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Defining flashover for fire hazard calculations: Part II

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Abstract

Comparison of available correlations and predictive models used to predict the minimum heat release rate (HRR) necessary to cause flashover show consistent trends for a range of empirical data. Nonetheless, available experimental data for HRR at flashover in compartments of similar geometry and venting show substantial scatter. Both the experimental data and theoretical predictions based on computer modeling indicate that a significant portion of the variability can be accounted for by the time period involved in the flashover. Although typically ignored in the available correlations, qualitatively a clear trend emerges—shorter exposure times increase the needed minimum HRR at flashover, due at least in part to the effects of heat transfer to the compartment surfaces. Additional measurement needs are suggested to facilitate better understanding of conditions leading to flashover.

Keywords: Flashover; Fire hazard; Heat release rate

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 the occupants of other rooms within the building. Crucial to the increased use of performance-based design is an objective method of evaluating the ability of the proposed design to meet the established goals, without the need to resort to expert judgment. Key in providing such an objective

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evaluation is an appropriate criterion to judge performance. Perhaps the most common criterion used to date is the onset of flashover. In Part I of this paper [1], we reviewed experimental studies of real-scale fires that quantify the onset of flashover in terms of measurable physical properties. We then considered approximate and computer-modeling methods for the prediction of occurrence of flashover. Albeit with considerable scatter, definitions used for evaluation of flashover were also consistent with a broad range of experimental data: upper gas temperature of 600°C, or a heat flux at floor level of 20 kW m^{-2}. A range of simple correlations and more complex mathematical modeling provided 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. The similarity of all the predictions and their agreement with experimental data was seen to provide a level of verification of all the techniques and of their use in engineering design.

Still, it was also evident that there was considerable uncertainty in these definitions depending upon the materials and room configurations involved. In Part II, we expand the treatment of flashover in three regards, in part towards understanding the causes of this uncertainty:

1. the nature of flashover and its measurement in real-scale tests;
2. experimental values of heat release rate (HRR) at and time to flashover, as measured in fires either in the ISO 9705 room or in similarly sized and configured rooms; and
3. the theoretical effect of the HRR growth curve on the occurrence of flashover.

2. The nature of flashover

In Part I, we surveyed a number of experimental techniques used for defining flashover. Most, we found, provide results that are not very different from each other. In those cases where there is disagreement among the experimental conclusions, it can be helpful if recourse is had to a more fundamental definition of flashover. At least two types of fundamental definitions are possible:

1. *Flashover defined as the occurrence of criticality in a thermal balance sense*. Systems that include a heat generation term are susceptible to criticality (runaway) conditions if the heat generation rate, at a certain point, exceeds the ability of the system to lose heat at the boundaries. The Russian scientists N. N. Semenov and D. A. Frank-Kamenetskii studied these problems extensively in the 1930s; a good English-language review was presented by Gray and Lee [2]. This concept was applied to flashover of room fires by Thomas [3], Bullen [4], Babrauskas and Wickström [5], Hasemi [6], and many others.
2. *Flashover defined as a fluid-mechanical filling process*. Experimentally, if flashover is reached in a room fire, it is noted that this takes place during a short interval of time when the room goes from being mostly filled with cold air, to being mostly

filled with hot fire gases. Thus, the process can be viewed as roughly analogous to filling a water reservoir with a small, fixed opening for outflow (Fig. 1) [7]. Initially, the filling rate is analogous to the HRR of the fire and prior to flashover, this inflow simply defines a rate of filling. For a flashover analogy, the critical event in reservoir filling is the sufficient influx of water so that the outflow becomes restricted by the capacity of the outflow vent. In a post-flashover compartment fire, the heat generation of the fire is similarly limited to available combustion air, in turn controlled by the ability of the vent to exhaust hot gases and allow additional inflow air. While the analogy is not perfect since fire effects such as entrainment and thermal expansion of the hot gases are neglected, it provides a relatively easy to understand comparison.

Of the two fundamentally based definitions of flashover, the first is likely to appeal more to the mathematician, and this is confirmed by continuing papers exploring the implications (e.g., [8,9]). However, it does not provide a tool for the interpretation of experimental data. By contrast, the second fundamental approach can readily be used in analyzing experimental data. For example, the flashover *event* could experimentally be taken to be the dropping of the flaming hot gas layer below the halfway height of the room. The *effects* of flashover are then ignition of floor targets, high flux to the floor, flames out the doorway, etc. Such clear distinction between cause and effect should be very beneficial in being able to determine which measure of flashover is "right," when they do not agree. It is unfortunate that most experimentalists have not observed this important principle. In future programs on room fires, apart from recording the HRR, observations such as the height of the

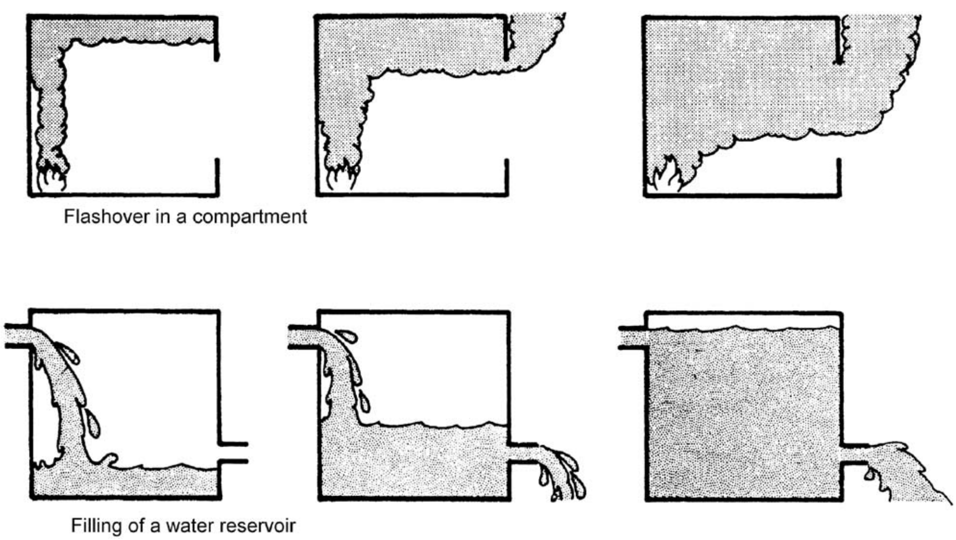

Fig. 1. Flashover as a room-filling process, and analogy to a water reservoir [7].

flaming hot gas layer, details of limiting vent flow, or surface heat transfer should be recorded so that the nature of flashover can be better understood.

3. Experimental HRR values at flashover

Over the last decade, HRR measurements in connection with room fires have become a fundamental way of characterizing wall linings and other combustible surfaces of large area. Internationally, the test by which this is done has been standardized as ISO 9705 [10]. This test room is 2.4 m × 3.6 m × 2.4 m high and contains a single 0.8 m × 2.0 m high doorway. For setting performance criteria, a numeric value of HRR is often specified for restricting materials to HRR values less than flashover level. Thus, in addition to the correlations that were presented in Part I, it is essential that the range of numeric HRR values occurring at flashover be known. Results of several test series are summarized in Table 1 which presents HRR measured at the occurrence of flashover. Where visual data were available, presence of flashover was determined by noting the time at which the thermal discontinuity progressed below the mid-height of the room. Otherwise, ignition of floor targets was taken to constitute evidence of flashover. In some cases, the times were based on the original author's visual observation of flashover. The tests were not all conducted at the same laboratory under ideal circumstance; nonetheless, they are representative of the best that can be found in the literature today, and more precise observations still await being done. The tests of Lee [11] were done in a room of 2.44 m × 3.66 m × 2.44 m and having a doorway of 0.76 m × 2.03 m high; these dimensions are insignificantly different from the ISO room. The results of Fang [12] cited here (he also did additional tests in a much larger room; these have not been considered) used a room of 3.26 m × 3.26 m × 2.44 m high with a doorway 0.76 × 2.03 m high. The total room surface area for Fang's room was 51.5 m^2, versus 44.5 m^2 for the ISO room. By considering Eq. (6) of Part I, it can be estimated that Fang's room required 55 kW more to achieve flashover than does the ISO room—this difference would not be detectable in the scatter of actual data; thus Fang's data were also considered to be representative of the ISO 9705 room. Tests in the exact ISO room configuration were conducted by Sundström [13] and Thureson [14].

The mean HRR value needed for flashover for the data assembled in Table 1 is 1975 ± 1060 kW. The median of 1700 kW is probably more characteristic of the data. Only three of the 33 data points are at or below 1000 kW, a value which has occasionally been implied as being the flashover level in the ISO 9705 room. It is clear that 1000 kW might represent the *minimum* level at which flashover could occur under extreme circumstances. It does not describe a more *typical* HRR value at flashover, for which the median value, 1700 kW, is more suitable.

However, a significant portion of the variability can be accounted for by the time period involved in the flashover. The tests summarized in Table 1 were generally conducted by using two levels of burner exposure during the test. Under standard ISO 9705 conditions, during the first 10 min of the test, the exposure is 100 kW, and

Table 1
HRR values needed for flashover of the ISO 9705 test room

Material	HRR at flashover (kW)	Time to flashover (s)	References
Plywood, 5.6 mm thick	1700	195	[11]
Plywood, 12.8 mm thick	1900	140	[11]
Polystyrene foam	4200	71	[11]
"" (different burner program)	3100	101	[11]
Polyisocyanurate foam	2200	19	[11]
"" (different burner program)	2900	42	[11]
"" (different burner program)	3200	315	[11]
Plywood walls, gwb ceiling, mixed furniture	1030	117	[12]
Concrete walls, gwb ceiling, mixed furniture	1620	178	[12]
Plywood walls, gwb ceiling, mixed furniture	1190	114	[12]
Plywood walls, gwb ceiling, mixed furniture	1880	108	[12]
Gwb walls and ceiling, mixed furniture	2420	100	[12]
Plywood walls, acoustic tile ceiling, mixed furniture	1560	123	[12]
Plywood walls, gwb ceiling, mixed furniture	1610	106	[12]
Plywood walls, gwb ceiling, mixed furniture	1470	225	[12]
Rigid polyurethane foam	5950	8	[13]
Textile wall covering on mineral wool	3490	33	[13]
Wood fiberboard	2210	64	[13]
Expanded polystyrene foam	1700	127	[13]
Medium density fiberboard	1080	128	[13]
Spruce paneling	1330	131	[13]
Paper wall covering on particle board	980	133	[13]
Particle board	950	138	[13]
"" (replicate of above)	1160	146	[13]
"" (different burner program)	1970	141	[13]
Melamine-faced particle board	1000	447	[13]
PVC wall covering on gwb	1160	609	[13]
Textile wall covering on gwb	2000	622	[13]
Acrylic glazing	1920	618	[14]
FR extruded polystyrene foam, 40 mm	1650	160	[14]
Lacquered wood paneling	1830	109	[14]
FR expanded polystyrene foam, 80 mm	1740	803	[14]
FR plywood	1080	645	[14]

gwb—paper-faced gypsum wallboard.

this is increased to 300 kW during the 10–20 min period. The tests of [11,12] however, used different burner programs. Because of the fact that burner exposure is not constant in the test and because not even all available test data relied on the same burner program, it is not appropriate to base conclusions on the burner program used. Although not typically included in the available correlations, the effect can be dramatic. For instance, the fire retardant (FR) plywood shown in Table 1 that flashed over at 1080 kW did so at slightly over 10 min after the start of test. By contrast, the rigid polyurethane foam that flashed over at 5950 kW did so just 14 s after burner ignition. Nonetheless, by simply correlating the HRR required for

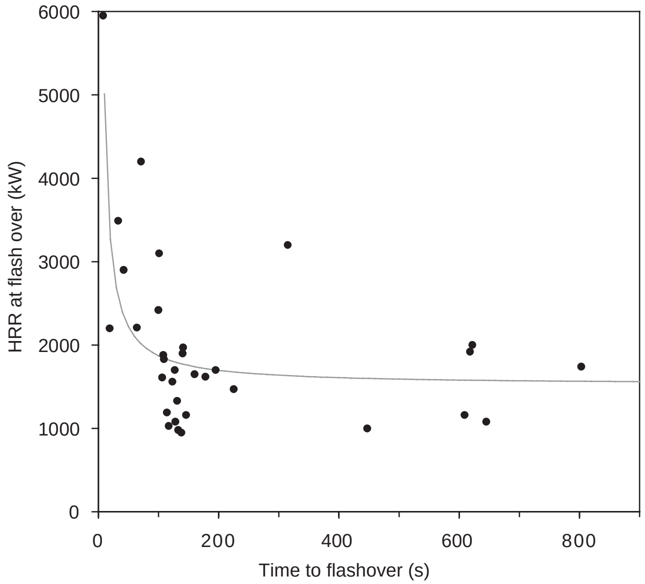

Fig. 2. Effect of time to flashover on the HRR required for flashover.

flashover against time, a trend emerges, as shown in Fig. 2. The best-fit curve is very steep for times below about 120 s, indicating that much greater HRR values are needed if flashover is to occur during the initial 2 min interval. During the early stages of the fire, the compartment fills with hot gases. For very short flashover times, the filling rate of the upper layer and thus the HRR must naturally be higher to reach a temperature and heat flux necessary for flashover. For very short times, this filling time is a large fraction of the total time to flashover. Thus, compartment filling plays a pivotal role.

4. Theoretical effect of the HRR curve on the time to and HRR at flashover

Perhaps most significant in the comparisons presented in Part I of this paper is that, with consistent assumptions, all the simple correlations provide estimates similar to the CFAST model and to available experimental data. For a simple scenario, little is gained with the use of the more complex models. For more complicated scenarios, the comparison may not be as simple. Fig. 3 shows an extension of a similar figure presented in Part I. It shows the HRR at flashover (q) as a function of the compartment surface area (A_T) and the vent size (expressed as $Ah^{1/2}$, where A is the vent area and h is the height of the vent). In Part I, only values representative of the minimum HRR necessary to achieve flashover were included. In Fig. 3 here, additional values from a range of sources are included that were not explicitly identified as being a minimum value at flashover. While some of the higher values may be attributable to uncertainty in identifying a precise time of the

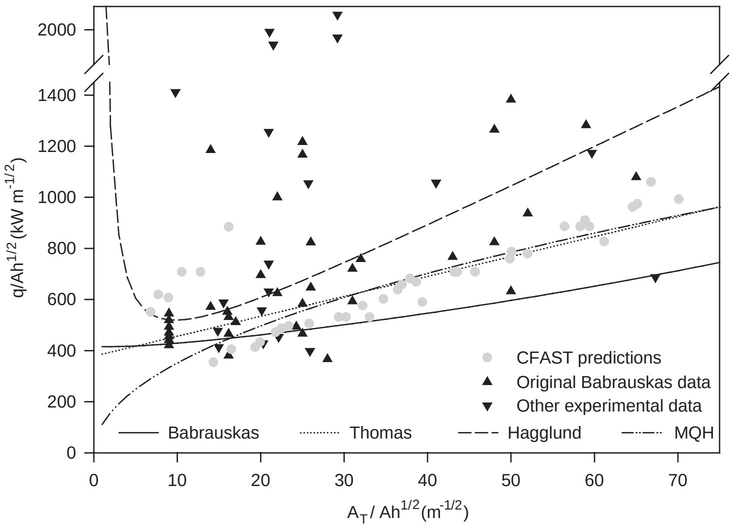

Fig. 3. Comparison of predictions of minimum flashover energy with additional real-scale fires for a range of compartment and opening sizes.

occurrence of flashover from the rapidly changing conditions in a growing compartment fire, others are due to differences in fire growth rate. Both the correlations and the CFAST model predictions in Fig. 3 assume a steady-state fire and an assumed time to flashover. In the correlations and model predictions for Part I, this characteristic time to flashover varied from 200 to 900 s, whereas many of the experimental results shown in Table 1 are below 200 s.

Fig. 4 shows the predicted HRR at flashover for a range of characteristic times. For these simulations, an ISO 9705 sized compartment and vent were used. The fire was assumed to follow a t^2 growth curve with a range of times to a 2 MW peak. Like the experimental data discussed earlier, shorter times increase the HRR at the onset of flashover for both a temperature-based and heat-flux-based definition of flashover. As noted in the previous section, for shorter times, rapid filling results in higher HRR values to reach chosen flashover criteria. Although qualitatively similar, there is considerable spread in the experimental data. Again, additional experimental measurements could help to better understand appropriate metrics in addition to HRR that may be key in predicting the occurrence of flashover.

The shape of the fire growth curve can also have an effect on the minimum energy necessary to produce flashover. Fig. 5(a) shows the results of several simulations for a single compartment fire scenario where the shape of the HRR curve was changed. The total heat released by the fire was held constant for all the simulations at 250 MJ—an average 1 MW fire over the entire 250 s duration of the simulation. The shape varied from a 250 s step function (the "rectangle" shape) with a constant 1 MW HRR, to a triangle with a peak 2 MW HRR. In between were three trapezoidal shapes with the duration of the peak HRR equal to 25%, 50%, and 75% of the base 250 s fire duration. From Fig. 5(a), the minimum HRR necessary to cause

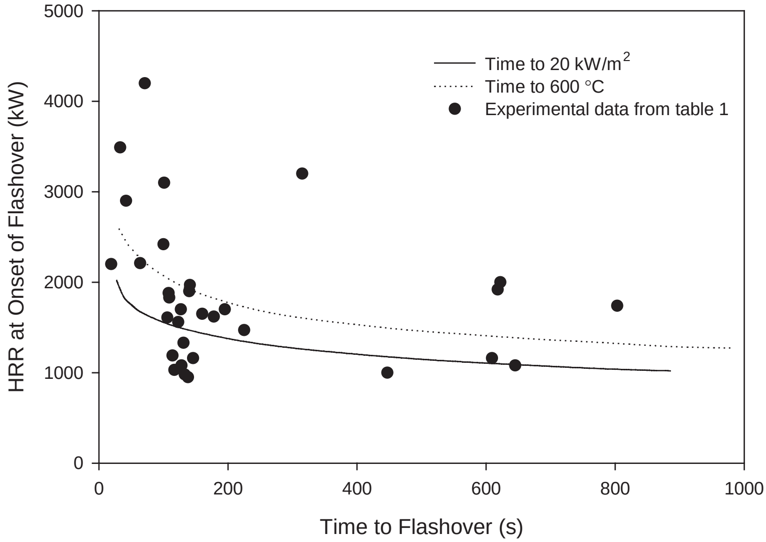

Fig. 4. Predicted HRR at flashover for t^2 fires with a range of characteristic fire-growth rates, compared to experimental data.

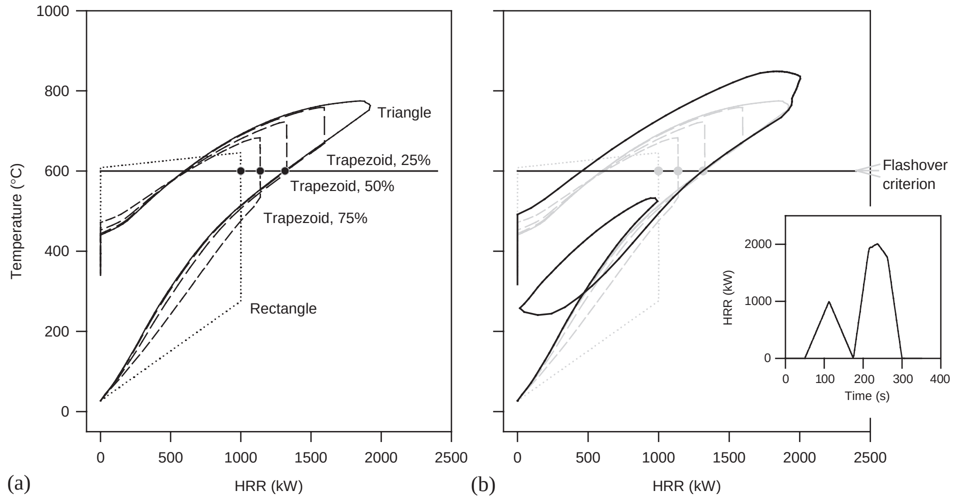

Fig. 5. Effect of the shape of the HRR curve on the upper layer temperature for a single compartment scenario.

flashover (defined by the 600°C criterion) ranges from a low of 1 MW for the "rectangle" shape to 1.3 MW for the "triangle," "25% trapezoid," and "50% trapezoid." Typical t^2 growth rate fires (with the same total heat released) show similar results. Once the HRR is sufficiently high to allow the temperature to reach 600°C during the growing phase of the fire, the shape of the curve has but a minor effect on the minimum HRR necessary to cause flashover. To extend this further,

Fig. 5(b) overlays this original graph with a more complex fire growth curve involving two peaks as shown in the small inset graph in Fig. 5(b). Although this is a fictitious curve, such multiple peaks are commonly seen in furniture fires. The first peak was held sufficiently small not to lead to flashover in the compartment. Again, the minimum HRR necessary to cause flashover was nearly identical to the 1.3 MW calculated for the simpler curves. The curve follows the simpler curves quite closely, with only an excursion for the decay portion past the first peak in the HRR curve. While extreme fire growth rates will lead to a higher necessary minimum HRR necessary to cause flashover, for many different fire growth rates, the minimum HRR can be rather similar.

5. Summary and conclusions

Several available experimental correlations and predictive models have long been used to provide estimates of the HRR necessary to lead to flashover conditions in compartment fires. Like all engineering tools, effective application requires knowledge of the underlying principles and limitations inherent in the development of the correlations and models and their impact on the resulting predictions. Differences of as much as a factor of two are seen in experimental and predicted estimates of the energy necessary to cause flashover, depending on the characteristics of the fire growth. From this paper, it is seen that:

1. Existing correlations used to predict the HRR at flashover provide lower-bound estimates. Since safety designs normally need to identify the actual HRR in a compartment that will result in flashover, the lower-bound estimates produced by existing correlations will be conservative. Actual HRR at flashover may be significantly higher than currently assumed for design purposes, depending on the time at which flashover conditions are reached. Designs that depend on a predicted HRR from any particular correlation should also consider the uncertainty entailed in these predictions.
2. Typical research to date has concentrated on the effects of flashover rather than causal factors leading to flashover conditions. Future research should better characterize conditions and geometry of the fire plume, upper layer, and compartment surfaces to facilitate better understanding of conditions prior to flashover.
3. Flashover is largely determined by a HRR/time relation (such as illustrated in Fig. 4). For a range of fire growth types, details of the shape of the fire growth curve up to the time of flashover are of secondary importance. Even curves with multiple HRR peaks prior to flashover have little impact on the HRR value found at flashover.
4. Experimentalists should be urged to carefully record the main features of flashover in room fires, especially the time that at which filling of the space with flaming gases reaches down to the halfway mark.

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