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# Defining flashover for fire hazard calculations

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**Abstract**

As the use of performance-based methods for evaluating the fire behavior of materials and systems becomes more widespread, objective criteria to judge fire behavior become more important. This paper reviews techniques for predicting the most common of these criteria, the onset of flashover. The experimental basis for working definitions of flashover is reviewed. Comparisons of available calculational procedures ranging from simple correlations to computer-based fire models that can be used to estimate flashover are presented. Although the techniques range in complexity and results, the various predictions give estimates commensurate with the precision of available experimental data. © 1999 Published by Elsevier Science Ltd. All rights reserved.

## 1. Introduction

The occurrence of flashover within a room is of considerable interest since it is perhaps the ultimate signal of untenable conditions within the room of fire origin and a sign of greatly increased risk to other rooms within the building. Many experimental studies of full-scale fires have been performed that quantify the onset of flashover in terms of measurable physical properties.

Analytical models for predicting fire growth have been evolving since the 1960s. During this time, the completeness of the models has grown. These models have progressed to the point of providing predictions of fire behavior with an accuracy

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suitable for engineering applications. The computer models now available vary considerably in scope, complexity, and purpose. Fire models show particular promise as the basis of performance-based methods for evaluating the fire behavior of materials and systems as alternatives to current prescriptive-based codes. Performance codes establish safety goals and leave the means of achieving those goals to the designer. Crucial to the practicability of performance codes is an objective method of evaluating the ability of the proposed design to meet the established goals, without the need to resort to expert judgement. The lack of such an evaluation tool has been a primary impediment to the implementation of performance codes to date.

Key in providing an objective evaluation is an appropriate criterion to judge performance. Perhaps the most common criterion used to date is the onset of flashover. This paper extends an earlier review [1] of experimental data that provides the basis of a working definition of flashover and compares some calculations of flashover using available analytical techniques with available experimental data. These comparisons with data provide a level of verification of all of the analytical techniques with additional confidence arising from the similarity of all the predictions.

## 2. A working definition of flashover

Visually, flashover has been reported as a discrete event in full-scale fire tests and by the fire service in actual fire incidents. Numerous variables can affect the transition of a compartment fire to flashover. Thermal influences where radiative and convective heat flux are assumed to be the driving forces are clearly important. Ventilation conditions, compartment volume, and the chemistry of the hot gas layer can also influence the occurrence of flashover. The rapid transition to flashover adds to the uncertainty of attempts to quantify the onset of flashover with laboratory measurements. Although quantification of the flashover process in terms of measurable physical parameters is not as easy to obtain, a considerable body of full-scale fire test data studying flashover exists from a variety of sources from which a working definition can be formulated.

### *2.1. Temperature*

Hägglund et al. [2] report that flashover defined by them as flames exiting the doorway was experimentally observed when the gas temperature about 10 mm below the ceiling reached 600°C. Babrauskas [3] applied this criterion to a series of full-scale mattress fires. Of the 10 mattresses tested, only two exhibited potential to flash over the test room. These two mattress fires led to maximum gas temperatures well in excess of 600°C, with flashover observed near 600°C.

Fang [4] reported on experiments conducted in a full-scale enclosure at NBS. An average upper room temperature ranging from 450 to 650°C provided a level of radiation transfer sufficient to result in the ignition of crumpled newspaper indicators at floor level in the compartment. The average upper room gas temperature necessary for spontaneous ignition of newsprint was $540 \pm 40$°C. It should be noted that this average included low temperatures at the mid-height of the room and that temperatures measured 25 mm below the ceiling in his test series usually exceeded 600°C.

Budnick and Klein [5] performed several series of tests to study the fire safety of mobile homes. During tests in the living room of a mobile home [6,7], ignition of crumpled newspaper indicators was observed with upper room temperatures ranging from 673 to 771°C. For tests where full room involvement was not noted, maximum upper room temperatures ranged from 311 to 520°C. Results of tests conducted in the master bedroom of a typically constructed single-width mobile home indicated peak temperatures ranging from 300 to 375°C for tests where flashover was not observed and temperatures ranging from 634 to 734°C at flashover [8]. All temperatures reported were measured 25 mm (1 in) below the ceiling in the center of the bedroom.

Lee and Breese [9] report ignition of newsprint on the floor as a flashover indicator in full-scale and 1/4-scale tests of submarine hull insulation at room air and doorway air temperatures of at least 650 and 550°C, respectively. For tests where flashover was not obtained, these temperatures reached a maximum of 427 and 324°C. They note, however, that ignition of newsprint or some designated minimum doorway or interior air temperatures are only rough indicators of flashover because of the variation in the thermal and physical properties of crumpled newsprint, the non-uniform distribution of temperatures throughout the compartment, and the differences between tests of the combined thermal radiation from the smoke, the hot air and the heated surfaces. The hot air inside the compartment usually became well mixed by the time it exited through the doorway. They concluded that doorway temperatures may be more reliable flashover indicators than interior air temperatures.

Babrauskas [10] observed flashover during a test of a urethane foam block chair resulting in maximum temperatures more than 800°C. For other tests of upholstered chairs that did not achieve flashover, temperatures were below 600°C.

Fang and Breese [11] observed ignition of paper flashover indicators at floor level with an average upper room gas temperature of $706 \pm 92$°C with a 90% confidence level for a series of 16 full-scale fire tests of residential basement rooms.

To assess the relative fire risk of cellular plastic materials as compared to wood for use in furniture, Quintiere and McCaffrey [12,13] studied the burning of wood and plastic cribs in a room. They divided their experiments into two groups: lower-temperature fires (ceiling layer gas temperature less than 450°C) and high-temperature fires (ceiling layer gas temperature greater than 600°C) which exhibited characteristics of flashover evidenced by ignition of cellulose filter paper telltales in the five cases (out of 16) involving high gas temperatures.

Thomas [14] developed a semi-empirical calculation of the rate of heat release required to cause flashover in a compartment. He presents a simple model of flashover in a room and with it studies the influence of wall-lining materials and thermal feedback to the burning items. He predicts a temperature rise of 520°C and a black body radiation level of 22 $kW/m^2$ to an ambient surface away from the neighborhood of a burning wood fuel at the predicted critical heat release rate necessary to cause flashover. This calculation will be discussed in more detail later.

### 2.2. Heat flux

Heat flux to exposed items within the fire room has also been used as a criterion for the definition of flashover. Parker and Lee [15] have suggested using a level of 20 kW/m$^2$ as the heat flux at floor level at which cellulosic fuels in the lower part of the room are likely to ignite.

A range of materials tested for ignition time and fluxes are reported by Babrauskas [3]. For some common materials, the ignition fluxes are given in Table 1 for a 60-s exposure. The unpiloted values are considered more appropriate for determination of full-room involvement since ignition at considerable distance from the flames is involved. A value of 20 kW/m$^2$ represents, according to Smith [3, 16] an unpiloted ignition time of approximately 180 s for box cardboard and is close to an ultimate asymptotic value.

Budnick and Klein [5] found that, for tests in which flashover occurred, the minimum total incident heat flux at the center of the floor was 15 kW/m$^2$.

Fang [4] found in a series of room burns that strips of newsprint placed at floor level ignited at fluxes of 17–25 kW/m$^2$ while 6.4 mm (1/4 in) thick fir plywood ignited at 21–33 kW/m$^2$. Lee and Breese [9] report average heat fluxes at floor level of 17–30 kW/m$^2$ at flashover for full-scale tests of submarine compartments. Fang and Breese [11] found good agreement between the time to ignition of newsprint flashover indicators and the time at which the incident heat flux measured at the center of the floor in the burn room reached a level of 20 kW/m$^2$ during tests in a basement recreation room.

A nominal incident floor heat flux of 20 kW/m$^2$ may be used as an indicator of the potential onset of flashover according to Quintiere and McCaffrey [12]. Ignition of filter paper, as a flashover indicator was observed at a minimum of 17.7 kW/m$^2$ applied for roughly 200 s or more. Under more controlled laboratory conditions, with radiant exposure to the same target configuration, the paper charred black at 25 kW/m$^2$ and ripped at 120 s, but only decomposed to a brown color at less than 15 kW/m$^2$.

While the researchers used different definitions for the onset of flashover, some level agreement was evident from a number of researchers on two criteria for the onset of flashover (Table 2). For the temperature criterion, the range of values in the table is quite wide with a range of 450–771°C. This wide range of values is due both to the

Table 1
Minimum flux for ignition of common materials

| | Flux (kW/m$^2$) | |
|---|---|---|
| | Piloted | Unpiloted |
| Newspaper want ads | 46 | 48 |
| Box cardboard | 33 | 43 |
| Polyurethane Foam | 19 | – |

Table 2
Minimum conditions at onset of flashover observed by several research studies

| Source | Temperature (°C) | Heat flux ($kW/m^2$) |
|---|---|---|
| Häggland | 600 | No data |
| Fang | 450–650 | 17–33 |
| Budnick and Klein | 673–771 | 15 |
| | 634–734 | |
| Lee and Breese | 650 | 17–30 |
| Babrauskas | 600 | 20 |
| Fang and Breese | 706 ± 92 | 20 |
| Quintiere and McCaffrey | 600 | 17.7–25 |
| Thomas | 520 | 22 |
| Parker and Lee | No data | 20 |

different definitions used by the researchers and to the fact that during the transition to flashover, the temperature gradient is very steep. Still, for the tests in Table 2, most of the values are in the 600–700°C range. For heat flux, the values range from a low of 15 $kW/m^2$ to a high of 33 $kW/m^2$.

The following values for the upper gas layer temperature and heat flux at the floor, appear to be predictive of the onset of full-room involvement: upper gas layer temperature > 600°C or heat flux to the floor > 20 $kW/m^2$.

These values are consistent with common practice and the wide range of experimental data examined in this paper. It is also evident from Table 2 that there is considerable uncertainty in this definition depending upon the materials and room configurations involved. Much of this uncertainty is understandable given the nature of flashover. Although the above definitions are workable and provide an engineering approach that can be used in calculational techniques, it is perhaps more appropriate to view flashover as Drysdale [17] has as the transition between the pre-flashover fire that burns as it would in the open but gradually becoming influenced by energy feedback from it surroundings. This increase in energy eventually leads to a rapid spread to all combustibles in the compartment. This transition is not an instantaneous event. The transition to flashover is also affected by chemical processes in addition to the thermal effects considered here. Thus, some uncertainty in a deterministic definition is to be expected.

## 3. Estimating room flashover potential

In a recent international survey [18], 62 actively supported models were identified. Of these, 31 predict the fire generated environment (mainly temperature and smoke movement in some way), 12 models predict fire endurance, eight address detector or sprinkler response, and four calculate evacuation times. The computer models now available vary considerably in scope, complexity, and purpose. Simple calculations such as the MQH correlation [19] or "room-filling" models such as the Available Safe

Egress Time (ASET) model [20] provide estimates of a few parameters of interest for a fire in a single compartment. A special purpose model can provide a single function. For example, COMPF2 [21] calculates post-flashover room temperatures and LAVENT [22] includes the interaction of ceiling jets with fusible links in a room containing ceiling vents and draft curtains. More detailed zone models like the HARVARD 5 code [23] or FIRST [24] predict the burning behavior of multiple items in a room, along with the time-dependent conditions therein. In addition to the single-room models mentioned above, there are a smaller number of multi-room models which have been developed. These include the BRI transport model [25], the HARVARD 6 code [26] (which is a multi-room version of HARVARD 5), FAST [27], CCFM [28] and CFAST [29]. In addition, 10 field models are identified which can provide detailed information on the environment within compartments.

### 3.1. Correlation techniques

Several approaches have been taken to estimate the onset of flashover within a room. These methods are typically based on simplified mass and energy balances on a single-compartment fire along with correlations to fire experiments. Walton and Thomas [30] provide a review of available methods for calculating temperatures in compartment fires. Three methods are identified from the works of Babrauskas [31], McCaffrey et al. [19] and Thomas [14]. Additional correlations by Babrauskas [31] and Hägglund [32] are available. Deal and Beyler [33] evaluated some of these correlations with a database derived from more than 250 room fire experiments and provided additional guidance for cases involving forced ventilation.

Babrauskas [31] developed a simple combustion model with a flashover criterion based upon a temperature rise, $\Delta T$, of 575°C and compared the results of the predictions using the model with experimental results. He provides a simple rule to estimate the minimum heat release rate to produce flashover:

$$\dot{Q} = 750A\sqrt{h}, \tag{1}$$

where $\dot{Q}$ is the estimated rate of heat release in kW, $A$ is the door area in $m^2$ and $h$ is the door height in m. The $A\sqrt{h}$ factor is usually called the "ventilation factor". He reports adequate agreement with experimental data with 2/3 of the data studied falling between $\dot{Q} = 450A\sqrt{h}$ and $1050A\sqrt{h}$.

To account for varying heat losses due to room wall size or property variations, Babrauskas proposed another closed-form expression to estimate compartment fire temperatures. Using a consistent temperature rise to indicate flashover ($\Delta T = 575$°C), assuming gypsum walls, and an ambient temperature of 25°C, an expression for minimum heat release rate (HRR) to achieve flashover is obtained:

$$\frac{600-25}{1725-25} = 0.83\left(1 + 0.51\ln\frac{\dot{Q}}{1520A\sqrt{h}}\right)\left(1 - 0.94\exp\left(-33\left(\frac{A\sqrt{h}}{A_T}\right)^{2/3}\right)\right) \times\left(1 - 0.92\exp\left(-11.9\left(\frac{A\sqrt{h}}{A_T}\right)^{0.6}\right)\right). \tag{2}$$

Hägglund's expression [32] was derived from simulations with a two-zone computer model and expressed by Babrauskas [31] in a form consistent with the other predictions presented in this paper as

$$\dot{Q} = 1050A_T\left(\frac{1.2}{A_T/A\sqrt{h}} + 0.247\right)^3. \tag{3}$$

McCaffrey et al. [19] performed a regression analysis to provide a correlation to predict upper layer gas temperature. Using data from more than 100 experiments, they found a correlation based on two dimensionless quantities:

$$\Delta T = 480\left(\frac{\dot{Q}}{\sqrt{g}C_p\rho_0 T_0 A\sqrt{h}}\right)^{2/3}\left(\frac{h_k A_T}{\sqrt{g}C_p\rho_0 A\sqrt{h}}\right)^{-1/3} \tag{4}$$

where $\Delta T$ is the temperature rise relative to ambient in °C, $h_K$ is the effective heat transfer coefficient to ceilings/walls, and $A_T$ is the effective surface area for heat transfer including door area. A means to calculate the effective heat transfer coefficient, $h_k$ is given in Ref. [19]. They report a multiple correlation coefficient of 0.959 or 0.947 depending upon whether the floor is included in the calculation of the wall area and the effective heat transfer coefficient.

By substituting typical values for $C_p$, $\rho_0$, $T_0$ and a flashover criterion consistent with the above criterion of $T \geqslant 600$°C ($\Delta T = 575$°C), the above equation can be reduced to

$$\dot{Q} = 740(h_k A_T A\sqrt{h})^{1/2}, \tag{5}$$

where $\dot{q}$ is in kW, $A_T$ and $A$ are in $m^2$, $h$ is in m and $h_k$ is in kW/($m^2$K) (for this paper, the value of $h_k$ was taken to be $\sqrt{k\rho c/t}$ kW/($m^2$K) with $k$, $\rho$, and $c$ taking values for gypsum wallboard and the characteristic time, $t$, is taken to be 200 s, appropriate for an upholstered furniture fire and consistent with the original work of Babrauskas [34]). This results in predictions higher than the original work, primarily due to the choice of a more conservative $\Delta T$ of 500°C in the original work. For this paper, a consistent value was used for all of the predictive methods.

Mowrer and Williamson [35] have modified the MQH correlation for fires in corners and along walls. For simple geometries, they showed the validity of the MQH correlation for fires in the center of a compartment. By multiplying the temperature rise estimated by the MQH correlation by 1.7 for fires in corners and by 1.3 for fires along walls, reasonably accurate layer temperature estimates were achieved.

Thomas' flashover correlation [14] is the result of simplifications applied to an energy balance of a compartment fire. The simplifications resulted in Eq. (6) that has a term representing heat loss to the "... total internal surface area of the compartment ...," and a term representing enthalpy flow out of the vent. The constants in Eq. (6) represent values correlated to experiments producing flashover:

$$\dot{Q} = 7.8A_T + 378A\sqrt{h}. \tag{6}$$

### 3.2. Limitations of the correlations

Several limitations of these correlations were noted by the authors. The limitations presented by Deal [36] are representative:

- Most of the correlations were developed from a simplified mass and energy balance on a single compartment with a single door-like vent. Unusual geometries or venting have been given limited study. Foote et al. [37] have considered compartments with forced ventilation.
- The equations were correlated from experiments conducted in rooms similar in scale and aspect ratio to residential rooms and typically smaller than 16 $m^2$ in floor area. Long corridors and/or compartments orders of magnitude larger were not considered.
- The experiments used to develop the correlations included compartments with thermally thick walls and fires of wood cribs and furniture fires. Typically, heat transfer through compartment surfaces is accounted for with a semi-infinite solid approximation. The variations presented above used typical values for gypsum surfaces.

There has been discussion in the past on appropriate choice for the term $A_T$ in most of the expressions. In most of the original literature references, the definition is unclear. It has been subject to several interpretations: total compartment surface area, total compartment surface area not including the floor surface, or total compartment surface area not including vents. For the comparisons presented in this paper, we chose the last of these, simply to make a consistent comparison – not because it was thought to be a better choice.

### 3.3. Compartment fire modeling

Different models divide the building into different numbers of control volumes depending on the desired level of detail. The most common fire model, known as a *zone model*, generally uses two control volumes to describe a room – an upper layer and a lower layer. In the room with the fire, additional control volumes for the fire plume or the ceiling jet may be included to improve the accuracy of the prediction (see Fig. 1).

Mitler [38], Jones [39], and more recently Forney [40] reviewed the underlying physics in several zone fire models in detail. These compartment fire models start with the principles of conservation of mass, momentum, and energy to understand the underlying relationship among a set of parameters. Errors arise where some important phenomenon was not included, a simplifying assumption was made, or a mathematical short cut was taken.

Other types of models include *network models* and *field models*. The former uses one element per room and is used to predict conditions in spaces far removed from the fire room or when buoyancy is not important, where temperatures are near ambient and layering does not occur. The field model goes to the other extreme, dividing the room into thousands or even hundreds of thousands of control volumes. Such models can

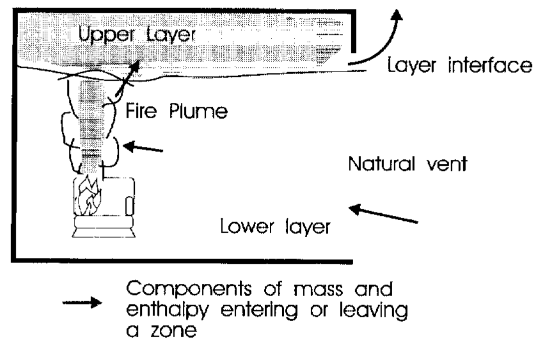


Fig. 1. Typical terms in a zone fire model.

predict the variation in conditions within the layers, but typically require far longer run times than zone models. Thus, they are used when highly detailed calculations are essential.

## 4. Evaluation of the predictions with experimental studies of flashover

### *4.1. Influence of compartment and vent size on minimum flashover energy*

The important test of all these prediction methods is in the comparison of the predictions with observations of actual fires. Fig. 2 presents predictions of the minimum HRR required to achieve flashover for a range of room and vent sizes, along with observed conditions from a range of independent real-scale fire tests. This figure is an extension of the earlier work of Babrauskas [34] and includes additional experimental measurements from a variety of sources, most notably data from Deal and Beyler [33] (data from wall and corner fires were not included to simplfy the presentation of the comparisons). In addition, it includes predictions from a current generation zone fire model. For this paper, only the data which represent minimum observed energy at the transition to flashover were included. For a considerable range in the ratio $A_T/A\sqrt{h}$, the correlations of Babrauskas, Thomas, and McCaffrey, Quintiere, and Harkelroad provide nearly identical estimates of the minimum HRR required to produce flashover. The estimates of Hägglund yields somewhat higher estimates for values of $A_T/A\sqrt{h}$ greater than 20.

The CFAST model was also used to simulate a range of geometries and fire conditions to predict the development of the fire up to the point of flashover. The gray-shaded area in the graph represents the locus of individual simulation results for the CFAST model for a range of compartment sizes from 8 to 1327 m$^3$, with ceiling height varying from 2.4 to 12.2 m and vent openings from 10 to 100% of the length of the short wall (plus a "standard" door, 0.76 m in width). For the simulations included in Fig. 2, the surface lining material was gypsum wallboard, 12.7 mm in thickness,

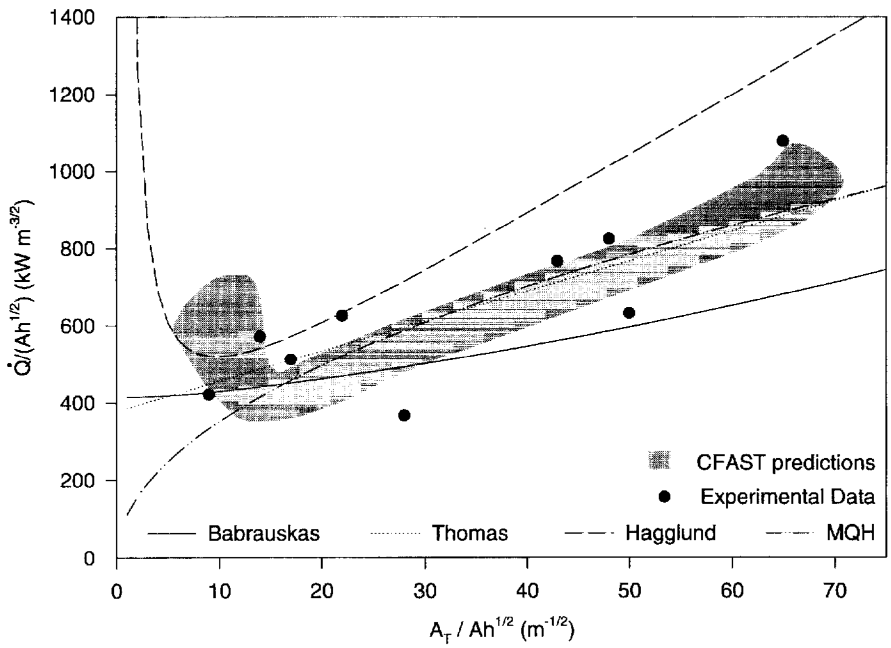


Fig. 2. Comparison of predictions of minimum flashover energy with observed conditions in real-scale fires for a range of compartment and opening sizes.

consistent with the values used in the correlations. To estimate the minimum flashover energy with CFAST, a simple constant fire size was varied until the calculated upper-layer temperature reached 600°C at the end of the simulation (900 s in this study) – chosen as an indicator of impending flashover consistent with the literature discussed earlier in this paper.

The results from the CFAST model for this single compartment scenario provide similar results to the experiments and the correlations for most of the range of $A_T/A\sqrt{h}$. For small values of $A_T/A\sqrt{h}$, the CFAST values rise somewhat above the values from the correlations. These small values of $A_T/A\sqrt{h}$ result from either very small compartments (small $A_T$) or very large openings (large $A\sqrt{h}$), both of which stretch the limits of the assumptions inherent in the model. For very small compartments, radiation from the fire to the compartment surfaces becomes more important, enhancing the conductive heat losses through the walls. However, the basic two-zone assumption may break down as the room becomes very small. For very large openings, the calculation of vent flow via an orifice flow coefficient approach is likely inaccurate. Indeed, for such openings, this limitation has been observed experimentally [34]. Still, the estimates are close to the ranges provided by the correlations which also diverge from each other at very small values of $A_T/A\sqrt{h}$. Perhaps most significant in these comparisons is that all the simple correlations provide estimates similar to the CFAST model. For this simple scenario, little is gained with the use of the more complex models.

*4.2. Influence of surface material properties on minimum flashover energy*

For more complicated scenarios, the comparison may not be as simple. Although most of the correlations were developed using data from gypsum-lined compartments, some have been extended to other wall materials. For example, the MQH correlation, Eq. (4), explicitly includes an effective heat transfer coefficient based on the thermal properties of the compartment surfaces. Fig. 3 shows the minimum heat release rate at flashover predicted by the MQH correlation and the CFAST model for a wide range of compartment lining materials. The thermal properties for the materials were taken from Incorpera and DeWitt [41]. The materials ranged from conductive aluminum to highly insulative urethane. The functional form of the MQH correlation derived from a simple model of a compartment fire suggests that the minimum HRR necessary to achieve flashover (assuming the 600°C definition) from Eq. (4), should be proportional to the square root of an effective heat transfer coefficient. Fig. 3 uses this functional form for presentation. The effective heat transfer coefficient, $h_k$, defined for the MQH correlation is a simplified representation assuming conduction through the surfaces is

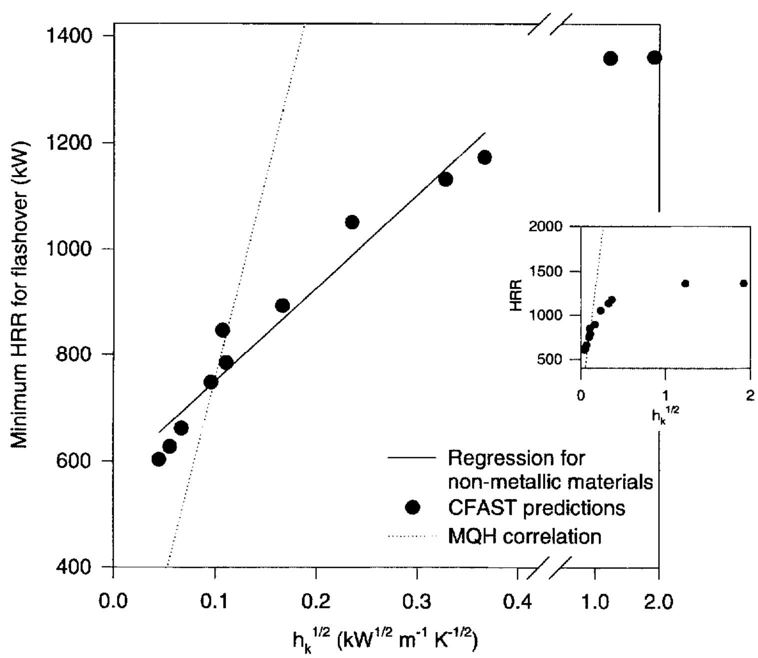


Fig. 3. Predictions for minimum heat release rate at flashover (defined by an upper gas temperature of 600°C) for a range of surface materials in a 2.44 m × 3.66 m × 2.44 m compartment with a single 0.76 m × 2.03 m doorway.

the dominant factor in the heat transfer – with convection and radiation implicit in the correlation. For steady-state conduction, $h_k$ is approximated by $h_k = k/\delta$. For a growing fire, a semi-infinite approximation is used with $h_k = \sqrt{\rho ck/t}$. Although the CFAST model includes a far more complicated transient solution accounting for radiation, convection, and conduction, the predictions still fall reasonably on a straight line on the graph for most of the materials. The scatter about the straight line regressions for the CFAST predictions is likely illustrative of the more complex solution to the heat transfer equations. For materials whose thermal properties are close to gypsum ($h_k$ of approximately 0.1), the MQH correlation and the CFAST predictions provide similar estimates. For the highly conductive materials simulated with CFAST, the predictions seem to reach a plateau. This implies that the heat transfer through the compartment surfaces for these scenarios is not controlled by the conduction through the surface, but rather by convection on the external surfaces (which in CFAST are assumed to be exposed to ambient air). In contrast, the predictions of the MQH correlation for these materials are extremely high, exceeding 30 MW for the aluminum-lined compartment. Since the MQH correlation was developed largely with data from fire in compartments with similar thermal properties, the correlation should be expected to provide the best estimates in the region close to gypsum. For materials whose thermal properties are wildly different from gypsum, the more complex treatment of heat transfer in complex zone models like CFAST are more appropriate. Recent comparisons of the CFAST model with experiments involving steel-lined compartments [42] suggest the accuracy of the model in this regime is similar to earlier studies with more traditional lining materials [43].

The implications of the simplifying assumptions in the treatment of heat transfer in the correlations can be seen in Fig. 4. For gypsum linings, the predictions of the MQH correlation and CFAST model are quite close, within 5% for both thermally thin and thermally thick materials. For thin materials, the effect is inversely proportional to the thickness of the material. For thick materials, the effect is independent of the thickness of the material, consistent with a thermally thick assumption.

In the transition between the thermally thin and thermally thick regimes, the estimates vary by as little as 5% for insulating materials but as much as 25% for highly conductive materials such as the aluminum shown in the figure. It is in this range of material thicknesses that most common building materials lie making accurate estimation of the heat transfer more difficult. Part of the power of the more complex fire models is in their more thorough calculation of the effects of heat transfer on the environment within compartments.

## 5. Summary and conclusions

Albeit with considerable variation in experimental data, definitions of flashover consistent with common practice are also consistent with a broad range of experimental data: upper gas temperature $\geq 600°C$ or heat flux at floor level $\geq 20\ kW/m^2$. It is also evident that there is considerable uncertainty in this definition depending

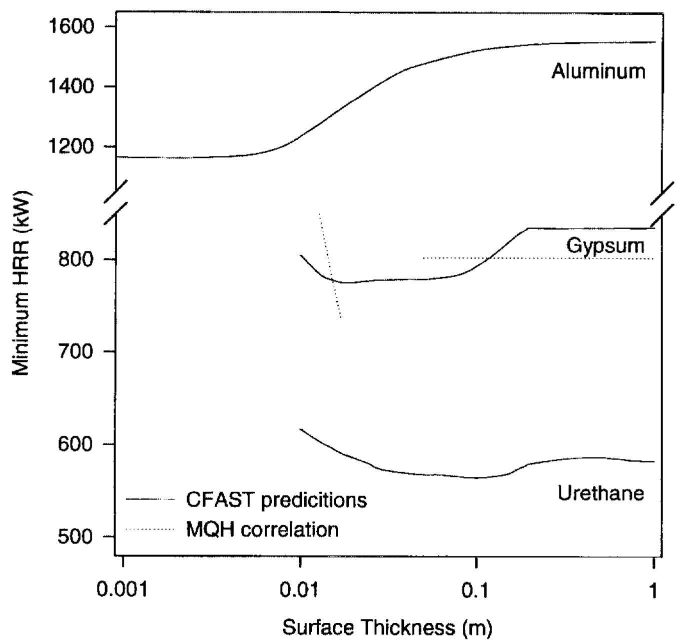


Fig. 4. Prediction of the effect of compartment surface thichness of minimum HRR to achieve flashover for several surface materials.

upon the materials and room configurations involved. Much of this uncertainty is understandable given the nature of flashover as a transition from individual burning items to full room involvement.

A range of simple correlations and more complex mathematical modeling provide estimates of flashover consistent with a wide range of independent experimental observations for fire in compartments of typical construction, even with considerable variation in compartment geometry, ventilation conditions, and fire source. Since all the correlations are just that – correlations of experimental data of temperature and heat release rate, they should be expected to be limited to the extent of the data available for a given correlation. Still, the similarity of all the predictions and their agreement with experimental data independent from the predictions provides a level of verification of all the techniques.

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