

APPLICATION OF UPWARD FLAME SPREAD FOR THE PREDICTION OF SBI AND ISO ROOM CORNER (and parallel wall) EXPERIMENTS AND CLASSIFICATION

by

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The flammability hazard assessment of wall and ceiling linings has occupied the attention of fire scientists and engineers and regulators over the last fifty years. Several tests (small, medium, and large) have been developed to classify the flammability of linings and predict their burning behaviour in real enclosure fire situations. We examine in some detail three such efforts: (a) the development of an experimental room and a 9 ft vertical wall full scale test by Ferris leading to the Early Fire Hazard test in Australia, (b) the ISO room corner test, and (c) The new SBI (Single Burning Item test) which maybe the most thoroughly examined test in the history of flammability testing. Of these tests, the experimental room used by Ferris and the ISO room corner test may be considered as end use applications for medium size rooms whereas the SBI test and the vertical wall test by Ferris are intermediate scale test designed to represent the room fire behaviour in a more controlled way. Performance criterion in the ISO room corner test is the time to reach flashover. Performance criteria in the SBI test are related to the fire growth in an open corner (no ceiling) configuration due to upward flame spread. Performance criterion in the experimental room of Ferris was the time to reach untenable conditions in the room. Finally, performance criterion in the vertical wall of Ferris was the time interval from ignition until the flames reach the top of the wall. Examination of all these efforts has led to consistently validating a new correlation of the performance criteria of these tests with small-scale cone calorimeter tests whenever both data are available. Previous correlations are also discussed. The new correlation compares well with essential features of upward flame spread as this is related to flammability properties. Comparison between the ISO room corner test and the SBI test leads to suggestions regarding the suitability of these tests as a regulatory tool. Some comments are also directed towards a new test method of parallel wall panels recently proposed by Fmglobal. This test method can be analyzed using the same methodology outlined in this paper.

Key words: *fire spread, fire growth, single burning item, ISO room corner*

Introduction

Material testing for flammability hazard classification continues to be a developing area in fire safety, regulations, and applications. There still remains a difference

between tests used for regulatory purposes (prescribed test methods) and measurements from tests that can be used for performance based regulation and performance based design (performance based test methods).

Major criteria for the selection of performance test methods have been well set by the CIB Working commission W060 [1]:

- conditions of test under which the behavior of the article is being assessed must be realistic in relation to the expected conditions of use, or related to them in some known way,
- there needs to be a clear scientific basis for relating the results of performance testing under simplifying conditions to conditions in practice, and
- it is important to consider and reconsider whether the method will be suitable for predicting the behavior of the product under real conditions of use.

For selecting and verifying a methodology for building materials, experience has shown that three types of testing have been developed:

- (1) end use scenarios such as the ISO room corner test (see fig. 1), the Factory Mutual 25 ft corner test, the Room- Corridor test and many others,

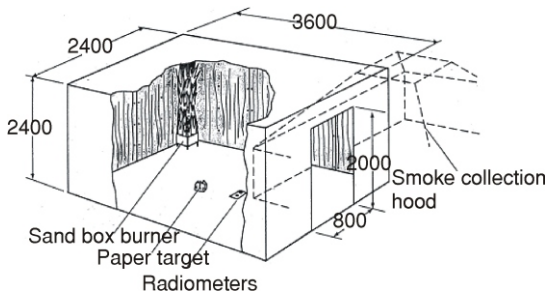


Figure 1. A sketch of the ISO room corner test

- (2) Intermediate scale tests such as the Australian EFH (Early Fire Hazard) test, the SBI test (fig. 2), ASTM intermediate calorimeter test, Flooring Radiant Panel, and
- (3) small scale tests such as the cone calorimeter (fig. 3) or the FM flammability apparatus.

Some of the tests in category 2 may also fall into categories 1 or 3 as for example the Flooring Radiant Panel

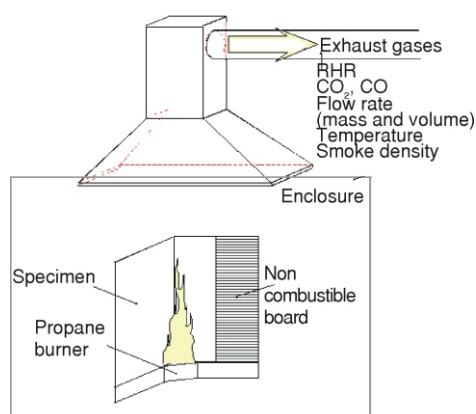


Figure 2. A sketch of the SBI corner test

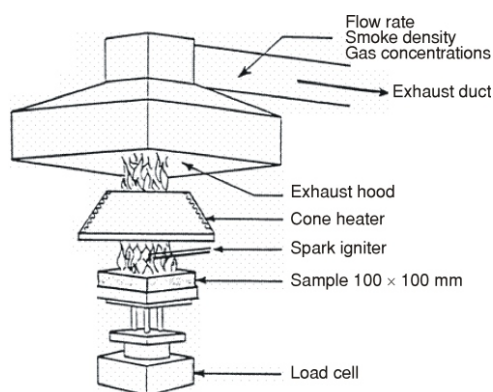


Figure 3. The cone calorimeter

test. Intermediate scale tests can be used for regulation as well as for validation of models using data from category 3 thus bridging categories 3 to 1. The question is what small-scale test measurements can provide what properties to predict the end use scenarios and the intermediate scale tests. A lot of progress has been made to establish confidence that one can predict the characteristics of large-scale tests related to upward flame spread. In this work we focus on the flammability classification and hazard evaluation of wall linings. The end use application is the hazard quantification of a fire developing in a room. The cause of ignition of wall linings is different "furniture" fires which might occur in a number of different occupancies such as office, living room or hotel-bedroom type s of occupancy. Some "furniture" fires are so intense that wall linings would add little to the initial overall hazard. Others are so feeble that they have little effect on any wall linings [2].

All the cited considerations may have been debated for the design and development of the ISO room (2.4 × 3.6 × 2.4 m high) corner test for wall linings (ISO 9705) using a propane fire source in a corner and having a specific door opening [3]. This test has been accepted in many countries as a reference scenario for small rooms. Ferris [2] used a reference room having size of 4.2 × 3.7 × 2.85 m (high) having a door and two window openings as shown in fig. 4. In this experimental room, a gas fire burner was designed and used near the corner. The gas fire burner produced intermediate size fire intensity so that the contribution of the wall and ceiling linings would be essential for hazardous conditions to develop. Several types of wallboards treated and untreated were used. The wallboards were nailed to their position according to the usual methods or trade practices. Figure 5 illustrates the spread of flame in the Ferris (fig.4) room for various treated timber

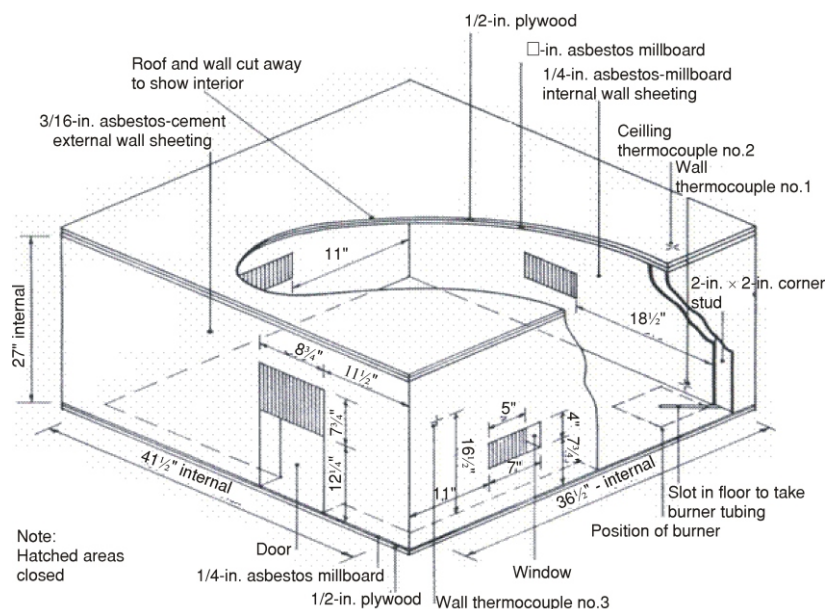


Figure 4. Experimental room of Ferris, 1/4 scale, isometric sketch

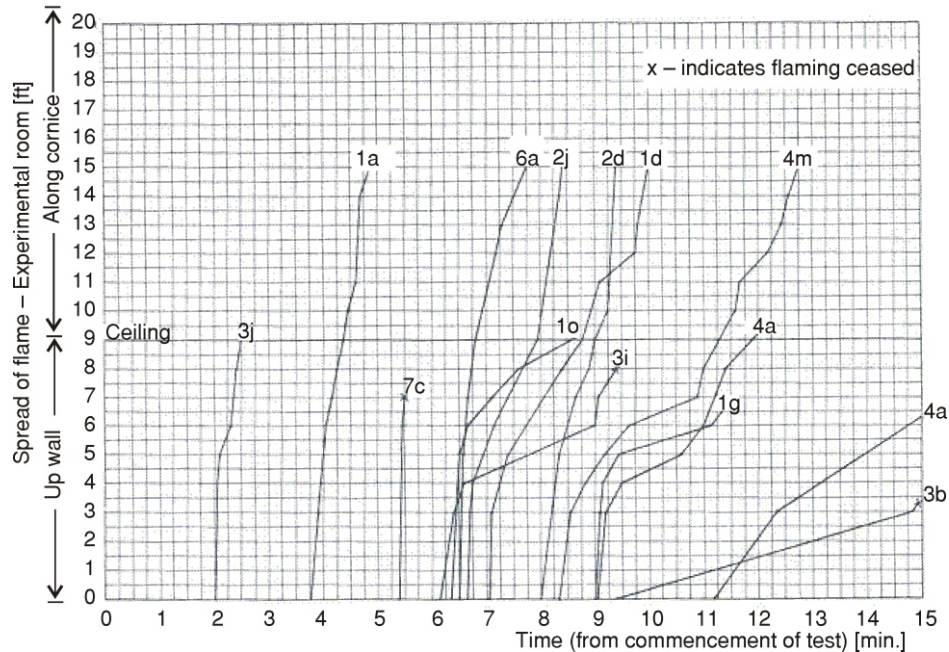


Figure 5. Spread of flame front in the experimental room for timber boards listed in tab. 1

boards installed both on the walls and the ceiling. Short description of wallboard properties are included in tab. 1. The rate of fire spread up the wall is related to the wallboard and its treatment. The rate of spread across the ceiling cornice is still a function of the wallboard and its treatment. Ferris [2] also states (but it is not clear from this figure) that only at later times the ceiling board and its treatment affects flame spread. Differences in ignition times shown in fig. 5 are due to different wallboards and thickness, different treatment, and different drywall construction.

Similar observations as in Ferris's experimental room were made in much later work [4] in ISO room corner tests of wall linings as part of the EUREFIC program.

Some conclusions reached from Ferris's [2] and EUREFIC project are:

- (1) vertical flame spread of flame was deemed to be an important characteristic of wallboards or other wall linings in addition to ignition time. For the medium size room in Ferris's experiments [2], once flames reached the ceiling, little time elapsed until the whole room was engulfed in flame,
- (2) the rate of flame spread was related to the type of wallboard and its treatment and to lesser extent on the duration between the commencement of the tests and ignition in each case (see fig. 5), and
- (3) most important measure for hazard assessment and classification is the time from ignition until the flames reach the ceiling. It is noted that untenable conditions in the room [2] are developed when the flames reached the ceiling.

Table 1. Timber boards shown in fig. 5 [2]

Test number	Combustible wall lining	Thickness, [in.]	Treatment
1a	Australian Softboard	1/2	None
1d	Australian Hardboard	3/16	None
1o	European Chipboard	3/8	None
1q	Australian Hardboard	1/2	–
2d	Australian Hardboard	3/16	Oil paint
2j	Australian Hardboard	3/16	Laquer
3b	Australian Softboard	1/2	Synthetic flat paint
3i	Australian Softboard	1/2	Water paint
3j	Australian Hardboard	1/2	Lacquer
4a	Australian Hardboard	3/16	Fire retardant water paint
4m	Australian Hardboard	3/16	Fire retardant water paint + finish 1
4o	Australian Hardboard	3/16	Fire retardant water paint + finish 2
6a	Plywood	3/16	Varnish
7c	Plywood	3/16	Fire retardant impregnated

Similar conclusions have been also reached as part of the EUREFIC [4] project, about forty years later, and noticeably that upward flame spread determines the hazardous conditions. We should point out that in the EUREFIC project the criterion for hazard assessment is the time to flashover and not the time to reach untenable conditions.

An important conclusion from the previous discussion is that instead of modeling the room fire development it is sufficient to use small-scale data to model upward flame spread in a corner configuration or simply on a single wall, which may also be pre-heated by an external heat flux. Therefore, the more general question of how to model the room fire development using small-scale data is focused and limited on how to model upward flame spread using small-scale data. Similar conclusion is reached when considering the performance of materials in the parallel wall test being developed by Fmglobal [13].

Fortunately the single wall situation is simpler to deal with. Several models have been developed for upward flame spread (Saito *et al.* [5], Delichatsios *et al.* [6], Beyler *et al.* [7], the Nordic group: Karlsson *et al.* [8], Kokkala [9]). It is out of the scope of this work to review in detail the upward flame spread models except for limited comments as follows:

- (1) the Saito *et al.* model [5] is based on an approximation that the flame height is proportional to heat release rate (HRR) for convenience in solving a flame spread equation. Such an approximation does not represent the physics of mixing and combustion well.

- (2) the Nordic group's contributions can be distinguished as:
- regression type analysis to relate cone calorimeter data for ignition and heat with the ISO room's time to Flashover [8]. Kokkala *et al.* [9] replaced this regression analysis using two indices I_{ign} and I_Q , an ignition and heat index which we will discuss later,
 - later Kokkala [10] used a simple flame spread equation to represent the flame spread on wood panels.
- (3) the model by Delichatsios [6] and later by Beyler [7] represents better the physics of combustion and pyrolysis rates using data and models based on measurements in the Cone calorimeter. More recently, this model [11] has been further validated by predicting flame spread in varying oxygen atmospheres.

There has been additional effort to include the flame spread model in room fire correlations [12 as well as others] by accounting also for downward and lateral flame spread. But the results by Ferris [2] and the Nordic group [8] indicate that the lateral or downward flame spread does not control, in general, the fire hazard in room fires.

We will continue the present work utilizing the later observation namely that upward flame spread in a corner controls the fire hazard of wall linings in room fires.

Brief description of Kokkala's method [8]

This method was developed to replace regression correlations between the flashover time in the ISO room corner test and cone results [7]. It is not based on modeling of flame spread but it is using two indices:

- an ignition index

$$I_{\text{ign}} = \frac{1}{t_{\text{ign}}} \quad (1)$$

where the ignition time is determined as the time when the heat release rate from the sample reaches 50 kW/m², and

- a heat release index

$$I_Q = \int_{t_{\text{ign}}}^{\infty} \frac{\dot{q}}{(t - t_{\text{ign}})^m} dt \quad (2)$$

where the HRR per unit area $\dot{q}$ is measured in the cone calorimeter. The exponent m is selected to better represent the hazard in the ISO room configuration [8].

Both ignition times and heat release are to be determined at an imposed heat flux of 50 kW/m².

There are some observations that may help when using these indices to classify and reproduce the ISO room flashover times:

- (a) the definition of ignition time may not be appropriate for fire retardant materials where flaming ignition may occur later than the time at which the heat release rate reaches the value of 50 kW/m²,
- (b) there is a delay in the system when measuring the heat release rate due to the flow transients in the cone calorimeter measurements, and

(c) if a metal facing is installed on the wall lining, the so defined ignition time [8] is not very useful for describing the upward flame spread that occurs after the facing melts away.

In tab. 2, we include times to ignition measured by visual observations and by the 50 kW/m² criterion. There are significant differences, some of which may be explained by the previous remarks. This casts some doubts on the usefulness of the definition of ignition time by using the 50 kW/m² criterion.

Table 2. Comparison of ignition times based on visual observations and on the criterion that heat release by the sample reaches 50 kW/m² for a set of tests conducted in Japan provided by Dr. Nakaya [9, 10]

Code	Material	Tig (visual) [s]	Tig at 50 kW/m ² HRR [s]
7-A0	Gypsum board and PVC wall paper 300 g/m ²	11.6	19
7-A1	Gypsum board and PVC wall paper 500 g/m ²	8.5	15.5
7-F1	Isocyanurate sprayed on gypsum board	2	20
7-G	FR plywood 15 mm (Japanese Cedar)	21.3	25.7
7-Q	Insulation board	7.2	12
7-R	Gypsum board 9.5 mm	37.3	42.7
8-A	Gypsum board and rayon wall paper 700 g/m ²	36.8	41.3
8-B	Gypsum board and rayon wall paper 300 g/m ²	23.5	30
8-C	Gypsum board and emulsion paint	56.4	57.3
8-D	Gypsum board and acrylic enamel	29.1	35.3
8-E	Gypsum board and surface treatment 70 g/m ²	41	46
8-F	Gypsum board and surface treatment 111 g/m ²	38.6	48.7
8-H	Metal plate covered with FR polyethylene foam	51.1	61.3
8-K	Gypsum board with PVC wall paper 299 g/m ²	15.1	25
8-L	Gypsum board with PVC wall paper 800 g/m ²	8.7	19.7
9-B	Slate board with PVC wall paper 800 g/m ²	4.2	49.3
9-I	Paint coated slate board 6 mm	139.3	153.3
The following materials have not been tested in the ISO room fire test			
7-B	Gypsum board and PVC wall paper 800 g/m ²	18.6	46.7
7-Q1	Medium density fiber board 12 mm	36	41.7
8-J	Gypsum board and rayon wall paper 446 g/m ²	19.55	27.3
8-M	Treated glasswool	4	31.7
9-F	Polycarbonate 5 mm	40	44.7
9-L	Polyvinyl chloride board 5 mm	41	44.3

The second parameter I_Q (eq. 2) is somewhat arbitrary too. The selection of $m = 0.93$ is proposed to segregate the flashover times in three classes whereas the exponent $m = 0.34$ is used to segregate the flashover times in two classes [8].

To illustrate what the effects of these exponents are we consider a top hat profile of maximum heat release rate $\dot{q}_{\max}$ and duration t_B , which may be characterized as a burn-out time. Then for $m = 0.93$:

$$I_Q = \frac{\dot{q}_{\max} t_B^{0.07}}{0.07} \quad \text{for } m = 0.93 \quad (3)$$

$$I_Q = \frac{\dot{q}_{\max} t_B^{0.66}}{0.66} \quad \text{for } m = 0.34 \quad (4)$$

In the first case emphasis is given to the maximum heat release rate while in the second case the burnout duration is also more pronounced. In either case the physics of flame spread are not well reproduced.

Figures 6a and 6b shows how these indices are applied for the SBI related round robin ISO room corner tests [10]. Figure 6a for the three or four class hazard classification and fig. 6b for the two-class hazard classification. The lines in fig. 6a indicate the times to flashover at 2 minutes and 12 minutes [8]. The line in figure 6b indicates the flashover time of 10 min. Although most of the products are plotted in the correct part of the two-index plane, there are still several “problematic” products. Table 3 includes the products tested in the SBI round robin project including the cone data and the time to flashover in the corresponding ISO room corner test.

A consistent upward flame spread model and correlations

Based on our work [11], it is shown that upward flame spread can be characterized by two quantities a length scale L_m and an ignition time t_{ign} that also characterizes the spread

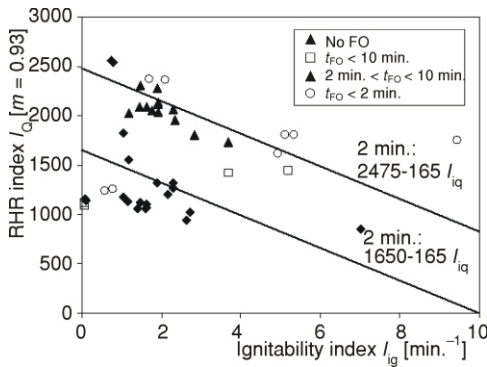


Figure 6a. Correlations of ISO room corner test time to flashover using Kokkal's 3 class correlation (materials and data are shown in tab. 2)

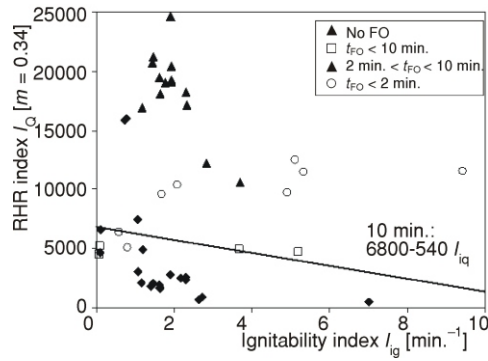


Figure 6b. Correlations of ISO room corner test time to flashover using Kokkal's 2 class correlation (materials and data are shown in tab. 2)

Table 3. Cone calorimeter data measured at 50 kW/m² and ISO 9705 time to flashover (= t_{FO}) for the SBI Round Robin products [9, 10]

Code	Product name	t_{ig} [g]	$\dot{q}_{max}$ [kW/m ²]	t_{FO} [min.:s]
M01	Paper-faced gypsum plasterboard	37	122	>20:00
M02	FR PVC	54	319	>20:00
M03	FR extruded polystyrene board	32	459	01:36
M04	PUR foam panel with aluminum foil faces	91	115	00:41
M05	Mass timber (spruce), varnished	11	234	01:46
M06	FR chip board	678	106	>20:00
M07	FR polycarbonate panel, 2-layered	79	639	>20:00
M08	Painted paper-faced gypsum plasterboard	42	148	>20:00
M09	Paper wall covering on gypsum plasterboard	27	206	>20:00
M10	PVC wall carpet on gypsum plasterboard	14	163	11:15
M11	Plastic-faced steel sheet on mineral wool	22	95	>20:00
M12	Mass timber (spruce), unvarnished	19	201	0.2:50
M13	Gypsum plasterboard on polystyrene	37	128	>20:00
M14	Phenolic foam	834	53	10:40
M15	Intumescent coating on particle board	No ignition	24	11:40
M16	Melamine faced MDF board	39	269	02:30
M19	Unfaced rockwool	No ignition	11	>20:00
M20	Melamine faced particle board	44	262	02:45
M21	Steel clad EPS sandwich panel	No ignition	32	16:10
M22	Ordinary particle board	33	236	02:35
M23	Ordinary plywood (birch)	29	208	02:40
M24	Paper wall covering on particle board	29	229	02:45
M25	Medium density fibreboard	36	259	03:10
M26	Low density fibreboard	9	174	00:58
M27	Gypsum plasterboard / FR PUR foam core	54	121	>20:00
M28	Acoustic mineral fibre tiles	9	71	>20:00
M29	Textile wall paper on CaSi board	29	259	>20:00
M30	Paper-faced glass wool	1	353	00:18

time. In the Appendix, we present a simplified derivation of these relations together with a discussion of the importance of burnout time or otherwise described as the duration of material burning. The length scale is proportional to the square of the HRR per unit area. This heat release rate can be measured in the cone calorimeter at an imposed heat flux that would

depend on the specific application. A heat flux of 50 kW/m² is chosen* for illustration as in other correlations [8, 9]. Ignition times are also measured at this heat flux. For simplification that is not necessary [see ref. 11], we consider that the heat release rate has a top hat profile of total time duration t_B after ignition starts. The present application is valid for any material thickness (from thermally thin to thick conditions).

If times of interest are less than the burnout time t_B , the location of the front is given by the functional relation (see Appendix):

$$\frac{X_p}{L_m} = f \left(\frac{t}{t_{\text{ign}}} \right) \quad (5)$$

In this case the characteristic spread velocity is:

$$U_s = \frac{L_m}{t_{\text{ign}}} \frac{\dot{q}^2}{t_{\text{ign}}} \quad (6)$$

In eq. (6) $\dot{q}$ is the heat release rate per unit surface area at 50 kW/m².

If the times of interest are longer than the burnout time, the characteristic spread velocity is still given by eq. (6) and the maximum pyrolysis length is given by eq. (9) of the Appendix:

$$X_{p \text{ max}} = L_m \frac{0.052(t_B/t_{\text{ign}})^3}{1 - t_B/t_{\text{ign}}} \quad (7)$$

In the present report, we will ignore the burnout times and consider only the maximum HRR (this would be similar to Kokkala's [9] using the exponent $m = 0.93$). We can also check whether the characteristic flame spread speed in eq. 6 is appropriate to classify various wall materials. We plot in fig. 7, this parameter vs. the classification of SBI related round robin ISO room corner tests. For this figure (1) indicates flashover times over 20 minutes, (2) flashover times over 10 minutes (and less than 20 minutes), (3) flashover times over 2 minutes (and less than 10 minutes), and (4) flashover times less than 2 minutes.

This figure shows that there are "problematic" materials as in the correlation of Kokkala in fig. 6a and 6b. What we can definitely say from fig. 7 is the following:

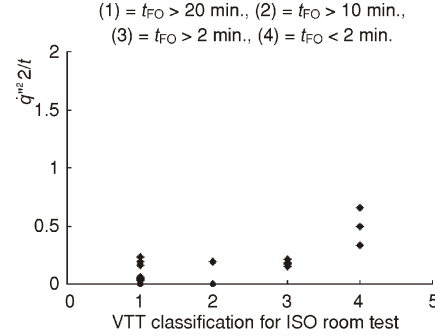
– for "bad" materials

$$U_s = \frac{L_m}{t_{\text{ign}}} \frac{\dot{q}^2}{t_{\text{ign}}} \approx 0.34 \text{ (flashover time less than 2 minutes),}$$

– for "good" materials

* The choice of the imposed heat flux needs considerable investigation. Its magnitude would depend on the HRR and the flame height of an exposure fire causing the ignition of the wall material. It would also depend on the radiative properties of the wall material. Both these factors can be included by considering the smoke points of the exposure fire and the wall material. We limit here the analysis for wall heights less than 2 meters and provide only a relative fire behaviour of wall materials.

Figure 7. Correlations of ISO room corner test time to flashover using present material flammability parameter as given by eq. 6



$$U_s \frac{L_m}{t_{ign}} \frac{\dot{q}^2}{t_{ign}} \approx 0.15 \text{ (no flashover or flashover over 10 minutes).}$$

For values of the characteristic spread velocity between 0.15 and 0.34 flashover can occur at times greater than 2 min. as fig. 7 shows. The time to flashover in this case depends also on the thickness of the material and the method of substrate application on the room walls.

Comments on using upward flame spread parameters for the time to flashover in the ISO room corner test

Even though observations show that flashover generally follows soon after flames reach the ceiling height, the time to flashover may not be directly proportional to this time because other phenomena are involved as soon as a hot layer is formed in the room. For example burnout time may be very important in this case: although the flames may reach the ceiling relatively fast flashover may not occur because there is not enough material to burn. On the other hand, even if the spread up the corner is relatively slow, formation of the hot layer may induce heat fluxes that can cause lateral and downward flame spread and lead to flashover.

For these reasons, the ISO room corner test is not a good method of classifying materials that are in a borderline situation regarding the time to spread up the corner of the room. This discussion explains also the problematic materials in figs. 6a and 6b as well as in fig. 7.

Interpretation of FIGRA index for HRR in the SBI using cone data

The classification method in the SBI (fig. 2) was developed to be consistent with product rankings obtained according to the Room/Corner test. The basic idea was to relate the class limits to flashover. Thus, the Fire Growth Rate index FIGRA was selected to be the principal classification parameter [10].

The definition and determination of FIGRA index for heat is obtained in the following way [10].

$FIGRA = \max \dot{Q} / t$ where $\dot{Q}$ is the HRR measured in the SBI test averaged over 30 seconds (in kW) and t is the time from the beginning of test (in seconds).

The fire flow near the corner behaves as the fire flow on a vertical wall [10]. Based on our model [11, see also Appendix], the pyrolysis front and the HRR can be approximately expressed as a second power of time:

$$\frac{X_p}{L_m} = \frac{t}{t_{ign}}^2 \quad (8a)$$

and

$$\frac{\dot{Q}}{W} = \frac{t}{t_{ign}}^2 \quad (8b)$$

Here W is the width of the flow in the corner and we notice that: $\dot{Q} / W = X_p \dot{q}$.

If L is the height of the corner configuration in the SBI test, the last two relations can be used to express FIGRA as:

$$FIGRA = \max \frac{\dot{Q}}{t} = W L \frac{\dot{q}^2}{t_{ign}^2} = \frac{\dot{q}^2}{t_{ign}^2} \quad (9)$$

This relation is derived by noticing that FIGRA occurs when $X_p = L =$ the height of the open corner. The last parameter is exactly the one proposed by our modeling approach. This observation explains the good correlation in fig. 8.

In fig. 8 we plot the same parameter vs. the FIGRA HRR parameter in the SBI test for all materials listed in tab. 3. FIGRA provides a more consistent discrimination and correlation with small scale flammability properties in comparison to flashover time in the ISO room corner tests (see fig. 7).

Figures 9 and 10 also provide an additional proof that upward flame spread on a wall reproduces quite well the similar spread time as in enclosure [2]. Figure 9 is a picture of a 9 ft vertical wall heated by a moving bank of radiant panels [2] wherein the maximum heat flux is applied to the bottom of the wall. A small pilot initiates ignition. Figure 10 compares upward spread times in the corner of the enclosure and the single wall of fig. 9. These results in fig. 10 may be considered as another justification for using the SBI for material classification.

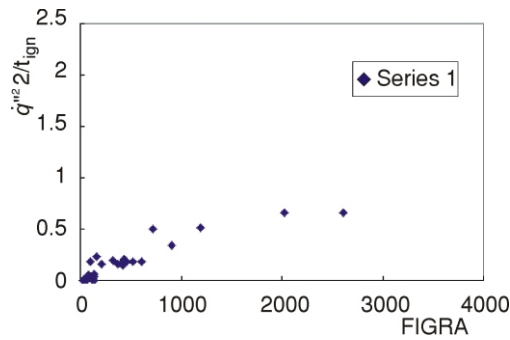


Figure 8. Heat release FIGRA parameter of the SBI test correlated vs. the present material flammability parameter as given by eq. 6

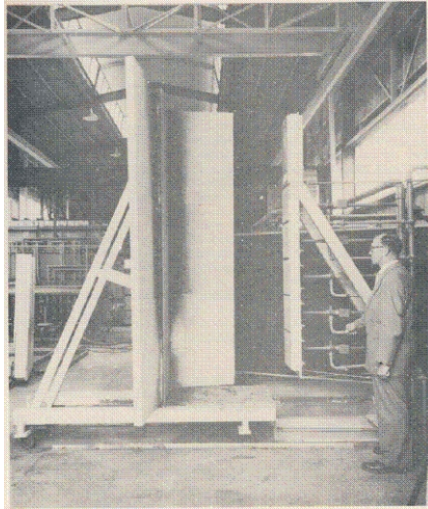


Figure 9. A sketch of the 9 ft vertical wall heated by a moving bank of radiant heaters [2]

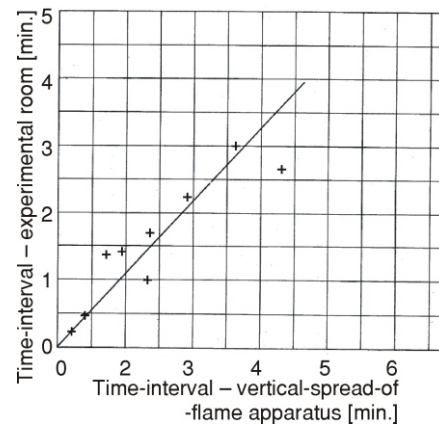


Figure 10. Correlation of the time to reach the upper part of the wall in the experimental room (see fig. 4) and in the 9 ft vertical wall test of Ferris (see fig. 9)

Conclusions

The main conclusions are: (1) the SBI test is more “clean” and consistent test than the room corner test to be used for wall lining classification, (2) there is a good correlation between the FIGRA parameter of SBI test and a simple parameter derived from cone calorimeter measurements but not between the ISO room corner test and the cone, and (3) because of progress in fire safety science, there is no reason to use empirical indices to correlate SBI or ISO room corner tests with small-scale tests.

References

- [1] ***, CIB Working with the Performance Approach in Building, CIB Report 64, 1982
- [2] Ferris, J. E., Fire Hazards of Combustible Walboards, Special Report No. 18, Commonwealth Experimental Building Station, 1955
- [3] ***, ISO: Fire-Tests Full-Scale Room Test for Surface Products, ISO 9705, ISO Geneva, 1993a
- [4] ***, *Proceedings*, International EURIFIC Seminar, Copenhagen, 1991, Interscience Communications Limited, London, 1992
- [5] Saito, K., Quintiere, J. G., Williams, F. A., Upward Turbulent Flame Spread, *Proceedings* (Eds. C. E. Grant, P. J. Pagni), 1st International Symposium on Fire Safety Science, Hemisphere Publishing Corporation, New York, 1986, pp. 75-86
- [6] Delichatsios, M. A., Saito, K., Upward Fire Spread, Key Flammability Properties, Similarity Solutions and Flammability Indices, *Proceedings*, 3rd International Symposium, on Fire Safety Science (Eds. G. Cox., B. Langford), Elsevier Science Publishers Ltd, London, 1991, pp. 217-226

- [7] Beyler, C., L., Hunt, S. P., Ibqal, N., Williams, F. W., A Computer Model of Upward Flame Spread on Vertical Surfaces, *Proceedings*, 5th International Symposium on Fire Safety Science, Melbourne, Australia, 1997, pp. 297-308
- [8] Karlsson, B., Modeling Fire Growth on Combustible Lining Materials in Enclosures, Report TVBB-1009, Department of Fire Safety Engineering, Lund University, Lund, Sweden, 1992
- [9] Kokkala, M. A., Thomas, P. H., Karlsson, B., Rate of Heat Release and Ignitability Indices for Surface Linings, *Fire and Materials*, 17 (1993), 5, pp. 209-216
- [10] Hakkarainen, T., Kokkala, M. A., Application of a One-Dimensional Thermal Flame Spread Model on Predicting the Rate of Heat Release in the SBI Test, 2000, *Fire and Materials*, 25 (2001), 2, pp. 61-70
- [11] Delichatsios, M. A., Flame Heat Fluxes and Correlations of Upward Flame Spread Along Vertical Cylinders in Various Oxygen Environments, *Proceedings*, 28th Symposium (Int.), on Combustion, 2000, The Combustion Institute Pittsburgh, Pa., USA, 2001, p. 2899
- [12] Quintiere, J. G., A Simulation Model for Fire Growth on Materials Subject to a Room-Corner Test, *Fire Safety Journal*, 20 (1993), 4, pp. 313-339
- [13] DeRis, J. L., Orloff, L., Flame Heat Transfer Between Parallel Panels, *Proceedings*, 8th International Symposium on Fire Safety Science, Beijing, 2005, pp. 999-1010

Appendix

Simple relations and correlations for flame spread in wall and corner configurations

In several previous occasions, we have used simple correlations of measurements in the cone with predictions of material behaviour in the EFH, ISO room corner tests and carpets in stairs. These relations were derived from a detailed flame spread model [6, 11]. Recently, these correlations have been adopted by Phil Thomas and are implicit in the recent modeling work of Kokkala [9].

We present here a simple derivation for these relations to make them easier to understand.

We start with a flame spread equation, although not quantitatively exact, that captures the main physics. This equation gives the rate of spread of the pyrolysis front location, X_p , as:

$$\frac{dX_p}{dt} = \frac{X_f - X_p}{t_{\text{ign}}} \quad (\text{A1})$$

Here X_f is the (50% intermittency) flame height, t is the time, and t_{ign} is the ignition time of the material heated from the flames over the length $X_f - X_p$.

The flame height is well known to be given by:

$$X_f = 0.0523 \sqrt{\frac{\dot{Q}}{W}} \quad (\text{A2})$$

where W is the width of the wall and the heat release rate $\dot{Q}$ is given by:

$$\frac{\dot{Q}}{W} = X_p \dot{q} \quad (A3)$$

Here the heat release rate $\dot{q}$ per unit area is known from the cone calorimeter for an imposed heat flux of the same magnitude as in the wall flames. For the present illustration, we assume that this flame heat flux is constant over the period of interest (but it may change for different materials and length scales, see some previous papers). The ignition time in eq. 1 corresponds to the same imposed heat flux and it is measured in the cone.

In the correlation analysis we will use first the maximum heat release rate per unit area without considering its time history (but more analysis follows later). In addition, without loss of generality we ignore the effects of initial exposure (external) fire.

Using eqs. (A2) and (A3) and after some algebra, eq. (A1) becomes:

$$\frac{d \frac{X_p}{L_m}}{d \frac{t}{t_{\text{ign}}}} = 0.0523 \sqrt{\frac{X_p}{L_m}}^2 \frac{X_p}{L_m} \quad (A4)$$

where

$$L_m = \dot{q}^{-2} \quad (A5)$$

These relations show that X_p/L_m is a function of t/t_{ign} which is in agreement with previous detailed derivation.

In addition, it is easy to see by inspection that a simple most important parameter is a characteristic flame spread velocity given by:

$$U_{\text{USF}} = \frac{L_m}{t_{\text{ign}}} \quad (A6)$$

These results apply for any thickness of the material assuming that substrates in the cone and the specific application are the same.

This relation has been used to correlate ISO room corner fires with cone data and for carpets in stairs. It can be used also for conveyor belts, wherein however lateral spread may also be important. A simple way to consider the history of pyrolysis is included next.

The pyrolysis and heat release rate histories can be in many cases represented by a maximum (constant) value that decays over a burnout time t_B . This time can be experimentally determined to be the time period between the time the heat release rate per unit area increases to 50 kW/m² to the time it decays to 50 kW/m² (charring effect of wood can thus be included).

By simple inspection one can see that the maximum pyrolysis length before burnout of the material occurs is:

$$X_{p \text{ max}} = t_B \frac{dX_p}{dt} \quad (A7)$$

Using eq. (A7) in eq. (A1), one obtains using also eqs. (A2) and (A3).

$$X_{p \max} = t_B \frac{dX_p}{dt} = t_B \frac{X_f - X_{p \max}}{t_{\text{ign}}} = t_B \frac{0.052 \sqrt[3]{(X_{p \max} \dot{q})^2}}{t_{\text{ign}}} X_{p \max} \quad (\text{A8})$$

After some algebra, one can find from eq. (8) and using the definition in eq. (A5) that:

$$\sqrt[3]{\frac{X_{p \max}}{L_m}} = \frac{0.052 \frac{t_B}{t_{\text{ign}}}}{1 + \frac{t_B}{t_{\text{ign}}}} \quad (\text{A9})$$

If $t_B/t_{\text{ign}} \gg 1$ (say 4) the proper length scale is L_m (as before). Other wise the proper length scale is $X_{p \max}$ as given by eq. (A9).

The specific application of the present results will depend on the full-scale test considered. They can be applied, as they have, to ISO room corner and EFH. They can also be applied to SBI and the conveyor belts (the effective heat flux from the flames and/or enclosure and the lengths of the test case are some important choices).

Solution of eq. (A4)

Equation A4 can be integrated to give the following solution:

$$3 \ln 1 + \frac{\sqrt[3]{\frac{X_p}{L_m}}}{0.052} = \frac{t}{t_{\text{ign}}} \quad (\text{A10})$$

which for small times gives: $(X_p/L_m) = (t/t_{\text{ign}})^3$.

For later times the power dependence on time becomes nearly a square power as in eq. 11 (see also [7]).

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