A New T-equivalent Method for Fire Rated Wall Constructions using Cumulative Radiation Energy

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ABSTRACT: Recent tests have shown that some wall and door constructions, when exposed to temperature conditions greater than those used for the standard ISO 834 test, fail in lesser time than their standard time rating. The premature failures that occur have been known for some time but specific tests have been conducted only recently to demonstrate the facts. It has been widely-accepted since the late 1970s that the predominant mode of heat transfer in a fire compartment is by radiation rather than convection. Analysis of the specific tests mentioned above demonstrates the benefit of using cumulative radiation energy (CRE) as a prediction method for wooden doors and drywall construction. This article demonstrates how the CRE prediction method can also be applied to other values of thermal inertia such as those that occur in constructions using concrete or steel.

KEY WORDS: equivalent time, fire rating, radiation, cumulative radiation.

INTRODUCTION

EQUIVALENT TIME WAS originally developed for structural steel members by Margaret Law in 1971 [1,2] and was defined more or less as 'the time taken in a real fire for a protected steel member to reach the same temperature as in a standard exposure fire test'. The concept has also been extended to concrete members [3]. The New Zealand Building Industry Authority [4] adopted into its fire code two forms of 'equivalent time', namely the structural (S) rating and the firecell (F) rating.

In 1992, the New Zealand Building Code adopted the equivalent time concept from the 1991 Eurocode [5] and introduced it into its

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'Acceptable Solutions' as an S rating based on a thermal inertia value of 1160 J/($m^2s^{0.5}$K) and a conversion factor, k_b (Eurocode [5] Annex F) equal to 0.067 min m^2/MJ.

The S rating is intended to be an estimate of the burn-out time for a firecell before structural failure commences. The structural member must meet a standard ISO 834 test [6] equal to or greater than the S rating time. These times are published in tables in [7] and [8]. The F rating is intended to provide fire separations around firecells to allow the occupants to escape and firemen to enter the building for the purpose of rescue of occupants or limited fire fighting.

Following the research by Thomas in 1997 [4] on drywall construction, New Zealand increased its S ratings in 2001 by one-third, based on a thermal inertia value of zero; i.e., 0 J/($m^2s^{0.5}$K) and $k_b = 0.090$. This was considered to be a conservative step in that the published S rating tables covered the worst case situations, namely insulated or drywall constructions. S ratings lower than the figures published in these tables can be used for the types of constructions other than the drywall if the rating is determined by approved specific fire engineering design methods. This is generally done for concrete buildings or steel clad buildings in which the S ratings can be of the order of 65 and 45%, respectively, of the times published for drywall construction in the S rating tables. Further New Zealand research on drywall was carried out by Jones in 2001 [9].

Based on Babrauskas' work in 1974 [10] and further research on the subject by Nyman [11] in 2002 using full-scale fire tests, the New Zealand Building Industry Authority increased its F rating values to allow for premature failure of fire separations during fires that have a temperature curve greater than that of a standard ISO fire. For example, it was found that some construction, typically drywall construction, with a 30-min ISO tested rating failed in less than 20 min [11]. Joyeux [12] found a similar problem with wooden doors where a 30-min ISO rated door failed in 16 min.

New Zealand therefore adopted an 'equivalent time' method which compared the incident radiant flux in the case of a real fire with the incident radiant flux in a standard fire. The method compares the areas under the cumulative radiation curves for both the design fire exposure and ISO fire exposure. Instead of using the 'time to failure' (TTF) as if it had occurred under ISO conditions, it predicted the TTF under real fire conditions. From these predictions it was then possible to determine the required ISO time to meet the required TTF for a particular type of construction. The NZ Building Authority published its revised F ratings in October 2005 [8, Table 4.1]. (The NZ Building Industry Authority is now renamed as the Department of Building and Housing.)

In this article, the term 'high-temperature curve' means a time–temperature curve that is higher than an ISO time–temperature curve. Conversely, a 'low-temperature curve' refers to a curve that is lower than an ISO curve. In fully involved enclosure fires having the same fire load and openings, the time–temperature performance differs between the constructions which behave as 'thermally thick' or 'thermally thin'. For a 'thermally thick' behavior the inner surface temperature will increase rapidly to match the gas temperature, but starting from this point there will be a considerable delay in any heat conduction through the construction. In contrast, in a 'thermally thin' behavior the whole construction is rapidly heated up to the point where the temperature of the construction is determined by the amount of the radiation and convection losses from it to the exterior. These heat losses are generally of such magnitude that the time–temperature curve of an enclosure which exhibits a thermally thin behavior will be lower than for that which exhibits a thermally thick behavior. This in turn has a greater impact on the radiant energy received by the elements forming the enclosure and hence on the TTF of these elements.

Radiant heat transfer is a function of the absolute temperature T (K) raised to the fourth power. The severity of a fire can therefore be quantified by calculating the area under the radiation energy plot to obtain the cumulative radiation energy (CRE) to which the assembly is exposed, and can be expressed mathematically as:

$$\mathrm{CRE} = \int_0^t Q_{\mathrm{R}}\,\mathrm{d}t = \varepsilon\sigma \int_0^t \left(T^4\right)\mathrm{d}t \quad (\mathrm{J/m^2}) \tag{1}$$

where CRE is the cumulative radiation energy on the assembly over a time, t ($\mathrm{J/m^2}$); Q_{R}, incident radiant heat flux upon the assembly at any point in time ($\mathrm{W/m^2}$); ε, emissivity (conservatively taken as 1.00); σ, Stefan–Boltzmann constant ($5.67 \times 10^{-8}\,\mathrm{W/(m^2K^4)}$); t, time from the start of the test (s); and T, compartment gas temperature (K).

For convenience this quantification of fire severity has been termed as the Cumulative Radiation Energy Method or CRE Method. Table 1 sets out the CRE values for the standard ISO 834 time–temperature curve from 0 to 90 min based on an ambient temperature of 20°C. The ISO values are also shown in graphical form in Figures 1(b)–10(b) inclusive. If the CRE values for any given time can be determined for any other time–temperature curve, then the values can be compared directly with the ISO CRE values, thus enabling the equivalent ISO times for the other curve to be arrived at.

For a time–temperature curve with temperature values higher than the ISO curve and equal CRE values, the TTF will be less than the ISO time.

Table 1. Cumulative radiation energy values for ISO 834 curve.

Time (min)	Temp (°C)	CRE (MJ/m^2)	Time (min)	Temp (°C)	CRE (MJ/m^2)	Time (min)	Temp (°C)	CRE (MJ/m^2)
1	349	0	31	847	104	61	948	299
2	445	1	32	851	109	62	950	307
3	502	2	33	856	115	63	953	314
4	544	3	34	860	120	64	955	322
5	576	5	35	865	126	65	957	330
6	603	7	36	869	132	66	960	338
7	626	9	37	873	138	67	962	345
8	645	11	38	877	144	68	964	353
9	663	14	39	881	149	69	966	361
10	678	16	40	885	156	70	968	369
11	693	19	41	888	162	71	971	377
12	705	22	42	892	168	72	973	396
13	717	25	43	896	174	73	975	394
14	728	29	44	899	180	74	977	402
15	739	32	45	902	187	75	979	410
16	748	36	46	906	193	76	981	419
17	757	40	47	909	200	77	983	427
18	766	43	48	912	207	78	985	436
19	774	47	49	915	213	79	986	444
20	781	52	50	918	220	80	988	453
21	789	56	51	921	227	81	990	461
22	796	60	52	924	234	82	992	470
23	802	65	53	927	241	83	994	479
24	809	69	54	930	248	84	996	487
25	815	74	55	932	255	85	997	496
26	820	79	56	935	262	86	999	505
27	826	84	57	928	270	87	1001	514
28	832	89	58	940	277	88	1003	523
29	837	94	59	943	284	89	1004	532
30	842	99	60	945	292	90	1006	541

Similarly, for a time–temperature curve with temperature values lower than the ISO curve and equal CRE values, the TTF will be greater than the ISO time. This can be demonstrated by experimental fires. The CRE method can also be applied to design fires such as Eurocode [5,13] or BFD [14,15] design curves.

The standard ISO curve does not take into account the variations in the three factors, namely thermal inertia, opening factor, and fire load, whereas the design fire curves do. This variation has been demonstrated by Gerlich et al. [16] for three fire loads (400, 800, and 1200 MJ/m^2), six opening factors (0.02–0.10), and only one thermal inertia value of 700 J/(m^{2}s$^{0.5}$K).

EXPERIMENTAL FIRES

Joyeux in 1997 [12] carried out fire tests using high-temperature curves on a steel door and a wooden door. Figure 1(a) shows the experimental time–temperature results from the wooden door test. Figure 1(b) shows the corresponding CRE graphs. Under the ISO test conditions the door failed in 37 min and was therefore given the official ISO rating of 30 min. The actual failure time under the high-temperature fire exposure was 16 min. From Figure 1(b) it can be seen that for equal CRE values of 138 MJ/m^2 the ISO value of 37 min corresponds to a predicted failure time of 21 min. The CRE model therefore agrees to some extent with the test results. However, in addition to radiant energy from the furnace fire there is an added heat from the burning of the assembly itself. This combustible contribution may explain the difference in time between the 21 min predicted result and the 16 min test result for the wooden door assembly.

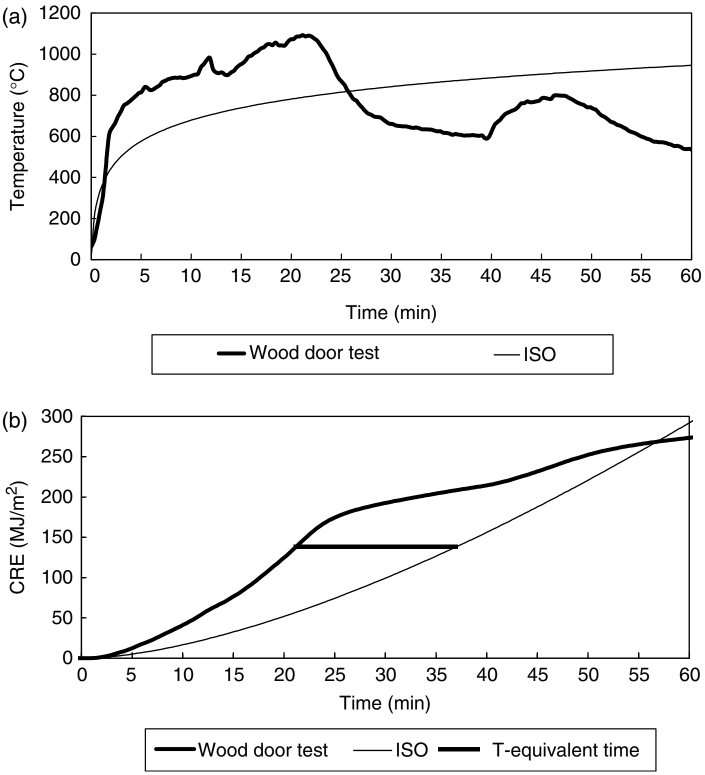

Figure 1. *Joyeux's wooden door test: (a) temperature vs time and (b) CRE vs time.*

Nyman in 2002 [11] carried out fire tests using high-temperature curves. Three tests were conducted outdoors using rooms set up on scales to measure the mass losses. The rooms were 2.4 m wide, 3.6 m deep, and 2.4 m high. Two tests were carried out with a 750-mm wide and 2000 mm high doorway using fire load energy densities of 800 and 1200 MJ/m^2, respectively. The third test was carried out with a fire load energy density of 800 MJ/m^2 but with a 1200 mm wide and 2000 mm high opening. Three wall assemblies were used in each test, and all had official ISO fire ratings. In Tests 1 and 2 the ISO rating was 30 min and in Test 3 the ISO fire rating was 60 min.

Figure 2 shows the results for one of the wall assemblies in Nyman Test 1. It can be seen that for equal CRE values of 99 MJ/m^2, the ISO value of 30 min corresponds to a predicted TTF of 17 min. In the test, the first wall assembly failed in 19 min. No fire tests were carried out using low-temperature curves or a fire load density of 400 MJ/m^2.

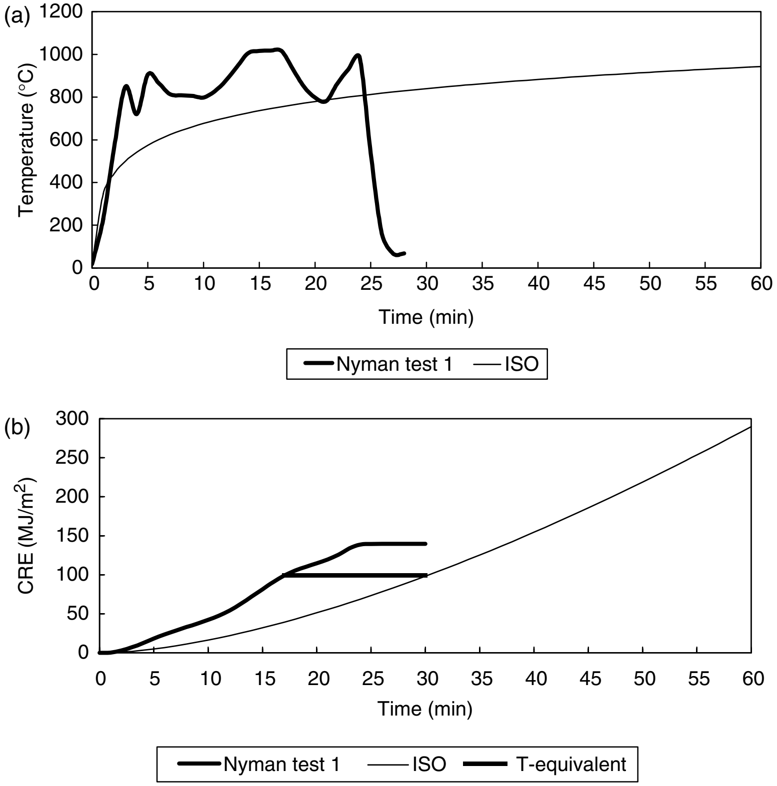

Figure 2. *Nymans's drywall Test No. 1: (a) temperature vs time and (b) CRE vs time.*

APPLICATION TO EUROCODE AND BFD FIRE CURVES

Figures 3 and 4 show the CRE method applied to Eurocode [13] curves for both high- and low-temperature fires.

Figures 5 and 6 show the CRE method applied to BFD [14] curves for both high- and low-temperature fires in uninsulated fire compartments.

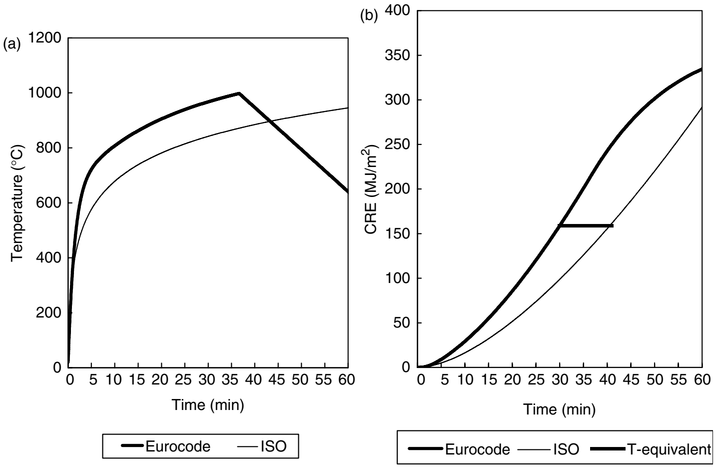

Figure 3. *High intensity Euro fire for which a TTF of 30 min corresponds to an ISO value of 41 min. Both have a CRE value of 159 MJ/m^2: (a) temperature vs time and (b) CRE vs time.*

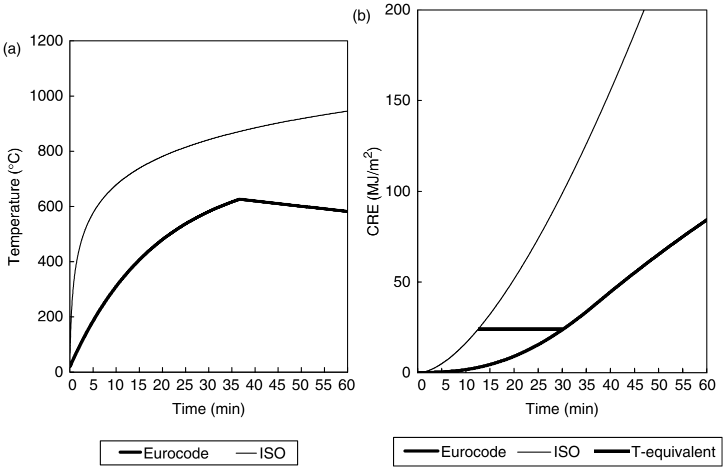

Figure 4. *Low intensity Euro fire for which a TTF of 30 min corresponds to an ISO value of 12 min. Both have a CRE value of 23 MJ/m^2: (a) temperature vs time and (b) CRE vs time.*

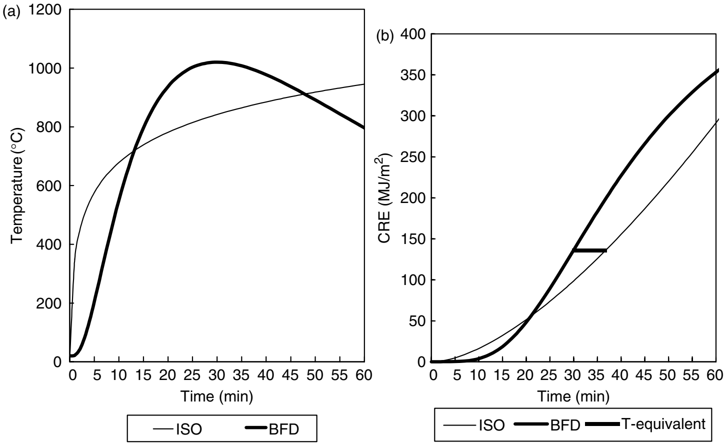

Figure 5. *High intensity BFD fire for which a TTF of 30 min corresponds to an ISO value of 37 min. Both have a CRE value of 136 MJ/m^2: (a) temperature vs time and (b) CRE vs time.*

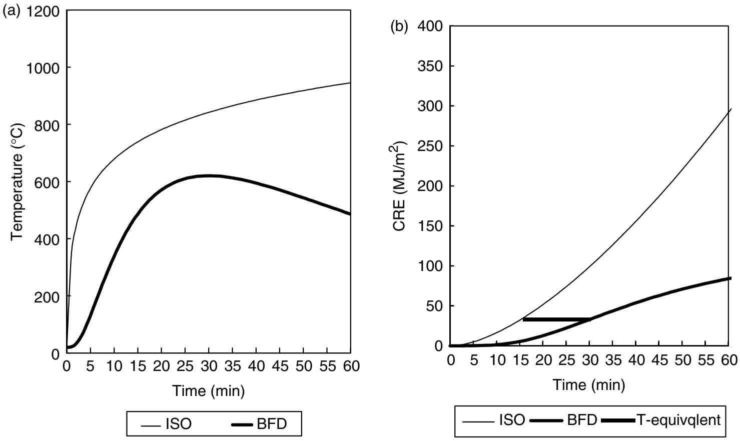

Figure 6. *Low intensity BFD fire for which a TTF of 30 min corresponds to an ISO value of 15 min. Both have a CRE value of 33 MJ/m^2: (a) temperature vs time and (b) CRE vs time.*

CASE STUDIES FOR WALL CONSTRUCTIONS

The following three examples are used to illustrate the fire separations required for an escape stair adjoining a 100-m^2 office building which has a fire load of 800 MJ/m^2 and an opening factor of 0.05. Examples A, B and C (see Figures 7, 8 and 9, respectively) compare the thermal inertia values of 700, 1600, and 2500 J/(m^{2}s$^{0.5}$K).

Case A – Thermal Inertia = 700 J/(m^{2}s$^{0.5}$K)

A thermal inertia value of 700 J/(m^{2}s$^{0.5}$K) would apply to a typical office building of two or more stories with timber framed walls and drywall construction. The Authorities require a fire separation having a TTF rating of 30 min between the stair shaft and the office space. The equivalent ISO value is 50 min.

- Time to failure = 30 min
- Cumulative radiation energy = 223 MJ/m^2
- T-equivalent ISO $\geq$ 50 min
- Rounded up ISO = 60 min

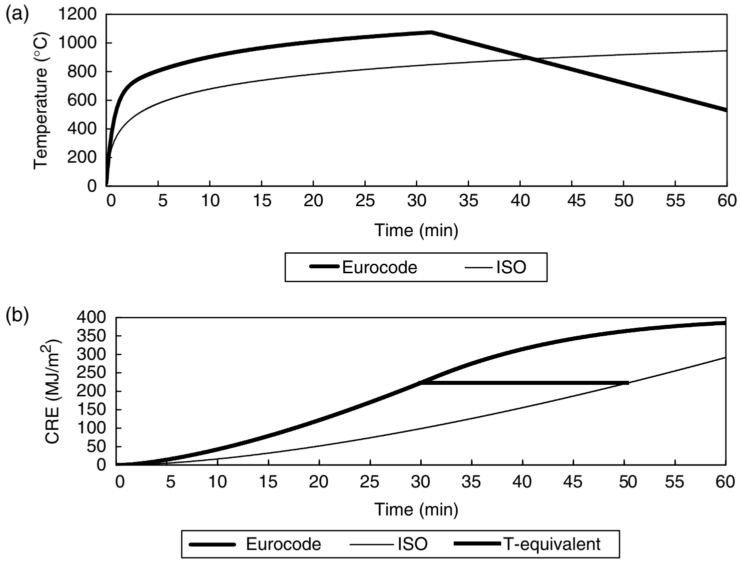

Figure 7. *Example of drywall construction (a) temperature vs time and (b) CRE vs time.*

Case B – Thermal Inertia = 1600 J/(m^{2}s$^{0.5}$K)

The following example has the same geometry and fire load as Case A but with a thermal inertia value of 1600 J/(m^{2}s$^{0.5}$K). This thermal inertia value would apply to a typical office building of two or more stories with glazed walls and concrete floors and ceilings. The Authorities require a fire separation having a TTF rating of 30 min between the stair shaft and the office space. The equivalent ISO value is 29 min.

- Time to failure = 30 min
- Cumulative radiation energy = 94 MJ/m^2
- T-equivalent ISO $\geq$ 29 min
- Rounded up ISO = 30 min

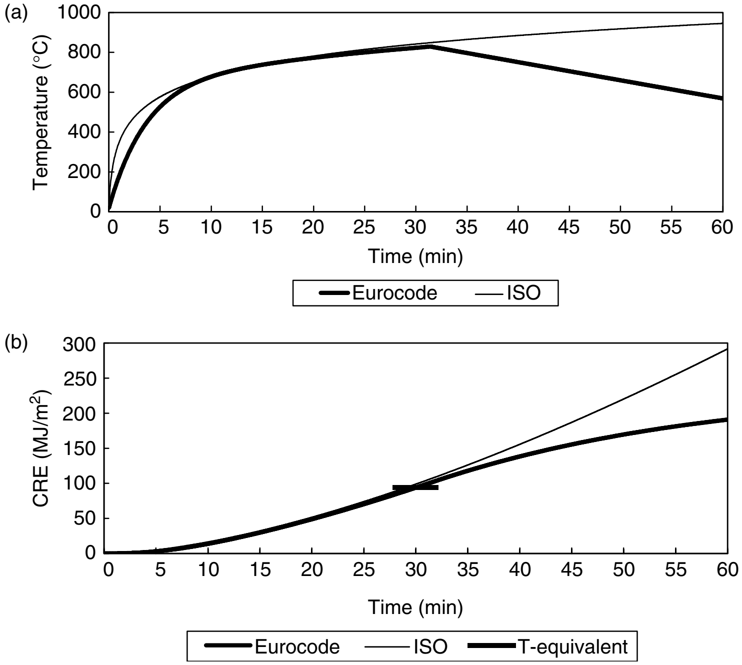

Figure 8. Example of concrete construction: (a) temperature vs time and (b) CRE vs time.

Case C – Thermal Inertia = 2500 J/(m^{2}s$^{0.5}$K)

The following example has the same geometry and fire load as Case A but with a thermal inertia value of 2500 J/(m^{2}s$^{0.5}$K). This thermal inertia value would apply to a typical large warehouse with sheet steel roof and walls. The Authorities require a fire separation having a TTF rating of 30 min between the stair shaft and the office space. The equivalent ISO value is 20 min.

- Time to failure = 30 min
- Cumulative radiation energy = 52 MJ/m^2
- T-equivalent ISO $\geq$ 20 min
- Rounded up ISO = 30 min

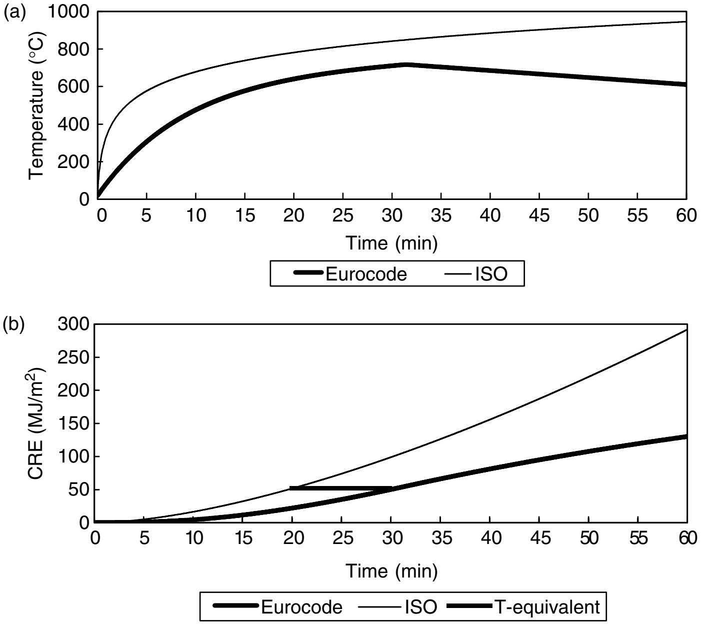

Figure 9. *Example of steel construction: (a) temperature vs time and (b) CRE vs time.*

Case D – Concrete Walls for a Single Story Warehouse

The following example (see Figure 10) demonstrates how a fire rating can be established for a concrete boundary wall around a single story warehouse with an un-fireproofed steel portal frame and a light gage steel roof. In a fire the portal frame will commence to distort and sag after ≈10–15 min, thereby creating a well-ventilated fire supplied with air through the damaged roof. In such a case an 'external' fire curve [13] would be a suitable design. With this curve, the temperature reaches a steady state of 660°C above the ambient temperature after ≈20 min. If the concrete walls are cantilevered from the floor, the internal steel structure can collapse without affecting the concrete walls. The walls require sufficient thickness and reinforcement such that the center-line section temperature does not exceed 250°C [17]. With a fast fire growth rate and a 'fire load energy density' (FLED) of 4000 MJ/m^2, a TTF value of 314 min could be expected. The equivalent ISO value would be 123 min as shown in Figure 10(b).

- Time to failure = >314 min
- Cumulative radiation energy = 861 MJ/m^2
- T-equivalent ISO $\geq$ 123 min
- Rounded up ISO = 120 min

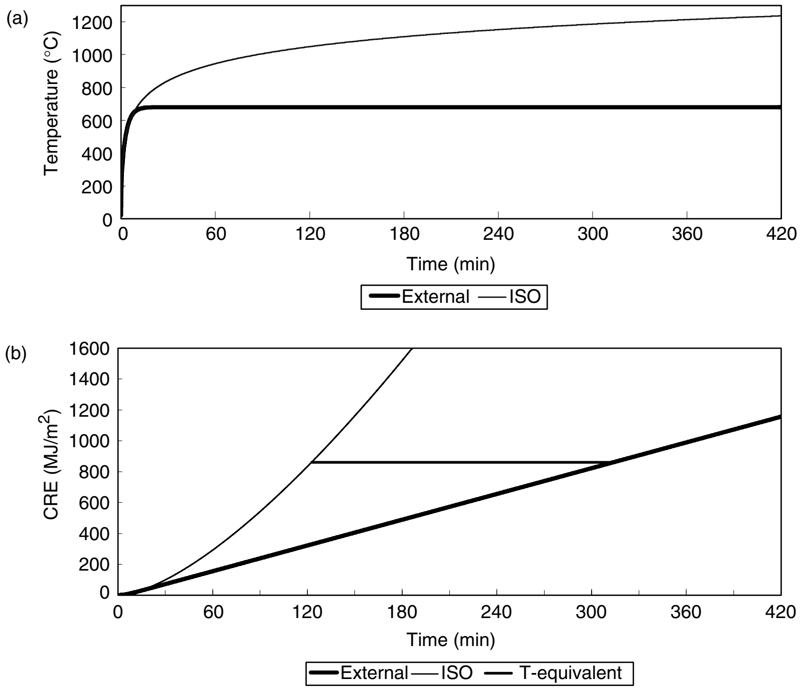

Figure 10. *Example of a concrete boundary wall on a warehouse: (a) temperature vs time and (b) CRE vs time.*

Various design methods can be used to determine the TTF value. One method is shown in Figure 19 of [14] where the maximum temperature is reached at the point C. These graphs are for a double t^2 fuel controlled fire and a double t^2 ventilation controlled fire. The latter would apply in the case of the warehouse fire mentioned previously. As a conservative answer, the TTF can be taken as having the same value as that time at which the maximum temperature is reached, namely the C point.

In a similar manner to Table 1 which shows the CRE values for the ISO curve, Table 2 shows the CRE values for the Eurocode 1 External curve. The values are shown in graphical form in Figure 10(b).

CONCLUSIONS

In fully involved enclosure fires having the same fire load and openings, the time–temperature performance will differ depending on whether the construction behaves as a thermally thick or thermally thin assembly. This in turn has an impact on the CRE received by the

Table 2. Cumulative radiation energy values for Eurocode 1 External curve.

Time (min)	Temp (°C)	CRE (MJ/m^2)	Time (min)	Temp (°C)	CRE (MJ/m^2)	Time (min)	Temp (°C)	CRE (MJ/m^2)
5	588	5	155	680	419	305	680	836
10	662	17	160	680	433	310	680	850
15	675	30	165	680	447	315	680	864
20	679	44	170	680	461	320	680	878
25	680	58	175	680	475	325	680	892
30	680	72	180	680	489	330	680	906
35	680	85	185	680	503	335	680	920
40	680	99	190	680	516	340	680	934
45	680	113	195	680	530	345	680	948
50	680	127	200	680	544	350	680	961
55	680	141	205	680	558	355	680	975
60	680	155	210	680	572	360	680	989
65	680	169	215	680	586	365	680	1003
70	680	183	220	680	600	370	680	1017
75	680	197	225	680	614	375	680	1031
80	680	211	230	680	628	380	680	1045
85	680	224	235	680	642	385	680	1059
90	680	238	240	680	656	390	680	1073
95	680	252	245	680	669	395	680	1087
100	680	266	250	680	683	400	680	1100
105	680	280	255	680	697	405	680	1114
110	680	294	260	680	711	410	680	1128
115	680	308	265	680	725	415	680	1142
120	680	322	270	680	739	420	680	1158
125	680	336	275	680	753	425	680	1170
130	680	350	280	680	767	430	680	1184
135	680	364	285	680	781	435	680	1198
140	680	377	290	680	795	440	680	1212
145	680	391	295	680	808	445	680	1226
150	680	405	300	680	822	450	680	1240

individual elements forming the enclosure and hence on the TTF of these elements. Figures 7–9 demonstrate that for the same TTF value of 30 min, the ISO 834 fire resistance rating of a concrete building or a steel clad building need to be only ≈60 and 40% of the requirements for drywall construction, respectively.

The CRE prediction design method can be applied to different construction assemblies depending on the thermal inertia, the opening factor and the fire load involved. However, the method has limitations in that, while it seems applicable to walls, it may not apply to ceilings. In combustible assemblies, the added heat energy from the burning of the assembly itself causes failure earlier than that predicted from the CRE alone. Recent developments may overcome this limitation.

The most significant question raised by this research is that while many fire codes around the world currently rely on standard fire curves such as ISO 834 to provide the times needed for fire separations for life protection, property protection, and firemen's safety; should these codes now be revised to meet the real TTF values as New Zealand did in 2005 [8]?

FURTHER RESEARCH

Further research on wall constructions which behave in a thermally thin manner would be of value in validating the CRE method for high thermal inertia situations. The preceding discussion is based on walls. Ceilings may not follow the CRE method as ceilings are subject to the full effect of hot-gas layer temperatures whereas walls may not be. Research is needed to determine if a difference between walls and ceilings does occur. Further research is suggested using fire load energy densities outside the range used by Nyman [11].

RECENT DEVELOPMENTS

In September 2004 research was conducted [18] using a new computer fire model called 'Fire Barrier' that implements the CRE method. The model showed reasonable agreement against the test results for 'onset of char' and very close agreement for 'insulation failure'. The conclusion reached was that, in the growth phase and early parts of the decay phase, the CRE method was reliable for predicting the fire resistance and the onset of char for drywall constructions exposed to the design fires that differ from the standard ISO 834 exposure.

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