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ROOM FIRES AND COMBUSTIBLE LININGS

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It is a pleasure to acknowledge the work of Berit Andersson who collected and compared different bench-scale data referred to in this report.

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Björn Karlsson
Abstract

An extensive research program on combustible wall lining materials has been carried out in Sweden.

Several lining materials were tested in full scale room tests and 1/3 scale model room tests for two different scenarios, A and B. Scenario A refers to the case where walls and ceiling are covered by the lining material, scenario B where lining materials are mounted on walls only.

A model is presented using material properties derived from standardized bench-scale tests as input data. The model predicts the fire growth in the full or 1/3 scale tests, which includes predicting the rate of heat release, gas temperatures, radiation to walls, wall surface temperatures and downward flame spread on the wall lining material.
List of symbols

\( A_p \) = Pyrolysis area
\( A_o \) = Area of opening
\( A_w \) = Wall surface area
\( C \) = Flame spread constant in eqn. (5)
\( C \) = Constant in eqn. (14)
\( c_p \) = Heat capacity (of air unless otherwise stated)
\( F \) = Configuration factor
\( g \) = Gravitational acceleration
\( h \) = Convective and radiative heat transfer coefficient
\( h_k \) = Convective heat transfer coefficient
\( H_o \) = Height of opening
\( k \) = Constant in eqn. (12)
\( \kappa_{pc} \) = Thermal inertia
\( q'' \) = Radiative heat transfer per area
\( q''_{0,ig} \) = Minimum radiant heat flux per area for sustained piloted ignition
\( q''_e \) = External radiant heat flux per area
\( Q' \) = Energy release rate per fuel area
\( Q''_{av} \) = Average heat release rate per fuel area in bench-scale test
\( Q_{ctf} \) = Non-combustible part of wall-corner flame reaching the ceiling
\( Q_{gb} \) = Heat release from gas burner
\( Q''_{max} \) = Maximum energy release rate per fuel area in bench-scale test
\( Q_{start} \) = Total heat release from gas burner and lining material behind burner
\( t_h \) = Time for pyrolysis front to move horizontally along wall-ceiling intersection to opposite corner
\( t_{ign} \) = Time to ignition in bench-scale test
\( t_p \) = Time to reach pyrolysis temperature
\( t_{start} \) = Time to reach \( Q_{start} \)
\( T \) = Temperature
\( T_{fl,f} \) = Material surface temperature just ahead of the flame front
\( T_{ig} \) = Ignition temperature
\( T_i \) = Initial temperature
\( T_s \) = Surface temperature
\( V_f \) = Flame spread velocity
\( V_p \) = Velocity of pyrolysis front
\( x_f \) = Position of the flame front in eqn. (4)
\( x_t \) = Flame height
\( x_p \) = Position of the pyrolysis front
\( \alpha \) = Entrainment coefficient in eqn. (17)
\( \alpha \) = Correlation coefficient
\[ \beta = \text{Correlation coefficient} \]
\[ \lambda = \text{Decay coefficient} \]
\[ \rho_0 = \text{Density of ambient air} \]
\[ \sigma = \text{Stefan-Boltzmann constant} \]
\[ \phi = \text{Flame spread parameter} \]
\[ \varepsilon = \text{Emissivity} \]
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1 Introduction

This report presents experimental and theoretical results from a study within the project "Fire Hazard - Fire Growth in Compartments in the Early Stage of Development (Preflashover)". The project is carried out jointly by the department of Fire Safety Engineering at Lund University and the Division of Fire Technology at the Swedish National Testing Institute. An outline of the research program is given by Pettersson [1].

Room fire growth on combustible linings has been a problem of concern to the legislators and authorities since the advent of building fire safety regulations. Work in this area has included development of bench-scale tests to derive basic flammability characteristics which could rationally be used as classification criteria. Also, full-scale standard tests have been developed to evaluate the fire performance of materials of products under actual in-use situations. The contribution of a specimen to the fire growth within a previously calibrated compartment can then be used to rate materials and to evaluate the validity of existing bench-scale test methods.

The purpose of the work presented here is to use results from bench-scale flammability tests as input to a mathematical model which could rationally predict full scale fire growth on combustible linings. Only two scenarios are considered here; scenario A, where the lining materials are mounted on compartment walls and ceiling; and, scenario B where the material is mounted on walls only.

Two room sizes were considered; the full scale test room with a single door opening in accordance with methods proposed by ASTM, ISO and NORDTEST; and, a 1/3 scale model of the full scale compartment.

The study reported here is of pilot character and should be seen as a first, preliminary attempt to arrive at a rational engineering solution of a recognized and important fire safety problem.
2 Bench-scale tests

2.1 Surface spread of flame test

The 13 materials listed in Table 1 were tested in the IMO and ISO surface spread of flame tests. The velocity of the flame front, \( V_f \), and the corresponding external heat flux, \( q''_e \), were measured at several positions along the sample. The sample surface temperature was also measured at some of these positions during the test. A detailed description of the test apparatus, procedure and results is given in [2].

2.1.1 Determination of the minimum radiant heat flux to sustain piloted ignition.

Harkleroad, Quintiere and Walton [3] determined \( q''_{0,ig} \) from the surface spread of flame test. The method of plotting \( 1/\sqrt{V_f} \) versus \( q''_e F(t) \) was introduced, where the intercept on the latter axes gave \( q''_{0,ig} \). An expression for the minimum radiant heat flux to sustained piloted ignition was given as

\[
q''_{0,ig} = h (T_{ig} - T_i)
\]  

The values of \( q''_{0,ig} \) used in this work were reported in Ref. 2. Andersson [4] used data from Ref. 2 and the method of plotting \( 1/\sqrt{V_f} \) versus \( q''_e F(t) \) to obtain the flame spread parameter C. Figure 1 shows, as an example, the plot for material no.3 from in Table I. The slope of the line resulting from the plot of \( 1/\sqrt{V_f} \) versus \( q''_e F(t) \) gives this parameter. The values of C reported in Ref. 4 and the values obtained in Ref. 3 were compared and there seemed to be no large differences in the data except for material no. 12, wood panel, spruce. Data are reproduced in Appendix A.

2.1.2 Determination of ignition temperature

The ignition temperature, \( T_{ig} \), is an important material parameter when studying opposed flow flame spread over a solid. This temperature can be calculated from equation (1) but to do this the parameters \( q''_{0,ig} \), \( h \) and \( T_i \) need to be determined.

The values of \( q''_{0,ig} \) used here were those derived by Sundström [2]. Ref. 3 gives an expression for the heat transfer coefficient, \( h \):

\[
h = 0.01 (1 + 0.0085 (T_s - T_i))
\]  

The initial temperature, \( T_i \), was fixed at 20°C for all materials. By assuming a value for \( T_{ig} \) and substituting it for \( T_s \) when calculating \( h \), \( T_{ig} \) could be calculated by an iterative process. The values of \( T_{ig} \) obtained in Ref. 3 were compared with similar materials from Ref. 4, the agreement was relatively good. Data are reproduced in Appendix A.
2.1.3 Determination of the flame spread parameter, φ

The following well known expression has been given ([5], [6], etc) for the velocity of the flame front for a slab initially at the temperature \( T = T_s \)

\[
V_f = \phi / (T_{ig} - T_s)^2
\]  

(3)

where \( \phi \) depends on the thermal properties of the solid, the ambient oxygen concentration, flow speed and the heat flux ahead of the advancing flame. \( V_f \) is determined from the surface spread of flame test as

\[
V_f = dx_f / dt
\]  

(4)

The flame spread parameter \( \phi \) can be determined from the experimentally-determined parameter \( C \)

\[
\phi = V_f (T_{ig} - T_s)^2 = 1/(Ch)^2
\]  

(5)

The heat transfer coefficient, \( h \), and the flame spread constant, \( C \), were determined as discussed above. Andersson [4] compared the resulting values of the flame spread parameter, \( \phi \), to those reported in Ref. 3 and found the agreement satisfactory. Data are reproduced in Appendix A. The values of \( \phi \) used in this work are listed in Table I.

2.2 Ignitability test

The test - ISO TC92 TR5657, Fire Tests, Reaction to Fire, Ignitability of Building Products - is described in [28]. The main quantitative information from the test is a set of values of \( t_e \) for a set of exposure radiation levels \( q''_e \). Data can also be extrapolated to give the minimum level of impressed flux to cause ignition, \( q''_{0,ig} \).

The time to ignition is closely related to the thermal inertia, \( kpc \), of the tested material. With additional thermocouples attached to both sides of the sample the test can be used to derive parameters such as thermal conductivity, \( k \), and thermal capacity, \( pc \), of the tested specimen. The values of thermal inertia used in this study were derived in this way and are listed in Table I. A full description of the method used to derive these parameters is given in Ref. 11.

2.3 Rate of Heat Release measurements

The 13 materials were tested in three different RHR apparatuses: the Ohio State University apparatus [7], an open configuration [8] based on a design originally developed by the National Institute of Standards and Technology (formerly National
The equipment consists of a vertical sampleholder and an electrical radiation panel placed under an open hood. The samples were tested at 5, 3 and 2 W/cm² and some easily ignitable materials also at 1 W/cm². An example of the test output is given in Fig. 2 for material 3.

An attempt to calculate the mass loss and RHR analytically was not successful, as described in [11]. Therefore it was decided to describe and make use of the RHR characteristics of the involved material directly, using a mathematical approximation of the curves shown in Fig. 2, primarily the curves valid for external flux equal to 3 W/cm². In the full scale experiments, heat fluxes to the lining material will vary considerably with time and location. A study of available literature indicated that an average value of 3 W/cm² might be more representative than 5 W/cm², but this has not been substantiated.

The experimental curves were idealized as seen in Fig. 3, resulting in the expression

$$Q'(t) = Q'_{\text{max}} e^{-\lambda(t - \tau_0)}$$

Equation (6) assumes semi-infinite sample (no returning heatwave) and may have to be changed. The $Q_{\text{max}}$ values were taken directly from measurements and are given together with the corresponding regression values of $\lambda$ in Table I. Equation (6) seemed phenomenologically correct except for materials 9 and 10. Full results are given in Ref. 11.

### 3 Corner test experiments carried out in Sweden

#### 3.1 Full scale tests carried out at the Swedish National Testing Institute, Borås, Sweden

The full scale tests, scenario A, were carried out according to the standard test method NT FIRE 025 [12]. The fire test room is 3.6 m long, 2.4 m wide and 2.4 m high with a doorway measuring 0.8 m wide and 2.0 m high. The walls are of lightweight concrete, 150 mm thick. The ignition source was a propane gas burner situated on the floor, in a corner of the room, with an effect of 100 kw. If this effect did not cause flashover in 10 minutes the effect was raised to 300 kw for another 10 minutes. The 13 different lining materials tested are listed in Table I. All tests were terminated after flashover, defined as flames emerging out of the doorway.

A detailed description of this test series is given by Sundström [13].
For scenario B, the same room, ignition source and procedure were used as described above for scenario A, except that no lining material was mounted on the ceiling. Only 3 materials were tested, namely materials no. 2, 3 and 8 in Table I.

Ondrus [14] described the test series summarily.

3.2 1/3 scale experiments carried out at the Department of Fire Safety Engineering, Lund University

The experiments were carried out in a room with a length of 1.2 m, width of 0.8 m and height of 0.8 m. A description of the test procedure and results is given by Andersson [15]. The room is a 1/3 scale model of the full scale compartment at the National Testing Institute in Borås. Scaling criteria was to achieve the same upper layer gas temperature in full- and 1/3 scale. The ignition source was a gas burner with an effect of 11 kw for 10 minutes and, if no flashover occurred, 33 kw for another 10 minutes.

For scenario A, where lining material was mounted on both ceiling and walls, the doorway measured 0.56 m wide and 0.67 m high.

In scenario B, where the lining material was mounted on walls only, the door opening measured 0.46 m wide and 0.67 m high.

3.3 Results from 1/3 scale and full scale tests

The four experimental series discussed above were carried out over the period of four years and therefore not very coherent. In some series heat flux was measured at floor level only, in others at different heights at the lining material surface as well as at the floor level. Similarly, gas temperatures and surface temperatures were measured at different heights resulting in difficulties when comparing results between series.
4 Calculation of RHR in room fire experiments

4.1 RHR in scenario A

Magnusson [11] developed a model allowing the RHR in scenario A to be calculated. The method presented in this chapter is based on that work. Scenario A, as mentioned above, refers to the case where lining materials are on three walls and ceiling. Soon after the gas burner is started in the corner test, the wall material behind it ignites. The time for this to happen must be evaluated as well as the RHR from the burning wall and ceiling lining material.

4.1.1 Time to ignition

A quantity $Q_{\text{start}}$ is defined as the sum of the heat release from the ignition source and the vertical wall area behind the burner, assuming complete combustion. The corresponding time $t_{\text{start}}$ denotes the time necessary for the whole of the lining material behind the burner to be pyrolysing. $t_{\text{start}}$ is taken directly from the experimental time - RHR curves and thus includes time delay components such as transportation time in the measurement system.

Comparison of $t_{\text{start}}$ values with results from the ISO ignitability test can be done in various ways. It was found that the simple procedure of correlating ignition time at the 30 kw/m² impressed radiation level with $t_{\text{start}}$ seemed to work best. For the full scale series

$$t_{\text{start}} = t_{\text{ign}} + 5$$

and for the 1/3 scale series

$$t_{\text{start}} = t_{\text{ign}} \times 1.85$$

gives a reasonable approximation of $t_{\text{start}}$. The different dependencies of $t_{\text{start}}$ on $t_{\text{ign}}$ reflects the difference in thermal load from the 100 kw and 11 kw gas burner flame respectively. Observe that the strength of the ignition source means that the total height of the corner is covered by flame from the start of the experiment.

4.1.2 Calculation of RHR

The model is based on the concepts presented in [16], [17] and [18] from which $A_p$ may be considered as a driving force in a process where the rate of increase of $A_p$ is proportional to the quantity $A_p$ itself; i.e. $A_p$ is exponentially increasing with time. In the regression model of ceiling flame spread and combustion presented in [11], which includes the horizontal wall flame propagation along the intersection ceiling - wall,
pyrolysis area $A_p$ was written as

$$A_p(t) = \alpha(e^{at} - 1)^\beta$$  \hspace{1cm} (7)

where $a = \frac{h^2}{kpC}$ and $\alpha$ and $\beta$ were coefficients to be determined statistically. The rate of heat release could then be expressed as

$$Q(t) = A_p(t) \ast Q^{''}_{\text{av}}$$  \hspace{1cm} (8)

where $Q^{''}_{\text{av}}$ denotes a suitable time and space averaged measure of material rate of heat release per unit area. It was shown in chapter 2.4 that $Q^{''}(t)$ for a certain constant impressed heat flux could be written as

$$Q^{''}(t) = Q^{''}_{\text{max}} e^{-\lambda(t - t_p)}$$  \hspace{1cm} (9)

Combining equations 7 to 9 and describing the interaction of flame spread and rate of heat release by a superposition, Duhamel-type integral [19], a final, non-dimensional form of the regression equation was given in Ref. 11 as

$$\frac{Q_{\text{rt}} - Q_{\text{start}}}{Q_{\text{cf}}} = \alpha' \left[ e^{at} - e^{-\lambda t} \right]^\beta Q^{''}_{\text{max}} \left( \frac{a}{a + \lambda} \right)$$  \hspace{1cm} (10)

where $Q_{\text{start}}$ is as defined earlier, $Q_{\text{rt}}$ denoting measured RHR (rt meaning room test) and $Q_{\text{cf}}$ the non-combusted part of wall corner flame reaching the ceiling (= $Q_{\text{start}}$ minus combustion in the vertical part of the corner flame). The time $t$ is measured from $t = t_{\text{start}}$. For the relatively short, initial period $0 < t < t_{\text{start}}$ the rate of heat release is assumed to grow linearly up to $Q_{\text{start}}$.

The overall average values and coefficients of variations for the parameters in model eqn (10) were given as:

$$\alpha'_{\text{aver}} = -4.58 \quad (= \ln \alpha) \quad \sigma_{\alpha'_{\text{aver}}} = 0.13$$

$$\beta_{\text{aver}} = 1.15 \quad \sigma_{\beta_{\text{aver}}} = 0.276$$

It remains to be studied how well time-RHR curves from the experiments can be recalculated using average values of $\alpha$ and $\beta$. Fig. 4 a) shows the results of using the regression equation on material 3 in Table I for the full scale test. Fig. 4 b) shows the same for the 1/3 scale test. The regression equation has been used for 6 materials in both full scale and 1/3 scale tests, showing similar results. The complete set of curves are shown in Appendices B and C (B1-B3 and C1-C3 respectively). Observe that the downward flamespread is not included in equation (10). Further comments on this point are found in Chapter 8.
4.2 RHR in scenario B

The procedure for calculating rate of heat release in scenario B builds on the same principles as the one described above. In this scenario there is, however, no material on the ceiling.

The total rate of heat release in the room is assumed to come from five sources; the gas burner, the vertical wall area behind the burner, a horizontal strip of material corresponding to the vertical height of the ceiling jet at the ceiling-wall intersection, the wall material in the upper layer and, when downward flame spread has started, from the wall linings below the hot gas layer.

The scenario we are considering is the following one: The walls of the test room are lined with the material. The ignition source in the corner ignites the wall corner material and spreads upward on an area, $A_w$, approximately equal to the width of the burner times the distance from the burner to the ceiling. In this initial period, $0 < t < t_{start}$, the rate of heat release is calculated in the same way as above, i.e. assumed to grow linearly up to $Q_{start}$ at time $t_{start}$.

The resulting ceiling jet, or flame, spreads along the intersections between the walls and the ceiling in the mode of concurrent flame propagation. After a time $t_h$ the pyrolysing area has propagated to the nearest corner in the room and a strip of material at the top of the walls is pyrolysing. In the experiments discussed here this strip has a height of around 5% of the room height. We assume we can calculate how long it will take for the pyrolysing area to reach the nearest corner. In the period $t_{start} < t < t_h$ there are thus three sources that contribute to the total heat release; the gas burner, the diminishing effect of the pyrolysing area behind the gas burner and the increasing pyrolysis area of the horizontal strip at the wall-ceiling intersection.

It remains to give expressions for $t_h$, the time at which the horizontal pyrolysing area reaches the an opposite corner. Saito, Quintiere and Williams [20] have given the upward spread velocity of the pyrolysis front as

$$V_p = 4 (q_0^o)^2 (x_f - x_p)/[\pi k \rho c(T_p - T_e)^2]$$

which has been employed in some recent studies by several workers ([21], [22] and others). The flame height $x_f$ has been shown to only depend on the energy release rate per unit wall width ([21], [22], [23] and [24]) and several expressions for $x_f$ have been given.

Efforts are being made to apply the above method to the horizontal concurrent flame spread. Some problems have been encountered in estimating the horizontal flame length $x_f$ since earlier reported flame height correlations may not be valid in the
horizontal ceiling-wall intersection configuration. Results from this part of the study will be reported later.

The problem of estimating $t_h$, the flame spread along intersection wall - ceiling and the resulting rate of heat release was therefore solved rather crudely as a first effort and is considered to be a temporary solution. Magnusson [25] suggested a simple expression for the calculation of $A_{ph}$, the horizontal pyrolysing area, assumed to increase linearly with time

$$A_{ph}(t) = k \cdot t \cdot (Q_{start} - Q_{gb}) / k_p c$$ \hspace{1cm} (12)

The factor $k$ was derived from experiments to be $= 0.004 \text{ w/(m K)^2}$. For each $\Delta t$ the pyrolysis area increases by $\Delta A_{ph}$. As mentioned above, equation (12) will eventually be changed, using for example the methodology described in [24] instead.

Following a similar procedure as for scenario A, the expression for the rate of heat release for the time period $t_{start} < t < t_h$ is then written at time step $j$ (counted from $t_{start}$) as

$$Q(t) = Q_{gb} + A_u \cdot Q''_{max} \cdot e^{(-\lambda \Delta t^j)} + \sum [\Delta A_{ph} \cdot Q''_{max} \cdot e^{(-\lambda \Delta t^j)}]$$ \hspace{1cm} (13)

where $Q_{gb}$ stand for the effect from the gas burner, $Q''_{max}$ is the maximum energy release rate per fuel area from the bench-scale test and $A_u$ is the area of wall material behind the burner.

The first term is the effect from the gas burner, the second the contribution from the wall behind the burner and the third from the part of the horizontal strip which is pyrolysing.

For the period $t > t_h$ the downward flame spread contributes to the increasing rate of heat release. To equation (13) is then added the contribution of the downward flame spread in the upper layer and, once the flames reach the intersection of the hot gas layer and the lower ambient layer, the downward flame spread below the hot layer.

Fig. 4 c) shows the results of using this procedure on material 3 in Table I for the full scale test. Fig. 4 d) shows the same for the 1/3 scale test. Appendix E shows results for other materials in the 1/3 scale test series, scenario B.

The following sections describe how the gas temperatures, surface temperatures in the hot layer and below the hot layer and the downward flame spread are calculated, thus adding to the rate of heat release.
5 Calculation of gas temperatures

The basic principle used to calculate the temperature in a compartment fire is the conservation of mass and energy. Since the energy release rate and the compartment temperature change with time, the application of the conservation laws will lead to a series of differential equations.

By making certain assumptions on the energy and mass transfer in and out of the compartment boundaries, the laws of mass and energy conservation can result in a relatively complete set of equations. Due to the complexity and the large number of equations involved, a complete solution of the set of equations would usually only be obtained from computer programs.

However, now there exist regression formulae which, with a number of limiting assumptions, allow the gas temperature in a naturally or mechanically ventilated compartment to be calculated by hand.

McCaffrey, Quintiere and Harkleroad [26] used a simple conservation of energy expression and a correlation of a relatively wide range of data to develop a hand-calculation formula for the hot layer temperature in a naturally ventilated compartment.

The upper layer temperature was written as a function of two dimensionless groups

\[
\frac{\Delta T}{T_0} = C \cdot X_1^N \cdot X_2^M
\]  

The constants C, N and M were determined from a wide range experimental data, the final form of the regression equation in [26] was given as

\[
\frac{\Delta T}{T_0} = 1.63 \left( \frac{Q}{\sqrt{g \cdot c_p \cdot \rho_o \cdot T_o \cdot A_o \cdot \sqrt{H_o}}} \right)^{2/3} \left( \frac{h_k \cdot A_w}{\sqrt{g \cdot c_p \cdot \rho_o \cdot A_o \cdot \sqrt{H_o}}} \right)^{-1/3}
\]

The heat transfer coefficient, \( h_k \), depends on the duration of the fire and the thermal characteristics of the compartment boundaries. The thickness of the lining materials treated here and the short duration of the corner test is such that the outer boundaries of the test compartment do not have an effect on the heat transfer coefficient. It can therefore be written as:

\[
h_k = \sqrt{k \cdot \rho \cdot c / t}
\]
5.1 Calculation of gastemperatures in the current paper

The energy released within the compartment in flame and upper layer combustion is restricted by the availability of oxygen. The heat release measured in the experiments includes the energy released in the flames coming out through the opening. This part of the heat release does not influence the gastemperature within the compartment. The availability of oxygen in the upper layer can be approximated by using a simple flame formula [27], calculating the entrainment of air into the corner flame

\[ m_\text{air}' = \frac{2}{3} \alpha \rho_a \sqrt{2g \left(1 - \frac{T_a}{T_\text{fl}}\right)} X_f^{3/2} \]  (17)

where \( X_f \) is the effective entrainment flame height, \( \alpha \) is the entrainment coefficient and \( T_\text{fl} \) is the flame temperature. Thus, the maximum rate of heat release inside the compartment was found to be approximately 600 kw for the full scale room and 40 kw for the 1/3 scale room.

The method developed in [26] was followed to calculate the upper layer gastemperatures in the corner test experiments. An attempt was made to determine the constants \( C, N \) and \( M \) by regression analysis but results were not satisfactory. The two constants, \( N \) and \( M \), as they appear in equation (4) did however seem to describe the slope and shape of the experimental curves well. The constant \( C \) was then determined for each of the experimental series with the following results:

- Full scale, scenario A \( C_{\text{aver}} = 2.048 \)
- 1/3 scale, scenario A \( C_{\text{aver}} = 2.237 \)
- Full scale, scenario B \( C_{\text{aver}} = 2.700 \)
- 1/3 scale, scenario B \( C_{\text{aver}} = 2.240 \)

The experimental gastemperature was measured by thermocouples 5 cm from the ceiling in both 1/3 scale tests series and 30 cm from the ceiling in full scale test, scenario A. But in the full scale B test series the gastemperature was measured only 10 cm from the ceiling, resulting in relatively much higher gastemperature values than in the other test series. This accounts for the much higher \( C_{\text{aver}} \) in the last mentioned test series.

The procedure of limiting the RHR by the air entrainment into the corner flame and finding a pre-exponential factor for each test series proved to be very robust and showed good agreement with experimental results. Fig. 5 a), b), c) and d) show results of using the above procedure on material 3 in Table I for both scenarios and both compartment sizes. This has also been done for most of the materials in Table I, showing similar results. The results are partly shown in Appendices B, C, D and E.
6. Heat transfer to walls

When the fire in the corner starts and the lining material in the corner ignites, combustion products and plume entrained air are transferred to the ceiling. The hot gas layer forms, descends and increases in temperature with time. Relatively early in the test the layer reaches the top of the opening, stabilizes and hot gases start flowing out through the opening.

Classical heat transfer provides expressions for quantities such as view factors, radiation and temperature fields in semi-infinite bodies. The lining materials studied here were treated as semi-infinite bodies since the test duration is relatively short.

One long side of the compartment wall was split into a large number of thin, horizontal strips and the instantaneous heat flux from the gas layer to the center of each strip calculated using the expression

\[ q'' = \varepsilon F \sigma (T_g^4 - T_0^4) \]  \hspace{1cm} (18)

The emission coefficient was taken to be a constant value close to unity. The configuration factor, \( F \), was calculated in a conventional way, treating the center of each strip as a point. Once the downward flame spread started the radiation from the wall flames and the pyrolysing lining material behind the flames was added to the smoke layer radiation. The instantaneous heat flux to the walls was then calculated from the expression

\[ q'' = \varepsilon_g F_g \sigma (T_g^4 - T_0^4) + \varepsilon_f F_f \sigma (T_f^4 - T_0^4) + \varepsilon_p F_p \sigma (T_p^4 - T_0^4) \]  \hspace{1cm} (19)

where the subscript \( g \) refers to the gaslayer, \( f \) to the flame and \( p \) to the pyrolysing wall material. The view factors from the flame and the pyrolysing wall material were assumed to be identical and equal to the total burning area of lining material. The flame temperature was taken to be \( = 1100^\circ \) K and the pyrolysing material surface temperature was assumed to be \( = 750^\circ \) K. Further, the flame emission coefficient was taken to be \( = 0.5 \) as was the surface of the pyrolysing material. A sensitivity analysis is necessary.
7 Wall surface temperatures

As explained above, one long side of the compartment wall was split into a large number of thin strips and the heat flux to the center of each strip calculated. Solving the general one-dimensional heat conduction equation by means of Laplace transformations the wall surface temperature at time \( t \) can be calculated from

\[
T_s - T_0 = \left(\frac{q''}{h}\right) \ast \left(1 - e^{h^2 u/kpc} \ast \text{erfc}(\sqrt{h^2 u/kpc})\right)
\]  

(20)

This assumes a semi-infinite wall and a constant heat flux \( q'' \).

Knowing the heat flux as a function of time, the wall surface temperature at timestep \( n \) can be calculated using the superposition principle. Equation (20) then becomes

\[
T_s(n) - T_0 = \sum_{i=1}^{n} \left(\frac{q''(i) - q''(i-1)}{h}\right) \exp\left(\frac{h^2 (n - i) dt}{kpc}\right) \text{erfc}\left(h \sqrt{\frac{(n - i) dt}{kpc}}\right)
\]

(21)

where \( dt \) is the size of the timestep.

The surface temperature can thus be calculated as a function of time and height from the floor. Here, the Newtonian cooling coefficient, \( h \), was assumed to be a constant value equal to 30 w/m\(^2\), throughout the test. An explicit form of the superposition integrals can be found in [29].

Similarly, the surface temperature of the wall material emerged in the hot layer can be calculated from the expression

\[
T_s(n) - T_0 = \sum_{i=1}^{n} T_e(i) - T_e(i-1) \exp\left(\frac{h^2 (n - i) dt}{kpc}\right) \text{erfc}\left(h \sqrt{\frac{(n - i) dt}{kpc}}\right)
\]

(22)

using the superposition principle and assuming a constant heat transfer coefficient. Putting the Newtonian cooling coefficient in (21) and the heat transfer coefficient in (22) equal to a constant value is of course an oversimplification and is seen only as a temporary measure.

No wall surface temperatures were measured in the full scale test series, scenario A and in the 1/3 scale test series, scenario B. Fig. 6 a) shows the experimental and calculated wall surface temperatures, at a height of 0.45 m from the floor, for material 3, 1/3 scale test, scenario A. Fig. 6 b) shows the same, but at a height of 1.2 m from the floor, for the full scale test, scenario B. Appendices C and D show surface temperatures for other materials and at different heights from the floor.
8 Downward flame spread

The RHR in scenario A is calculated from a regression equation (10) where the only dependent variable is time. Calculation according to equation (10) stops before downward flamespread has become significant or dominant.

In scenario B, however, both the horizontal concurrent flame spread and the downward flame spread, in and below the hot gas layer, are directly linked to the rate of heat release.

8.1 Downward flame spread for scenario A

Relatively early in the test the hot gas layer reaches the top of the opening, stabilizes and hot gases flow out through the opening. We have assumed that at the beginning of the test the hot layer is already stabilized at the height of the opening, this has a relatively small influence on the radiation from the hot layer to the walls since the layer is relatively cold to begin with.

No attempt is made to predict what happens within the hot smoke layer for scenario A. The smoke is quite thick in this scenario and it is difficult to visually see what happens there. When the smoke layer has been heating the wall surfaces for some time, occasional flames start appearing at the interface of the smoke layer and the walls. Shortly after, a thin, horizontal line of flames has been established on the lining material at this interface. The downward flame spread is quite slow to begin with but accelerates with time and can be calculated from a similar expression to equation (3)

\[ V_f = \varphi / (T_{ig} - T_{fl,t})^2 \]  

(23)

where \( T_{ig} \) and \( \varphi \) are obtained from the bench-scale tests discussed in Chapter 2 of the current paper. \( T_{fl,t} \) is the material surface temperature just ahead of the flame front. If the position of the flame front is known, this surface temperature at a certain wall height and certain time, can be extrapolated from the surface temperatures calculated at the center of each wall strip at each time step. The downward flame spread can thus be calculated.

Since what happens in the gaslayer is not treated in scenario A, the wall flames are assumed to start at the intersection of the walls and the hot layer, i.e. 40 cm from the ceiling in the full scale tests and 13 cm from the ceiling in the 1/3 scale tests.

In the full scale test series, scenario A, the test was terminated at flashover so no data is available for the downward flame spread in this series. Fig. 6 c) shows the experimental and calculated downward flame spread for material 3, 1/3 scale test, scenario A. Appendix C shows results for other materials (C11 - C13).
8.2 Downward flame spread for scenario B

Once the horizontal, concurrent flame spread along the wall ceiling intersection has reached an opposite corner in the compartment the downward flame spread in the upper layer starts. In reality, this could possibly start happening during the concurrent flame spread time interval. In the current version of the model, no account is taken of the relatively low oxygen concentration in the upper layer. The flame spread is quite slow at first since the wall material has a relatively low surface temperature. It then accelerates until it reaches the interface of the smoke layer and walls.

At this point the flame spread slows down since the walls beneath the smoke layer have a lower surface temperature than the walls immersed in the hot layer. The downward spread then accelerates again. The flame spread is calculated from equation (23) as above.

Fig 6 d) shows the experimental and calculated downward flame spread for material 3, full scale test, scenario B.

No results of the downward flamespread in the 1/3 scale test, scenario B are shown, due to lack of accurate experimental data. Some indicational data was available from slides taken during the experiments. Comparing this with the calculated downward flamespread it can be stated that the methodology outlined above seems to work. However, it is clear that the various sub-processes in the methodology and the parameters included in these, such as \( A_{ph} \), will have to be investigated in greater detail.

It should be noted that the calculated rate of heat release for this test series (see Appendix E) shows a good agreement with the experimental results for all four lining materials presented. This is taken as an indirect confirmation of the validity of the model for downward flamespread.
9 Remarks on the results

No sensitivity testing has so far been carried out with respect to the different
assumptions and procedures just enumerated. Changes will certainly be introduced,
especially regarding the horizontal concurrent flame spread which will follow the
methods outlined in [21], [22] and [24]. The Newtonian cooling coefficient and the
heat transfer coefficient in equations (21) and (22) will be calculated as functions of
surface temperatures. Certain other areas in the procedure need to be looked at more
closely, a sensitivity analyses with regards to emission coefficients and heat transfer
coefficients, as well as other input parameters, will need to be carried out.

The ISO surface spread of flame test seems to correlate well with room test behavior
when directly comparing times to ignition and rates of opposed flow flame spread. For
the RHR-test the correlation is more implicit. A simple model incorporating data from
this test and the ignitability test is capable of predicting the first phases of room fire
growth in scenario A. The basic structure of the model for predicting fire growth in
scenario B seems acceptable although it needs improving. This is valid for both full
scale and the 1/3 scale test room.
References


Table 1

<table>
<thead>
<tr>
<th>Material no.</th>
<th>Material name</th>
<th>$Q_{\text{max}}$ kW/m²</th>
<th>$\lambda$ s⁻¹</th>
<th>$\kappa p c \cdot 10^{-3}$ (W/m² K)²</th>
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</table>

Surface Spread of Flame Test
Flamespread correlations

Fig. 1. $1^{1/2} N t$ (mm/s)²

Fig. 2. Results from RHR bench-scale test

Fig. 3. Principle for analytical approximation of experimental RHR curves
# Appendix

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<td>B7 - B9</td>
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<td>E: Comparison of experimental and calculated data from 1/3 scale test series, scenario B</td>
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<td>E1 - E2</td>
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<tr>
<td>Hot gas temperatures</td>
<td>E3 - E4</td>
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# Appendix A

## Bench - Scale Test Results

### Contents

<table>
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<th>Page</th>
</tr>
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<td>---------------------------------</td>
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<tr>
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<td>11</td>
<td>0,4 *</td>
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<tr>
<td>12</td>
<td>0,4 *</td>
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<tr>
<td>13</td>
<td>1,7</td>
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</tbody>
</table>

\(\text{(BA)}\) refers to results published in reference [4].
\(\text{(JQ)}\) refers to results published in reference [3].
* These values are erroneous
Surface Spread of Flame Test
Flamespread correlations

1/\sqrt{V_f}
(mm/s)^{1/2}

\( F(t) \cdot q(t) \)
(kW/m^2)

Insulating fiberboard

Surface Spread of Flame Test
Flamespread correlations

1/\sqrt{V_f}
(mm/s)^{1/2}

\( F(t) \cdot q(t) \)
(kW/m^2)

Medium density fiberboard
Surface Spread of Flame Test
Flamespread correlations

![Graph of 1/√Vf vs. F(t)*q(t) for Particle board and Gypsum plasterboard.](image)

Surface Spread of Flame Test
Flamespread correlations
Surface Spread of Flame Test
Flamespread correlations

PVC wallcovering on gypsum plasterboard

Paperwallcovering on gypsum plaster board
Surface Spread of Flame Test
Flamespread correlations

Surface Spread of Flame Test
Flamespread correlations
Appendix B

Comparison of experimental and calculated data from full scale test series, scenario A

Contents

- Rate of heat release
- Hot gas temperatures
- Heat flux to floor

Page
B1 - B3
B4 - B6
B7 - B9

Note: No experimental data of wall temperatures or downward flame spread exists for this series.
RHR from full scale room test

Particle board

RHR (MW)

TIME (s)

Textile wallcovering on mineral wool

RHR (MW)

TIME (s)

- Experimental
- Theoretical
RHR from full scale room test

Wood panel, spruce

RHR (MW)

TIME (s)

Experimental
Theoretical

RHR from full scale room test

Paper wallcovering on particle board

RHR (MW)

TIME (s)

Experimental
Theoretical
HOT GAS TEMPERATURES
Full scale room test

Paper wallcovering
on particle board

Wood panel, spruce

Experimental
Theoretical
Heat flux to floor, full scale room test

Insulating fibreboard

Experimental

Theoretical

Heat flux to floor, full scale room test

Medium density fibreboard

Experimental

Theoretical

Q (kW/m²)

Time (s)

Q (kW/m²)

TIME (s)
Heat flux to floor, full scale room test

Particle board

Gypsum plaster board

Experimental
Theoretical
Appendix C

Comparison of experimental and calculated data from 1/3 scale test series, scenario A

Contents

- Rate of heat release  
  Page  
  C1 - C3

- Hot gas temperatures  
  C4 - C6

- Wall surface temperatures, 45 cm from floor  
  C7 - C8

- Wall surface temperatures, 30 cm from floor  
  C9 - C10

- Downward flamespeed  
  C11 - C13
RHR from 1/3 scale room test

Insulating fibreboard

RHR (kW)

TIME (s)

RHR from 1/3 scale room test

Medium density fibreboard

RHR (kW)

TIME (s)
RHR from 1/3 scale room test

Textile wallcovering on mineral wool

**Experimental**  
**Theoretical**

RHR (kW) vs. TIME (s)

RHR from 1/3 scale room test

Wood panel, spruce

**Experimental**  
**Theoretical**

RHR (kW) vs. TIME (s)
HOT GAS TEMPERATURES
1/3 scale room test

Particle board

Insulating fibreboard

Experimental
Theoretical
HOT GAS TEMPERATURES
1/3 scale room test

Wood panel, spruce

Paper wallcovering on parungle board

- Experimental
- Theoretical
HOT GAS TEMPERATURES
1/3 scale room test

Note: No temperature data is available for material no. 2, medium density fibreboard, due to thermocouple failure during the test.
Wall surface temperatures, 1/3 scale test, scenario A

Centre of rear wall, 45 cm from floor

Wall surface temperatures, 1/3 scale test, scenario A

Centre of rear wall, 45 cm from floor
Wall surface temperature, 1/3 scale test, scenario A

Centre of rear wall, 45 cm from floor

Particle board

Ts (°C)

Time (s)

Wall surface temperatures, 1/3 scale test, scenario A

Centre of rear wall, 45 cm from floor

Wood panel, spruce

Ts (°C)

Time (s)
Wall surface temperatures, 1/3 scale test, scenario A

Centre of rear wall, 30 cm from floor

Time (s)

Ts (°C)

Insulating fibreboard

- Ts 0.3 calc
- Ts 0.3 exp

Wall surface temperature, 1/3 scale test, scenario A

Centre of rear wall, 30 cm from floor

Time (s)

Mediu density fibreboard

- Ts 0.3 calc
- Ts 0.3 exp
Wall surface temperatures, 1/3 scale test, scenario A

Centre of rear wall, 30 cm from floor

Particle board

Time (s)

Wall surface temperatures, 1/3 scale test, scenario A

Centre of rear wall, 30 cm from floor

Wood panel, spruce

Time (s)
Downward flame spread, 1/3 scale test, scenario A

![Graph of insulating fibreboard flame spread](image1)

![Graph of medium density fibreboard flame spread](image2)
Downward flame spread, 1/3 scale test, scenario A

Particle board

Wood panel, spruce
Downward flame spread, 1/3 scale test, scenario A

Textile wallcovering on mineral wool

- $x$ (calc)
- $x$ (exp)
Appendix D

Comparison of experimental and calculated data from full scale test series, scenario B

Contents

- Rate of heat release
- Hot gas temperatures
- Heat flux to walls
- Heat flux to floor
- Wall surface temperatures
- Downward flame spread

Note: Only results from Particle board
RHR, full scale test, scenario B

Particle board

RHR (kW)

Time (s)

Hot gas temperatures, full scale test, scenario B

Particle board

$T_g$ (°C)

Time (s)
Heat flux to wall, full scale test, scenario B

Centre of long wall, 180 cm from floor

![Graph showing heat flux to wall, scenario B, 180 cm from floor.]

Heat flux to wall, full scale test, scenario B

Centre of long wall, 120 cm from floor

![Graph showing heat flux to wall, scenario B, 120 cm from floor.]
Heat flux to wall, full scale test, scenario B

Centre of long wall, 60 cm from floor

Particle board

Heat flux to floor, full scale test, Scenario B

Particle board

Q_W (kW)

Q_{f_l} (kW)

Time (s)

Time

Q_{w 60 exp}

Q_{w 60 cal}

Q_{f_l exp}

Q_{f_l cal}
Surface Temperatures, full scale test, scenario B

Centre of long wall, 180 cm from floor

Particle board

- Ts 180 exp
- Ts 180 cal

Surface temperatures, full scale test, Scenario B

Centre of long wall, 60 cm from floor

Particle board

- Ts 60 exp
- Ts 60 cal
Surface temperatures, full scale test, scenario B
Centre of long wall, 120 cm from floor

![Graph showing surface temperatures (°C) over time (s) for scenario B.]

Downward flame spread, full scale test, scenario B

![Graph showing downward flame spread (m) over time (s) for scenario B.]

- **Particle board**: Graphs showing experimental (X exp) and calculated (X cal) data points.
Appendix E

Comparison of experimental and calculated data from 1/3 scale test series, scenario B

Contents

- Rate of heat release
  
- Hot gas temperatures

Page

E1 - E2

E3 - E4

Note: No experimental data of wall temperatures or downward flame spread exists for this series
RHR, 1/3 scale test, scenario B

Insulating Fibreboard

RHR, 1/3 scale, scenario B

Medium density fibreboard
RHR, 1/3 scale test, Scenario B

Particle Board

RHR, 1/3 scale test, scenario B

Wood Panel, Spruce
Gastemperatures, 1/3 scale, Scenario B

Insulating Fibreboard

Medium Density Fibreboard

T_f (°C)

Time (s)
Gastemperatures, 1/3 scale test, Scenario B

Particle Board

Gastemperatures, 1/3 scale, Scenario B

Wood panel, Spruce