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Abstract

A complete testing and classification system requires both small- and large-scale test methods. In this article such a system is outlined employing the Cone Calorimeter and the Room/corner test for testing on a small and a large scale, respectively. Translation models are also described allowing the Room/corner test to be predicted by Cone Calorimeter results only. A proposal for a classification system for wall and ceiling linings is also given together with actual and predicted test results.

Key words: Room fires, Cone Calorimeters, Flammability testing.

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Full-scale/Bench-scale Correlations of Wall and Ceiling Linings

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A complete testing and classification system requires both small- and large-scale test methods. In this article such a system is outlined employing the Cone Calorimeter and the Room/corner Test for testing on a small and a large scale, respectively. Translation models are also described allowing the Room/corner test to be predicted by Cone Calorimeter results only. A proposal for a classification system for wall and ceiling linings is also given together with actual and predicted test results.

A translation model between large- and small-scale heat release rate measurements is needed in an efficient fire-classification system of products. Although, in principle, products should be evaluated in scenarios representative of their end-use situation, small-scale testing is usually preferable, as it is less expensive and more conveniently carried out. Many products are, however, not meaningful to test on a small scale. Products that melt have odd geometries or have joints decisive for their fire behaviour are not likely to give representative results in any small-scale test method. For such products large-scale testing is needed. They should, however, be evaluated by the same measurements as if they were tested on a small scale. There must therefore be an association between large- and small-scale test results.

The authors^{1,2} have shown that results from the Cone Calorimeter (ISO/DIS 5660) can be used to predict Room/corner Tests (ISO/DIS 9705 or Nordtest Fire 025). The room fire heat release rate curve is calculated. The only input needed comes from the Cone Calorimeter in terms of the time to ignition and the heat release rate per unit area as a function of time. The model is outlined in detail below. Another similar model has been developed by Östman and Nussbaum.³ They have succeeded in correlating time to flashover in the Room/corner Test with time to ignition and peak heat release rate measured in the Cone Calorimeter, and the density of the product. Their model is also outlined below.

Magnusson and Sundström⁴ have published a more complex model, later improved by Karlsson⁵ for predicting large-scale tests. The model requires input data from Surface Spread of Flame as well as from the Cone Calorimeter tests.

THE ROOM/CORNER TEST

The Room/corner Test is shown in Fig. 1. The specimen is mounted on the walls as well as on the ceiling. According to Nordtest Fire 025, the ignition source, a propane gas burner, is operated at two levels, 100 kW for the first 10 min and then 300 kW if flashover has not taken place after 10 min, (see Fig. 2). Flashover occurs when the total heat release reaches 1000 kW, which is roughly when flames emerge from the doorway.

The two burner output levels are introduced to allow for discriminating between products of a wide range of flammability properties. Products with good fire properties will not spread the fire beyond the vicinity of the burner for an exposure of 100 kW but may do so for 300 kW. The lower output level is high enough to cause flashover of some products used in practice while still being a relevant fire scenario, simulating, for example, a burning piece of furniture or a waste paper basket. By using an even lower initial heat source a better resolution of test results could be obtained. This is, however, only true for very flammable products with fire properties outside the building regulations. More relevant products would then not spread the fire beyond the vicinity of the burner. In fact a classification system for wall and ceiling linings has been proposed by Sundström and Göransson⁶ based on this test scenario. The flashover times for the proposed five classes are indicated in Fig. 2 and shown in Table 1 together with some typical products. Proposed requirements on smoke production are not given here.

The step-wise constant heat release rate of the ignition source (see Fig. 2) makes possible the analysis outlined in the next section. Criteria for whether flame spread will occur have been developed for the two burner heat release rate levels.

THE WICKSTRÖM/GÖRANSSON MODEL

In the Wickström/Göransson model^{1,2} ignition time as well as the complete heat release rate curve from the Cone Calorimeter are used. In principle results from a single-scale test could be employed to predict the full-scale behaviour of a product.

There are many products whose behaviour is not possible to predict on a large scale based on small-scale tests. Examples are products with a protective surface or with joints which, after heating, suddenly crack and expose highly flammable materials. These need to be tested on a large scale to obtain results that can be used for evaluating their potential fire hazard.

The calculation model is described in detail below in four sections, containing principles, area growth, heat release rate and criterion for flame spread, respectively.

Figure 1. The ISO Room/corner Test. The gas burner is run according to the Nordtest method, for 10 minutes at 100 kW and then for another 10 minutes at 300 kW.

Figure 2. Proposed class limits for the Room/corner Test. The classification depends on time to flash-over except for class A (the best class) where a maximum heat release rate of 600 kW must not be exceeded, see Table 1. Wood and plasterboard are given as examples of classified products. Normal wood is a class E product while plasterboard is a class A product.

Table 1. A proposed classification system based on time to reach 1000 kW (flashover) in the Room/corner test

Class	Time to flashover (min)	Typical product
A	20 ^a	Plasterboard, mineral wool
B	20	Light wallcoverings on plasterboard
C	12	Boards with protected surface
D	10	Heavy wallpapers
E	2	Wood

^aIn addition, the heat release rate is maximized to 600 kW.

Finally, calculated full-scale heat release rates are shown and compared with measured values.

PRINCIPLES OF PREDICTION

In the prediction model three major assumptions have been made of the heat release rate on a large scale:

- (1) The burning area growth rate and the heat release rate are decoupled.

- (2) The burning area growth rate is proportional to the ease of ignition, i.e. the inverse of the time to ignition on a small scale.
- (3) The history of the heat release rate per unit area at each location on a large scale is to be the same as on a small scale.

As shown in Fig. 3, the fire spread may follow three different routes. A product is assumed to spread along routes II and V if a calculated assumed surface temperature is higher than a critical value. The calculation is based on data from the Cone Calorimeter, as will be outlined below.

Within the different flame spread regimes the burning area growth rate depends on ignitability, i.e. time to ignition in the Cone Calorimeter. Once the flame spread rate is determined, the heat release rate is calculated assuming that products always give the same heat release rate per unit area as a function of time on a small and a large scale. In other words, all parts of the tested product are assumed to burn in the same way on a large scale as on a small scale. This is, of course, a great simplification. The heat release rate depends more or less on the actual heat flux level received by the product as a function of time. Experience of the model shows, however, that the errors average out and can be included in empirical constants.

The flame spread at the beginning of the test is divided into two parts. First, the area in the corner behind the burner is ignited. The size of the area is assumed to be the same for all products. In the second part, the burning area is assumed to grow according to a given function of time. It will, however, start to grow only if an assumed surface temperature is reached. This temperature depends on ignitability as well as on heat release properties of the product. These parameters are obtained from the Cone Calorimeter and together give sufficient information to predict flame spread development.

Figure 3 shows how the area behind the burner first ignites first (I) and burns at a certain heat release rate. As mentioned above, products then behave in one of two ways; either there is a progressive flame spread that eventually will involve the entire room (II) or there is no further flame spread outside the burner flame region (III).

Figure 3. A schematic pattern of burning area growth in the Room/corner test. The flame spread regimes are marked with Roman figures. The first part of the curve, I corresponds Eqn (1), part IV to Eqn (3) and parts II and V both to Eqn (2). At points A and B in the figure the burning area growth can go either way, II or V if the ignition temperature is exceeded and III or VI if not so.

Which category the product belongs to is determined by the flame spread propagation criterion described below.

When the burner heat output is raised to 300 kW the flames will become larger and a greater surface area will almost immediately be involved (IV). The situation is then similar to the one at the beginning of the test. Either there is a progressive flame spread (V) or not (VI). The two continuous flame spread developments, (II) and (V), are assumed to follow given functions of time as shown later in the section.

A more detailed description of how the flame spread rate is obtained in the model now follows. The formulae are empirical and must be seen as proposals that, at least with current experience, have given acceptable results.

First, the area behind the burner ignites (see Fig. 3). The size of this area (2 m^2) is assumed to be the same for all products while the growth of the burning area is assumed to vary with time normalized with the ignition time, t_{ign} , of the product considered:

$$A(t) = 4 \left(\frac{t}{t_{\text{ign}}} \right) - 1 \quad (1)$$

Along routes II and V in Fig. 3 the area involved, as a function of time, is written as

$$A(t) = A_0 \left[1 + a \frac{(t - t_x)^2}{t_{\text{ign}}} \right] \quad (2)$$

A_0 is the area behind the burner and a is an empirical constant found to be 0.025 s^{-1} for route II and t_x is chosen so that the burning area growth rate is the same as in Eqn (1) when Eqn (2) starts to be used, i.e. when the surface temperature criterion is exceeded.

After 10 min, when the burner output is raised, the burning area is initially expressed as:

$$A(t) = 2 + \frac{24}{t_{\text{ign}}} (t - t_{10}) \quad (3)$$

until $A(t)$ is 5 m^2 ; $t_{10} = 600 \text{ s}$ (10 min). If the surface temperature criterion is reached, growth of the burning area will continue as in Eqn (2) with the parameters $A_0 = 5 \text{ m}^2$ and $a = 0.1 \text{ s}^{-1}$ and t_x determined as above.

The total heat release from the room is obtained by summing the contributions from each part of the total burning area and the burner:

$$Q_{\text{total}} = Q_{\text{product}} + Q_{\text{burner}} \quad (4)$$

Q_{burner} is constant while Q_{product} varies with time as the fire spreads; the involved area $A(t)$ increases as described

above and the burning intensity and each position is time dependent. Q_{product} is obtained by adding the contributions from parts which have started to burn at various times. The heat release rate of the specimen at each location is then assumed to follow the same procedure as measured on a bench scale (i.e. the Cone Calorimeter).

A time-incremental approach is used to calculate Q_{product} . At each time step Δt , an area increment ΔA is calculated and the Q_{product} is obtained by adding the contributions from each area increment. Then we obtain, at time $t = N\Delta t$,

$$Q_{\text{product}} = \sum_{i=1}^N \Delta A_i q_{\text{bs}}^{N-i} \quad (5)$$

In an alternative form this equation may be written as an integral (Duhamel):

$$Q_{\text{product}} = \int_0^t A'(\tau) q_{\text{bs}}(t - \tau) d\tau \quad (6)$$

where A' is the time derivative of the burning area and τ is a dummy variable. No closed-form solution may, however, be obtained unless q_{bs} is given a suitable analytical form.

To explain the summation in Eqn (5) we will give a simple numerical example. Assume that the heat release rates as measured in the Cone Calorimeter and the involved area are as shown in Figs 4(a) and 4(b), respectively. The incremental contribution can then be calculated and added as shown in Table 2. The total heat release rate at the third time increment may, for instance, be calculated as:

$$(0.2)(250) + (0.45)(125) + (0.65)(50) = 50 + 56 + 32 = 138$$

This incremental technique is computationally very fast and may be carried out with such a small time increment that the details of the small-scale heat release curve can be adequately considered.

Time to ignition plays an important role in this analysis as it governs the growth rate of the burning area. An alternative form of calculation can be obtained by differentiating Eqn (2):

$$\Delta A = (2A_0 a / t_{\text{ign}}) t \Delta t \quad (7)$$

Thus the involved area for a given time is proportional to the inverse of the ignition time. The summation (Eqn (5)) may then be written in a more convenient form as⁷

$$Q_{\text{product}} = (2A_0 a / t_{\text{ign}}) \Sigma (t^i q_{\text{bs}}^{N-i} \Delta t) \quad (8)$$

Figure 4. (a) Schematic curve from heat release rate as measured in the cone calorimeter. (b) Burning area growth rate described by a parabolic relation.

Table 2. Example of heat release rate calculation

Time s	A m ²	ΔA m ² s ⁻¹	q_{bs} kW m ⁻²	Incremental contributions						Total kW
				1	2	3	4	5	6	
1 Δt	0.2	0.2	50	10						10
2 Δt	0.65	0.45	125	25	22					47
3 Δt	1.3	0.65	250	50	56	32				138
4 Δt	2.15	0.85	475	95	112	81	42			330
5 Δt	3.5	1.35	225	45	214	162	106	68		595
6 Δt	5.95	2.45	50	10	101	309	212	169	122	914

The q_{bs} column is the Cone Calorimeter result, the A column is the estimated burning area growth. By using the superposition technique with respect to when the different areas are ignited the total heat release rate is obtained.

This formula reveals how sensitive the calculated heat release rate is to the ignition time measured on a small scale. Therefore great care must be taken when preparing specimens and conducting the test. Several tests should be carried out to achieve reliable ignition time results. For this, some kind of averaging technique needs to be developed so that results from various irradiance level's can be considered. Note that all results reported here are based on single tests at an irradiance of 25 kW m⁻² in the Cone Calorimeter. It is, however, not expected that the model, in principle need be changed if ignition data of other irradiance levels are employed.

A CRITERION FOR FLAME PROPAGATION IS AN ASSUMED SURFACE TEMPERATURE

As indicated in Fig. 3, the fire may or may not spread away from the vicinity of the burner at the beginning or after 10 min when the burner output is raised to 300 kW, respectively. The criterion assumed in this model for flame spread to occur is that the surface temperature, θ_s , at an imaginary point just beyond the flame front reaches a critical value after a certain time. The calculation procedure as outlined below is very schematic but it is found for the tested products that, when the calculated surface temperature is above a particular value, flame spread occurs.

The surface temperature, θ_s , depends on the temperature of the combustion gases passing over the surface θ_{gas} , and on the thermal response of the product surface. θ_{gas} , in turn, is assumed in this model to depend on the sum of the heat release rate from the burner and the specimen product in the vicinity of the burner, i.e. Q_{total} .

The heat release from the product is calculated with involved areas as outlined above. An assumed gas temperature is then obtained in these calculations as

$$\theta_{gas} = \gamma Q_{total}^{2/5} \quad (9)$$

where γ is a proportionality factor empirically chosen to be 50 and 35 K/W^{2/5} at the burner rates of 100 and 300 kW, respectively. The expression could be compared with the plume temperatures beyond the flame (the intermittent regime) as calculated by, for instance, McCaffrey.⁸ The power 2/5 is derived for free flames, but as in this case the flames reach the ceiling a somewhat higher value could be considered.

The thermal response of the surface is assumed to be determined by the ignition time in the Cone Calorimeter only. This gives combined information about the thermal response of the surface and the ignition temperature. It is assumed in the calculation that the product is semi-infinite, i.e. thermally thick. The thermal response may then be expressed by the thermal inertia ($k\rho c$). This parameter varies by orders of magnitude while the ignition temperature lies within a relatively narrow range. The ignition time gives a measure mainly of the thermal response characteristics.

The thermal response is calculated below, assuming passing gas has a temperature varying with time, as shown above. The thermal response of the surface is then calculated by superposition. The response function, η , is chosen assuming that the body is semi-infinite and the $k\rho c$ is proportional to the ignition time measured in the Cone Calorimeter. Other response functions would, of course, be more adequate in many cases, but for the final result it seems, from our experience, not necessary to employ other functions.

Figure 5. Examples of calculated surface temperatures from three products. The dotted line (---) is one of the products that did not lead to progressive flame spread while two of the products that did give flashover are marked with full lines. The criterion for flame spread is a minimum surface temperature of 335°C. A similar procedure is outlined when the burner output is raised to 300 kW after 10 min. When the surface at any time passes a temperature of 335°C, the burning area is assumed to grow along the routes II or V, respectively, as shown in Fig. 3.

The thermal inertia, $k\rho c$, which, in theory, is relevant only for semi-infinite homogeneous products, is here replaced by what we call IRV (Ignition Response Value). IRV is assumed proportional to t_{ign} , and by matching it with the known thermal inertia of wood we get $\text{IRV} = 1250 t_{\text{ign}}$, where t_{ign} is measured in the Cone Calorimeter at an irradiance level of 25 kW m^{-2} . It would, of course, also be possible to obtain the IRV value at other irradiance levels or even by other methods.

The response function of the surface, η , expression for semi-infinite bodies exposed to a constant gas temperature θ_g , as taken from the literature^{9,10} is now employed:

$$\eta = \frac{\theta_s}{\theta_g} = \left[1 - \exp\left(-\frac{t}{\tau} \operatorname{erfc}\left(\sqrt{\frac{t}{\tau}}\right)\right) \right] \quad (10)$$

where

$$\tau = \text{IRV}/h^2 \quad (11)$$

The convection heat transfer coefficient, h , is, for numerical calculation, assumed to be $50 \text{ W m}^{-2} \text{ K}$. This rather high value is deemed reasonable for a point near the burner plume.

For gas temperature with time, surface temperature can now be obtained by superposition expressed as (the same numerical technique as outlined above for calculating heat release rate):

$$\theta_s(t) = \sum_{i=1}^N \Delta\theta_g^i \eta^{N-i} \quad (12)$$

where θ_g^i is the gas temperature at the i th time increment and η^{N-i} the response function at time $N-i$. Examples of

Figure 6. Results from experiments and calculations of the heat release rate in the standardized full-scale Room/corner Test.

calculated temperatures as a function of time are shown in Fig. 5.

CALCULATED HEAT RELEASE RATES AGREE WITH EXPERIMENTS

The model has been developed on a series of 13 products and the results are presented in Fig. 6 as the first 13 curves. As the model is designed for these products this must be noted when judging the precision of the model. There are, however, some additional tests (14–16) included, which show approximately the same prediction accuracy.

Note that the predictions are reasonably good for all products. There are no failures, although products over a

great span of fire properties are included, and there are no products predicted to be in wrong classes according to the system outlined in Table 1. The model is by no means perfect but it shows that results from the Cone Calorimeter can be employed to make accurate predictions of various aspects of fire growth.

Similar calculation techniques as has been shown here can, of course, also be developed for other scenarios. A model for predicting a product's behaviour in a surface-spread-of-flame test has recently been published. A number of other fire scenarios may be analysed if the same calculation models outlined here are developed. Possible examples of situations that can be predicted based on Cone Calorimeter results are

Other room fire scenarios
Flame spread along corridors
Flame spread along cable bunches, and

Table 3. Test materials and test data

Material	Heat release during peak period at 60 kW m ⁻² (MJ m ⁻²)	Time to ignition at 25 kW m ⁻² (s)	Density (kg m ⁻³)	Full scale time to flashover (min:s)
Rigid polyurethane foam	15.2	6	32	0:14
Textile wallcovering on rockwool	8.7	31	150	0:55
Insulating fibreboard	18.7	39	250	1:07
Expanded polystyrene	30.8	366	18	2:12
Medium density fibreboard	51.1	115	655	2:14
Wood panel (spruce)	25.3	114	450	2:18
Paper wallcovering on particleboard	48.7	132	670	2:22
Particleboard	42.8	123	670	2:30
Melamine-faced particleboard	30.1	234	870	7:45
PVC wallcovering on gypsum board	5.3	39	725	10:15*
Textile wall covering on gypsum board	11.3	108	725	10:37*
Paper wallcovering on gypsum board	7.3	105	725	No
Gypsum board	5.5	No ignition	725	No

* Flashover reached only after increase of burner heat output at 10:00 min.

Figure 7. (a) Correlation between parameters obtained in small-scale and full-scale time to flashover according to Eqn (13)³. (b) Stepwise ranking of materials obtained by an equation based on small-scale testing and measured in full-scale testing, respectively.³

Figure 8. (a) Total heat release during peak period at 50 kW/m² heat flux in the cone calorimeter. Plotted versus flashover time in full scale.³ (b) Time to ignition determined in the cone calorimeter at 25 kW/m². Plotted versus flashover time in full scale.³

Other small-scale tests (e.g. the German Brandschacht, the French Epiradiateur and the British Surface-spread-of-flame tests)

THE ÖSTMAN MODEL

Östman and Nussbaum³ have developed by linear regression a simple relationship between the Cone Calorimeter and time to flashover in the Room/corner Test. The model is derived from the same test series of 13 products described earlier.

The object of the analysis was to find a correlation between time to flashover in the ISO Room/corner test and material properties derived from Cone Calorimeter tests. After testing several possible parameter combinations Östman and Nussbaum found the best correlation to be:

$$T = \frac{t \cdot \sqrt{\rho}}{A} + b \quad (13)$$

where

T = time to flashover on a full scale(s)

t = time to ignition on a small scale at an irradiance level of 25 kW m⁻²(s)

A = heat release during the peak period at an irradiance level of 50 kW m⁻² (J m⁻²)

Figure 9. Principal sketch of total heat release during peak period after which effects are obtained.³

ρ = density (kg m⁻³)

$a = \text{constnat}, 2.76 \cdot 10^6 \frac{J}{\sqrt{kgm}}$

$b = \text{constant}, -46.0(\text{s})$

This function gave quite good correlation between the small-scale results and the large-scale behaviour as can be seen in Table 3 and Fig. 7. A difficulty with the model is that an effective density needs to be input. For non-homogeneous products this value may not be easy to find.

In their correlation study Östman and Nussbaum showed that neither ignition time nor heat release rate can, by themselves, be used to predict flashover (see Fig. 8). The A value (heat release during peak period) was also studied and it was shown that A , determined as in Fig. 9, gave better correlations than other alternatives tested.

REFERENCES

1. U. Wickström and U. Göransson, Prediction of heat release rates of surface materials in large-scale fire test based on cone calorimeter results. *ASTM J. of Testing and Evaluation*, November (1987).
2. U. Göransson and U. Wickström, Flame spread predictions in the room/corner test based on the cone calorimeter. *Interflam Symposium* (1990).
3. B. Östman and R. Nussbaum, Correlation between small-scale rate of heat release and full-scale room flashover for surface linings. *IAFSS Symposium*, Tokyo (1988).
4. S.-E. Magnusson and B. Sundström, Modelling of room fire growth—combustible lining materials. *ASTM/SFPE Symposium on Application of Fire Science to Fire Engineering*, Denver, USA (1984).

5. B. Karlsson, *Room Fires and Combustible Linings*, Department of Fire Safety Engineering, Lund Institute of Science and Technology, Report, Lund (1989).
6. B. Sundström and U. Göransson, *Possible Fire Classification Criteria and their implications for Surface Materials Tested in Full Scale According to ISO DP 9705 or Nordtest Fire 025*, SP-Report 1988:19, Statens Provningsanstalt, Borås Sweden (1988).
7. T. Überall, Personal communication, Materialprüfungsamt, Nordrhein-Westphalen, Germany (1990).
8. D. Drysdale, *An Introduction to Fire Dynamics*, p. 134, John Wiley, New York (1985).
9. J. P. Holman, *Heat Transfer*, McGraw-Hill, New York (1986).
10. J. Carslaw, *Conduction of Heat in Solids*, Oxford University Press, Oxford (1959).
11. B. Östman and R. Nussbaum, *National Standard Fire Tests in Small Scale Compared with the Full-Scale ISO Room Test*, Träteknikcentrum Rapport I 8702017, Stockholm (1987).
12. Qian Jianmin, *Prediction of Flame Spread Test Results From the Test Data of the Cone Calorimeter*, report to be published, Borås (1990).

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