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# Flashover: A Study of Parameter Effects on Time to Reach Flashover Conditions

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**Flashover is characterized by the rapid transition in fire behavior from localized burning of fuel to the involvement of all combustibles in the enclosure. The objective of the present contribution is to calculate the development of flashover in a typical single-room fire and show the effect of key parameters on the time required to reach flashover conditions. It is found that the major parameters affecting flashover are fire growth rate, ventilation opening area, wall and ceiling material, and room area. Parameters with little effect on the time to reach flashover are vent height above the floor, ceiling height, fire location, and fire radiation heat loss fraction.**

## Introduction

AN important feature during fire growth is the phenomena of flashover, which is the transition from local burning to full-room fire involvement. High-radiation heat-transfer levels from the original burning item, the flame and plume directly above it, and the hot smoke layer spreading across the ceiling are all considered to be responsible for the heating of the other items in the room, leading to their ignition. Warning signs are heat buildup and rollover (small, sporadic flashes of flame that appear near ceiling level or at the top of open doorways or windows of smoke-filled rooms). Major factors that would be expected to affect flashover include rapidity of growth of the fire, its location, availability air to assist the burning via ventilation openings, room size, ceiling and wall conductivity and flammability, and heat- and smoke-producing quality of room contents.

The objective of the present contribution is to use the FASTLite computer code [available from National Institute of Standards and Technology (NIST)], version 1.1.2, to compute developments in a typical single room up to flashover conditions. That is, calculation will illustrate the time required for the upper-layer temperature to reach 600°C (1112°F), this being the accepted flashover criterion in the model. This criterion usually yields high enough heat flux levels of from 20 to 25 kW/m$^2$ (6340 to 7925 Btu/hrft$^2$) to occur at floor level, with near-simultaneous ignition of combustibles not previously ignited. With initial inside and outside room temperatures of 20°C (68°F) and humidity of 50%, it is expected that the time from ignition of the fire to reach flashover conditions depends upon the 1) floor area (square meters), 2) vent width (meters), 3) vent height (meters), 4) vent height above floor (meters), 5) ceiling height (meters), 6) fire specification (slow, medium, fast and ultra-fast), 7) fire location (center, wall, corner), 8) wall and ceiling material, 9) fire radiation fraction, and 10) fire maximum heat-release rate (megawatts). The effect of each parameter is illustrated and discussed, from which conclusions are drawn.

Fire investigators can develop an appreciation toward technical/scientific understanding of the fire development phenomena and its applicability to real-world practical down-to-Earth situations. The scientific topics of chemistry, physics, aerodynamics and heat transfer all play their part. Technical information about fuels, burning rates, fire spread, and flashover and backdraft phenomena is also relevant. These topics are now addressed in the light of the relevant equations being embodied in computer programs like CFAST, FASTLite, FPETool, and HAZARD (all available from NIST). The references provide further details, including Jones et al.,[1] Portier et al.,[2] Deal,[3] and Peacock et al.[4]

## Burning Rates

Typically, the heat-release rate (heat energy evolving on a per unit time basis) of a fire $\dot{Q}$ (kilowatts) changes as the size of the fire changes, as a function of time $t$ (seconds) after fire ignition. That is, the variation of $\dot{Q}$ vs $t$ is extremely important in characterizing the rate of growth of a fire. Data are available for heat-release rate vs time for many items [for example, see Peacock et al.,[4] Babrauskas and Krasny,[5] Babrauskas and Grayson,[6] Krasny et al.,[7] and Society Fire Protection Engineering (SFPE) Handbook[8]].

Slow, medium, fast and ultra-fast fire growths can be specified by the $t^2$-fire growth model, where, after an initial incubation period,

$$\dot{Q} = \alpha_f (t - t_0)^2$$

where $\alpha_f$ is a fire-growth coefficient (kilowatts/square seconds) and $t_0$ is the length of the incubation period (seconds). The coefficient $\alpha_f$ appears to lie in the range $10^{-3}$ kW/s$^2$ for very slowly developing fires to 1 kW/s$^2$ for very fast fire growth. The incubation period $t_0$ will depend on the nature of the ignition source and its location, but data are now becoming available (see Ref. 9) on fire-growth rates of single items of furniture (upholstered chairs, beds, etc.), which can be quantified in these terms. The characterization as a $t^2$-fire model for many burning items is also available in Kim and Lilley.[10]

Suggested values for the coefficient $\alpha_f$ are also given in the formula section of FASTLite and FPETool Computer Programs (see Refs. 2 and 3, respectively). The specification there for the fire-growth coefficient $\alpha_f$ (kW/s$^2$) is as follows: slow, 0.00293 kW/s$^2$; medium, 0.01172 kW/s$^2$; fast, 0.04690 kW/s$^2$; ultra-fast, 0.18760 kW/s$^2$.

These correspond to growth times of the fire form zero site to 1 MW total heat output as follows: slow, 600 s; medium, 300 s; fast, 150 s; ultra-fast, 75 s.

## Flashover

Often the determination of whether or not flashover is expected is the single most important fire computation. This topic is addressed specifically in Thomas[11] and Drysdale.[12] The FASTLite computer program single-room simulation is used for calculations in this study. This is a zone-type fire simulation computer program, which was developed by NIST. FASTLite is based on solving a set of combined equations that simulate the change in the enthalpy and mass over time. The starting point is the set of conservation equations that are derived from the conservation equations for energy,

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mass, and momentum. The time to reach flashover is here characterized by the criterion of the upper-layer temperature reaching 600°C (1112°F) in the FASTLite computer program, this being an accepted value in the fire community for typical single-room fires in homes.

There are other methods of estimating when flashover conditions will occur (for example, see Refs. 13–15), and they are described, compared, and contrasted in Kim and Lilley.[16] All of the methods give similar, but in most cases only slightly different, results. They incorporate the ventilation factor for an opening in a vertical wall

$$A_0\sqrt{H_0}$$

where $A_0$ is the window or door ventilation area (square meters) and $H_0$ is the height of opening (meters) from bottom to top. In this way the width and height (from sill to soffit) of a vent from the enclosure to the outside are utilized in the flashover criterion. Then the rate of growth of the fire is used to determine how much time is needed to reach the specific amount of heat-release rate necessary to meet the specific criterion. The present paper permits the inclusion of the effect of many more parameters on this time to reach flashover.

## Results and Discussion

Figure 1 shows the single room considered, with just one ventilation opening. Some geometric parameters are illustrated in the figure (numbers 1, 2, 3, 4, 5, 8, which are defined in the following list). There are 10 parameters of interest that affect the time required to reach flashover conditions, which are calculated in this paper. The parameters and their standard (default) values are as follows:

1) Floor area is $4 \times 4 = 16$ m$^2$.
2) Vent width is 2 m.
3) Vent height is 1 m (distance from bottom to top of the vent).
4) Vent height above floor is 1.5 m (distance from floor to midpoint of the vent).
5) Ceiling height is 2.5 m.
6) Fire specification is medium fire.
7) Fire location is fire in center of floor.
8) Wall and ceiling material is 0.016-m ($\frac{5}{8}$-in.) thick gypsum board.
9) Fire radiation fraction is 0.3 (radiation heat loss fraction from the flame).
10) Fire maximum heat-release rate is 3 MW.

The standard values and the variation of each parameter are generally within the normal range of residential house fires. Again, the time to reach flashover is here characterized by the criterion of the upper-layer temperature reaching 600°C (1112°F), which is the flashover condition of the FASTLite computer program. FASTLite (the most recent version being version 1.1.2) computer program single-room simulation is used for calculations. Each of following sections show the calculated effect of varying one parameter only while keeping all other parameters at their standard default values.

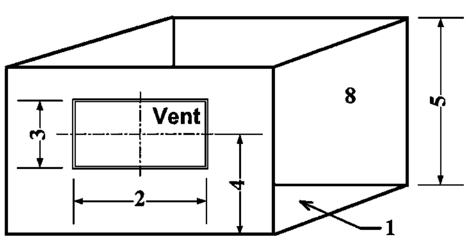


**Fig. 1 Parameters investigated.**

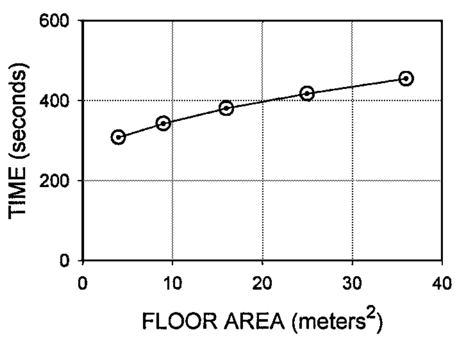


**Fig. 2 Flashover time vs floor area.**

### Floor Area

Figure 2 shows the effect of varying the floor area (parameter number 1) on the calculated time to reach flashover conditions. The floor area of the square room was varied through the range of 4, 9, 16, 25, and 36 m$^2$ with all other parameters retained at their default values. The calculations show that the time required to reach flashover relates only slightly to the floor area. In the case of the largest floor area (36 m$^2$), flashover occurs in about 450 s, as compared with the smallest floor area considered (4 m$^2$) taking about 300 s. This result is simply caused by the larger room needing a greater volume of combustion products to be generated in order to fill the larger horizontal space, and also that there is more mixing with cooler air as the smoke layer spreads out across the ceiling.

### Vent Width and Height

The vent supplies air (oxidant), which is needed for combustion, and so it is interesting to study the effect of vent size on the time to reach flashover conditions. The vent size was changed in two ways: its width and height from bottom to top (parameter numbers 2 and 3), while retaining all other parameters at their standard values. Figures 3 and 4 respectively show the results.

The calculations (Fig. 3) were performed with the vent width varied over the range 1, 1.5, 2, 3, or 4 m with all other parameters held at their standard values. The vent height was 1 m (its standard value) in these calculations of the width effect. The other calculation (Fig. 4) was performed with a range of different vent heights, varied over 0.5, 1.0, 1.5, and 2.0 m in height, while retaining all other parameters at their standard value, including, for example, the vent width retained at 2 m.

These calculations obtained from the single-room simulation part of FASTLite conform to the general trends and expectations, which can be obtained directly from the more simplistic empirical equations given in the Babrauskas and Thomas criteria for flashover. These simplistic approaches use only information about the vent width, vent height, and internal room surface area (in the case of Babrauskas only the first two of these). The trends are that a greater

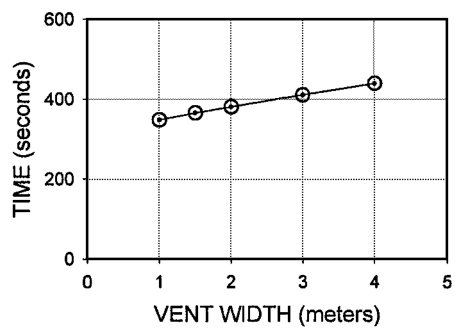


**Fig. 3 Flashover time vs vent width.**

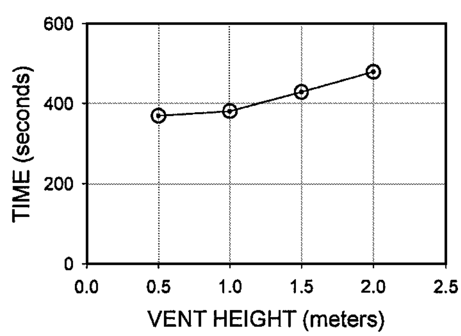


**Fig. 4 Flashover time vs vent height.**

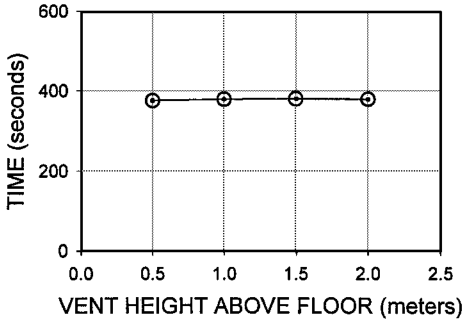


**Fig. 5 Flashover time vs vent height above floor.**

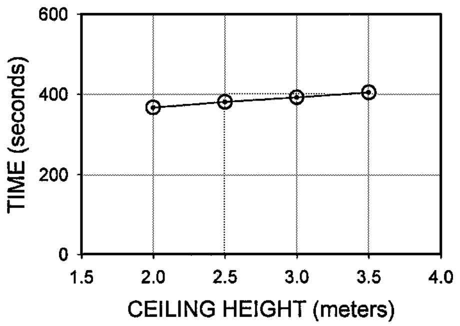


**Fig. 6 Flashover time vs ceiling height.**

amount of time is required to reach flashover when a larger vent is involved because more hot gas vents out and more cold air comes in with a larger vent. Almost a linear variation with width and height over the range of values is calculated for the particular standard values of the other parameters defining the problem. Air flowing in and smoke flowing out of vents in walls are also addressed in other parts of the FASTLite computer program.

### Vent Height Above Floor

The effect of the vent height above the floor (distance from floor to the midpoint of the vent) is now considered (parameter number 4). Varying this distance from 0.5 to 2.0 m in steps of 0.5 m considers vents (width 2 m and height 1 m) and corresponds to vents that range from those touching the floor to those touching the ceiling. Results are plotted in Fig. 5, illustrating that the vent height above floor has almost no effect on the time required to reach flashover conditions (within the confines of the standard values given to other parameters used in the calculations).

### Ceiling Height

The effect of the ceiling height (parameter number 5), changed from 2.0 to 3.5 m in steps of 0.5 m with other parameters at their standard values, is shown in Fig. 6. Ceiling height is hereby demonstrated to affect only slightly the time to reach flashover.

### Fire Specification

The relationship between the time to reach flashover and the rate of growth of the fire is extremely significant as expected. Slow, medium, fast, and ultra-fast $t^2$-fire models range over a wide range of fires of practical importance (parameter number 6). Medium-growth fires are typical of accidental fires; fast and ultra-fast fires are typical of accelerated fires and fires involving modern polyurethane-filled furniture. The dramatic effect of fire-growth rate is seen in Fig. 7. The time to reach flashover for the case of the slow-fire-growth model is off the scale at about 700 s. It is extremely important for reaching flashover to determine how quickly the fire grows. This dramatic effect of fire-growth rate on time to reach flashover is seen not only in the calculations given here for the particular values of the other parameters, but also for different values of the other parameters.

**Table 1 Properties of the wall and ceiling material**

| Material | Thickness, m | Conductivity, W/mK | Specific heat, J/kgK | Density, kg/m$^3$ | Emissivity |
|---|---|---|---|---|---|
| Gypsum $\frac{1}{2}$ in. | 0.013 | 0.100 | 900 | 790 | 0.90 |
| Gypsum $\frac{5}{8}$ in. | 0.016 | 0.160 | 900 | 790 | 0.90 |
| Gypsum $\frac{3}{4}$ in. | 0.019 | 0.160 | 900 | 790 | 0.90 |
| Common brick | 0.076 | 0.720 | 835 | 1920 | 0.90 |
| Light concrete | 0.150 | 0.125 | 1050 | 525 | 0.94 |
| Normal concrete | 0.150 | 1.750 | 1000 | 2200 | 0.94 |
| Glass fiber | 0.088 | 0.040 | 720 | 105 | 0.90 |

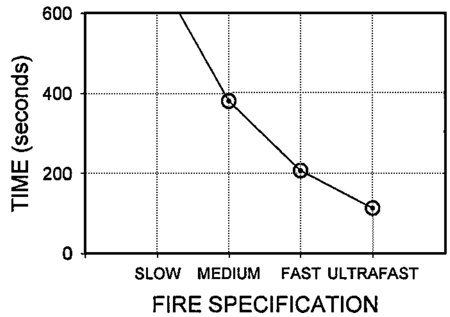


**Fig. 7 Flashover time vs fire specification.**

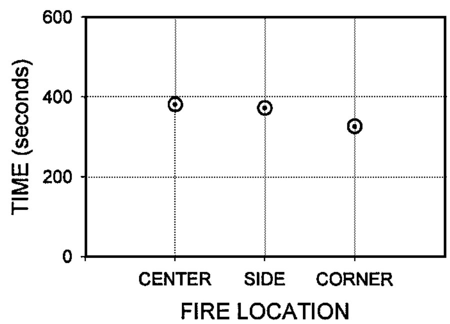


**Fig. 8 Flashover time vs fire location.**

### Fire Location

In Fig. 8 the result of different fire location is shown for a fire located in the center of the room at a side wall of the room and in a corner of the room (parameter number 7). It is seen that the progressive confinement of the walls (over the three fire locations considered) reduces cooling air entrainment into the fire plume and leads to more rapid temperature rise in the upper smoke layer. This qualitative reasoning explains the result seen in the calculations—that reduced time is required for flashover conditions with corner fires vs side-wall fires vs center-room fires.

### Wall and Ceiling Material

Seven wall and ceiling materials were considered, so as to illuminate on the effect of their properties on the time to reach flashover conditions. The array of materials considered here are gypsum of thickness $\frac{1}{2}$ in., $\frac{5}{8}$ in., and $\frac{3}{4}$ in., common brick 3 in., light concrete 6 in., normal concrete 6 in., and glass fiber 3.5 in. with properties given in Table 1. Conductivity and the associated property thermal diffusivity (equal to conductivity divided by the product of density times specific heat) are the major parameters affecting heat-transfer rates through the material for short time exposures. For longer time exposures the thickness of the material can also come into play

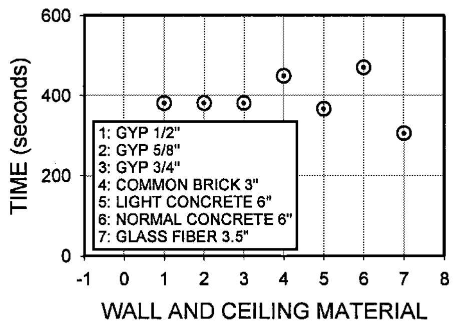


**Fig. 9 Flashover time vs wall and ceiling material.**

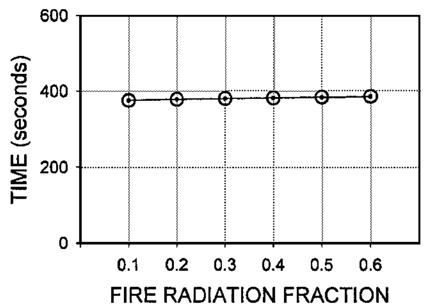


**Fig. 10 Flashover time vs fire radiation fraction.**

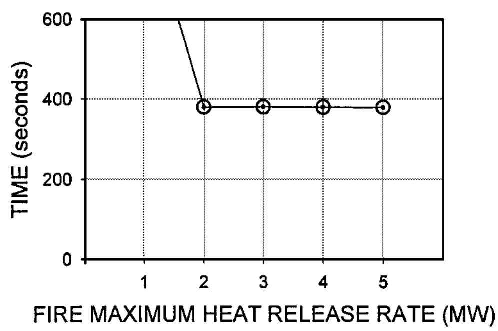


**Fig. 11 Flashover time vs maximum heat-release rate.**

(in fact, when the time exposure is such that the thermal penetration distance exceeds thickness of the material). The effect of the type of material specified on the relatively short time to reach flashover (parameter number 8) is shown in Fig. 9.

### Fire Radiation Fraction

The fraction of heat radiated from typical burning items in residential fires is about 0.25–0.35 (about 25–35%). However, for completeness, five different fire radiation fraction values (parameter number 9) are considered, which cover a large and exhaustive range (10–60% of fire heat loss by radiation). Most common fires have radiation heat losses within this range. For example, the radiation fraction of gasoline pool fires range from 10 to 60% for pool sizes in the range of 10 and 1 m pool diameter, respectively. More radiation fractions for other fires can be found in Lilley.[17] The effect on the calculated time to reach flashover is given in Fig. 10. We observe that the radiation factor has virtually no effect on the time to reach flashover. This might be because the total heat from the fire exhibits itself as heat convected in the plume above the fire and as heat radiated from the fire, and that whatever the particular split is between the two the totality of the heat generated is still within the room and affects the temperature in the smoke layer in a very similar fashion.

### Fire Maximum Heat-Release Rate

The effect of specified fire maximum heat-release rate (parameter number 10) on the time to flashover is covered in Fig. 11. When the maximum heat-release rate is 1 MW, flashover occurs in about 900 s, and this is off the scale. Flashover occurred at about 380 s for all of the other cases considered, that is, when the maximum heat-release rate was 2 MW or greater. The reason for all these times being equal is that, for the values of the other parameters specified, the upper-layer temperature reached 600°C (1112°F) during the growth phase of the medium growth rate fire, that is, before the heat release rate actually reached 2 MW. For other problem parameters (for example, fire-growth rate, room size, etc.) this might not necessarily be the case.

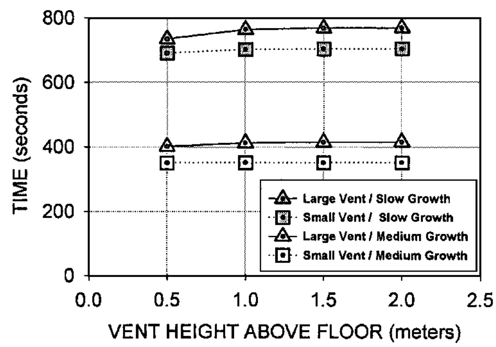


**Fig. 12 Flashover time vs vent height above floor of different vent sizes and fire-growth rates.**

### Multiple Parameter Variations

Earlier results are indicating the effect of a single parameter change when the other parameters held their standard (default) values. The standard values and the variation of each parameter are generally within the normal range for residential house fires. If any of the default values are changed, the effect of variation of a parameter can be different than those already illustrated. For example, the effect of vent height above the floor with different widths of the vent might be different than given earlier, as the standard (default) vent width of 2 m. Also the effect of vent height above the floor on the time to reach flashover can be more significant with a slower fire growth than the medium (default) growth fire just considered. All of these effects are shown in Fig. 12.

Time to reach flashover conditions are calculated for a larger vent (3 m wide × 1 m high) and a smaller vent (1 m wide × 1 m high) with two different fire-growth rates (that is, slow and medium). The calculated time to reach flashover conditions with different vent heights above floor are then plotted in Fig. 12. The vent height above floor has no effect on the time to reach flashover within the confines of the standard values of the other parameters. The vent height also has very little effect on the time to reach flashover in almost all cases, except that a small effect is found with a larger vent and for a slower growth fire.

## Conclusions

The objective of the this study was to calculate the development of flashover in a typical residential single-room fire and show how key parameters affect the time required to reach flashover conditions. The FASTLite (version 1.1.2) computer program was used for the calculations. Fire-growth rate, ventilation opening area, walls and ceiling material, and room area were the major parameters affecting flashover. Vent height above the floor, ceiling height, fire location, and fire radiation heat-loss fraction have very little effect on the time to required to reach flashover conditions in typical residential fires.

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