects of Insulation

We note that if we adopt the value 3 for k_f (well insulated compartments), then in Equation (7) the slope for Pettersson would be $1.21 \times \sqrt{3} = 2.1$ and the slope for Law would be $\sqrt{3} = 1.7$. Such lines would be close to the deep compartment data. However, before leaping to the conclusion that the higher values of t_e for the deep compartment can be attributed to the greater insulation, we should note that the small well-insulated compartment result appears to belong to the small *standard* compartment family. This is consistent with earlier work. Thomas and Heselden found that the fire was not very sensitive to changes in the conductance of the wall (conductance = thermal conductivity/wall thickness). A change of 100% in conductance gave about 5% change in fire temperature and 17% in rate of burning [6]. Heselden [15] carried out a heat balance for a small compartment and found that a mineral wool lining resulted in only slightly higher temperatures than when the surfaces were vermiculite plaster and refractory concrete. He points out though, that the proportion of the heat transferred to the walls, ceiling and floor was not more than 30% of the heat released, even with the less well insulated compartment. Law's values of t_e for small compartments [7] included a few for well insulated walls which gave results not dissimilar from the standard walls. If the $k_f = 3$ value is applied to A_t in the Harmathy and Mehaffey formula, we get some, but not sufficient improvement in slope, which again suggests that insulation is not necessarily the important effect. Finally, we may note that in Test 8 a plasterboard lining was added to the walls and ceiling. Some plasterboard panels on the ceiling opened, exposing timber studding and thereby increasing the fire load (from 20 to 20.6kg/m^2), but the wall panels remained intact for most of the test. This change in $(K\rho c)^{1/2}$, by a factor 10, made no significant difference to t_e, as can be seen by comparing the values for Tests 8 with those for Tests 2 and 9. However, the fire development was much slower in Test 8, an effect attributed by *Kirby et al* to the generation of copious amounts of water vapour. Accordingly the time taken to reach the critical temperature was about 45 minutes longer.

Effect of Location

The values of t_e calculated at the different locations, and shown in Table 2, indicate that the location has little effect on the value of t_e but affects the time at which the maximum steel temperature is attained.

Comparison with Furnace Test Data

Kirby et al reported values of t-equivalent using measured temperatures of protected steel elements in the well insulated compartments to compare with the results of standard fire tests. It would be expected that test furnaces tend to give larger values of t_e than an efficient furnace. Harmathy and Mehaffey estimated that the NRC/DBR furnace gave values nearly 10% greater. Table 3 shows the values derived from the test elements at the front of the well insulated compartments.

Table 3. Experimental values of t_e for protected elements at the front of the well insulated compartments. The calculated value of t_e from Table 1 also shown

Test	Thickness of Vicuclad (mm)			Calculated t_e
	20 Beam	30 Column	70 Column	
1	-	121	-	106
2	64	61	-	55
3	80	78	-	76
4	168	132	-	155
5	110	102	-	113
6	97	108	195	172
8	62	64	130	62
9	68	61	122	61
7	54,55	54,55	-	39

For most of the tests there is reasonable agreement between calculated and measured t_e. However, Tests 6, 8 and 9 show that the third sample element gives approximately double the value of t-equivalent derived from the other two. Kirby et al suggest that this might be attributed to the difference in maximum steel temperature, but it could not account for such a large discrepancy. Another possibility is an error in the standard test result used for comparison. A fourth sample element was installed for five of the tests, by another body collaborating in the experiments, but the results have not been published as yet (May 1996).

For Test 6 only there is a big difference between the calculated value of t_e and the results for the beam and the first column. The reason for this is not known. It is not expected that the calculated time would give larger values than the test elements. When the further data are published it may be possible to assess the reliability of the comparisons based on sample elements.

Discussion of the Deep Compartment Data

It appears that the depth of the compartment has an effect on t_e, over and above that which can be allowed for by the increases in insulation and in internal surface area A_t. Earlier work [6] has already shown that the ventilation controlled rate of burning is affected by the compartment depth to width ratio and some such effect on t_e appears to be important here.

THE FUTURE FOR T-EQUIVALENT

For the purposes of design, t-equivalent gives a general feel for the total heating effect of a fire but it does not differentiate between a short, hot fire and a longer, cooler fire with the same t_e. It is often important to know the temperature of the fire, in order to assess radiant heat transfer and the reaction of materials which are temperature sensitive. Fire engineers may wish to estimate the fire temperature and the fire duration separately. Such estimations will rely on performing a heat balance for the compartment. Earlier work has already demonstrated that the rate of burning can be affected by the depth of the compartment. The data yet to be published, by the collaborative body, for the deep compartment fires will assist a heat balance analysis.

CONCLUSIONS

None of the existing formulae give satisfactory correlations of t-equivalent for the experiments reported by Kirby et al for deep well-insulated compartments. The Eurocode formula is not satisfactory for small compartments either.The values of t_e for the deep compartments are strongly correlated with L'' and $A_v^{0.5}$ but h has no significant effect.The values of t_e for the deep compartments appear to be not sensitive to the insulation of the enclosure.There is an anomaly in the values of t_e derived from the sample elements and this should be explored further when all the test data are published.A heat balance should be carried out for the deep compartment fires when all the test data are published. Fire engineers may not find t-equivalent a useful parameter for design when it is important to assess fire temperature and fire duration. Such an assessment will need to take into account the heat balance yet to be performed for the deep compartment.

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APPENDIX

Calculation of t-equivalent from a temperature-time curve.

The maximum temperature obtained by a protected steel element in a compartment fire has been calculated using iterative procedures and the following equation:

$$\frac{d\theta_s}{dt} = \frac{\theta_f - \theta_s}{RC}$$

where θ_s is steel temperature, t is time, θ_f is fire temperature. R is the thermal resistance of the protective material, C is the thermal capacity of the steel, and the temperature of the heated surface of the protective material is assumed to be the same as the fire temperature. For a given fire temperature-time curve, a value of *RC* has been deduced which gives a maximum value of 550°C for θ_s. The time to attain 550°C with the standard temperature-time curve and this value of RC, gives the value of t-equivalent. The comparison is not sensitive to the value of maximumθ_s chosen for comparison, within the range 400-600°C. Some calculations of diffusion of heat through concrete have yielded similar values of t-equivalent [7].