NFPA TOXICITY ADVISORY COMMITTEE
STRAWMAN PROCEDURE FOR ESTIMATING SMOKE TOXICITY HAZARD

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The purpose of this exercise is to develop a procedure which might be used by an occupancy committee of the Life Safety Code to evaluate the potential hazard of a material in the context of use. The goal is to estimate the incremental change in hazard as a result of the material to support a decision to allow, ban, or limit (e.g., quantity, location, or use only in combination with specified optional fire protection features) the use of the material in that occupancy class.

The steps necessary to conduct such an analysis would include:

(1) Define the proposed use and context(s) of use.

(2) Outline scenario(s) of concern.

(3) Collect pertinent test data and algorithms.

(4) Estimate hazard development.

(5) Estimate occupant response time needs.

(6) Estimate possible mitigating effects of fire protection systems.

The proposed use and context of use includes the physical form of the material, quantity, and location within the structure.

The scenarios of concern should be specified in as much detail as possible and should include "typical" as well as "worst" cases.

Hopefully, some test or material property data is available. Sometimes, data from similar materials might be used to obtain performance estimates. Failing all else, the committee can require the proposer to submit the required data before action can be taken on the proposal.

The hazard development involves two areas. The material may result in a fire which develops faster or spreads farther, and/or it may result in more or "worse" smoke. All fires produce heat, smoke, and toxic gases, so the key issue here is estimating the incremental change resulting from the material (product) in question and then assessing the significance of this change in terms of occupant safety.

Occupant response time needs should be evaluated for various "typical" cases of occupant load, location, and physical/mental capabilities.

In evaluating the impact of fire protection systems, the "base case" should include only mandatory features. Provision of additional features may be suggested/evaluated to mitigate any increase in hazard identified with the use of the "new" material and form the basis for exceptions to any limitations imposed.

The following presents some potentially useful data and relationships for addressing steps 4 through 6 that provides "order of magnitude" estimates for the important parameters involved in a hazard analysis. This material has been assembled from various sources and, in some cases, simplified with the goal of providing estimates rather than exact solutions. Material property data for use in the calculations is presented in table 1. Test data from

upholstered furniture burns (peak heat release rates, time to peak, and heat of combustion) along with a simple formula to estimate peak heat release rate and time to peak for upholstered furniture items (correlated to the items tested) are presented on page 27 of the enclosed reprint by Babrauskas. Smoke yield (Y_s) values for these items can be taken as 0.03 for thermoplastic fabrics over polyurethane foam, 0.005 for cotton fabric over cotton batting, and 0.015 for all others. The smoke yield is the mass of smoke produced per unit mass consumed. The LC_{50} (30 min) for all construction types can be taken as 32 mg/ℓ. This is the mass concentration (fuel mass divided by the volume into which the combustion products are distributed) necessary to kill 50% of the test animals exposed for 30 minutes.

Extent of Fire Spread

The first question to be answered is whether the fire will remain in the first item ignited or <u>will it spread</u> to other combustibles. Any combustibles so located as to experience direct flame impingement from the first item should be assumed to ignite. We next estimate the potential of spread by radiative transfer. For each item involved by direct contact we assign a $\dot{Q}$, an estimate of the average heat release rate, and a ΔH_c, an effective heat of combustion. For i items burning together we estimate the combined mass loss rate from:

$$\dot{m}_{total} = \sum_i \frac{\dot{Q}_i}{\Delta H_{c_i}} \qquad (1)$$

Figure 1 will now allow us to estimate whether nearby objects will ignite. Note that this does not involve a direct calculation of radiation, but rather uses an empirical correlation developed by Babrauskas as cited on figure 1.

Another spread mechanism is flashover, which will involve all combustibles in the room. To estimate whether the room will be driven to flashover, we calculate the ventilation factor (vent area times square root of vent height) and sum the heat release rates of all items burning. Figure 2 can then be used to determine the minimum energy necessary to flash over a room of a given floor area for a specified ventilation factor. Alternately, the equation from Thomas for minimum required flashover energy (kW) may be used.

$$\dot{Q}_{fo} = 378\ A_v \sqrt{h_v} + 7.8\ A_w \qquad (2)$$

Source: Fire and Materials, Vol. 5, No. 3, 103-111, Sept. 1981.

where: A_v is the vent area (m^2),

h_v is the vent height (m), and

A_w is the total wall area (m^2).

If the combined heat release rate exceeds the minimum flashover energy for the compartment, all combustible items (which decompose below ~ 1000°C) must be assumed to pyrolyze.

A final mechanism of material involvement is <u>immersion in the hot gas</u> layer. The temperature of the layer can be estimated from the following equation:

$$T_{UL} = 6.85 \left[\frac{\sum_i \dot{Q}_i^{\,2}}{(A_v \sqrt{h_v})\ (h_k A)} \right]^{1/3} + T_{amb} \qquad (3)$$

Source: NBSIR 83-2712

where: $\sum_i \dot{Q}_i$ is the combined heat release rate (kW),

$A_v \sqrt{h_v}$ is the ventilation factor,

A is the total enclosure surface area (m^2),

$h_k = k/\delta^*$, k is the thermal conductivity (table 2), and

δ is the thickness (m) of the lining material.

Note: if multiple lining materials are present $\sum_i (h_k A)_i$ should be used.

T_{amb} is the ambient temperature (°C)

This will tell us if any materials immersed in the hot gas layer can be heated enough to decompose or ignite. If the previous flashover prediction showed no flashover and this calculation shows additional material ignites, the additional heat release rate should be added to the previous total and a new flashover prediction made. Equation 3 should only be used for cases where the combustion is not ventilation-limited (pre-flashover).

At this point, we have an estimate of the extent of spread of fire within the compartment of origin. If flashover is expected, and if there are combustibles in the next compartment we must probably assume that the fire will spread to it, and so on, until a closed, fire-rated partition is encountered. This leaves little time for evacuation from these compartments.

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*Use this form for steady state (long time) calculations. This gives the most conservative result. For shorter times, the initial heating solution is obtained by using $h_k = \sqrt{k\rho c/t}$. The $k\rho c$ product for common materials is given in table 2. An estimate of the time beyond which the long time form is valid is given by $t_p = (\rho c/k)(\delta/2)^2$ (sec).

Smoke and Gas Levels

The next step is to estimate the impact of smoke and toxic gases on the occupants of any compartments freely connected to the compartment of origin. We can estimate the filling time for the compartment of origin from the total heat release rate previously computed and figure 3. (Note: this figure is for a constant output fire). The filling time for freely connected compartments on the same floor will be of the same order of magnitude (use the total floor area).

For most fuels burning with sufficient oxygen, the smoke yield (fraction of fuel mass burned which is converted to smoke) is a constant, (Y_s), which varies over a range of a few tenths of a percent (for wood and cellulosic fuels) to about 30% (for some plastics).

We can estimate the smoke density in all compartments if we have the mass fraction of fuel converted to smoke (Y_s) for each fuel. For i fuels we find:

$$M_s = \frac{\sum_i (m_f Y_s)_i}{V_T} \tag{4}$$

where: m_f is the total mass of fuel i burned in milligrams, and

V_T is the total volume of all freely connected compartments in m^3.

M_s gives a soot mass concentration in each compartment once filled (assuming full mixing). Then, using the relation that a mass concentration of one milligram per cubic meter (of black smoke) has an optical density of .0035 per meter, an optical density can be obtained ($D = M_s/0.0035\ m^{-1}$). Finally, using the relation from Rasbash:

$$V = 1.4/D^{.767} \tag{5}$$

where: V is distance of vision (m),

D is optical density per meter,

we can estimate how far an occupant can see.

In the same manner as for smoke, the toxicity of the combustion products in each compartment can be estimated by:

$$C_{cp} = \sum_i \frac{(m_f)_i}{V_{T\ell}} \tag{6}$$

where: $(m_f)_i$ is the total mass of fuel i burned (mg),

$V_{T\ell}$ is the total volume of all compartments in ℓ (1000 ℓ = 1 m^3),

In this case a Y_{cp} similar to the Y_s is not included since the conversion efficiency is taken into account in the LC_{50} determination (Note the change in units for volume). C_{cp} gives the "combustion product" concentration in each compartment. If we then take the ratio of C_{cp} to the mass weighted average LC_{50} for each fuel we have the fraction of the 30 min. lethal concentration in each compartment. That is:

$$\% \text{ Tox} = \frac{C_{cp}}{\sum_i \frac{\{(LC_{50})_i \; [m_f]_i\}}{\sum_i (m_f)_i}} \times 100 \tag{7}$$

The denominator of equation 7 is a way of determining an average LC_{50} for a mixture of fuels for which the LC_{50} of each individual fuel is known. For

example, if we have a total fuel mass of 100 g made up of 25 g of fuel #1 and 75 g of fuel #2, the average LC_{50} for the two fuels together will be 25% of the LC_{50} of fuel 1 plus 75% of the LC_{50} of fuel 2. After calculating the percent toxicity by equation 7, we can apply the assumption (Haber's rule) that the product of concentration and time is a constant $\left(C_{cp}\Delta t = LC_{50} \cdot 30 \text{ min}\right)$. Thus, 50% of the 30 min lethal concentration is lethal in 60 min and 150% of the 30 min lethal concentration is lethal in 20 min.

Evacuation Time Required

The previous sections give an estimate of the development of hazardous conditions within the fire zone. To determine whether this represents a threat to the occupants in these spaces, it is necessary to obtain an estimate of the time required to evacuate these spaces. For any occupant, this time can be estimated from

$$\Delta t_{evac} = \Delta t_{notif} + \sum_i \left(\Delta t_{travel} + \Delta t_{door}\right)_i \tag{8}$$

where: Δt_{evac} is the total time required from start to a safe point (e.g., horizontal exit or stairwell,

Δt_{notif} is the time from ignition to when the occupant finds out there is a fire,

Δt_{travel} is the travel distance from start to the opening to the next compartment divided by a characteristic walking speed,

Δt_{door} is the time spent waiting to move through the door to the next compartment, and

i is the number of compartments between the person's starting point and the safe point.

To estimate these times, the following procedure can be used. In establishing the original scenario, a number of occupants should be assigned to each compartment, and a floor plan with dimensions and door locations should be prepared. For persons in the room of origin, $\Delta t_{notif} = 0$ (unless the fire is in a concealed space). For persons in spaces through which others will evacuate, Δt_{notif} is the time that the first person from the fire space reaches that space. If detectors are present Δt_{notif} is the estimated detector response time for persons not in the space of origin.

For estimating Δt_{travel}, walking speeds of 200 ft/min at a population density of 20 ft^2/person or greater and 100 ft/min at a density of 5 ft^2/person or less can be used.

For Δt_{door} use a pass-through rate of one person per second for each 2 ft of opening width (subtract 1 ft from the width if there are doors) or one person per second for a revolving door.

Estimating Response Time of Detectors and Sprinklers

To estimate possible mitigating effects of fire protection features, the key parameter is the response time of the actuating device. While this will

be a function of the fire growth rate, room size, ventilation parameter, and device characteristics, for most flaming fires of practical interest some simple estimates can be made. At recommended spacings in rooms with 8-10 ft ceilings, smoke detectors will activate in about one minute, heat detectors and fast response sprinklers in about three minutes and standard sprinklers in about six minutes. If estimates of heat release vs time for the early stage of the fire is available, closer estimates of operating times can be made by assuming that a smoke detector will respond when $\dot{Q}$ = 200 kW, heat detectors and fast response sprinklers at about 400 kW, and standard sprinklers at about 600 kW.

For detectors and sprinklers, the activation time defines Δt_{notif} for all occupants not in the room or origin unless the time for the first occupant of the room of origin to reach the compartment in question is less. It should be assumed that detectors will not effect the fire growth or smoke and gas transport. Sprinklers will stop the spread of the fire, reduce the upper layer temperature in all compartments, and limit further addition of smoke and gas mass to the volume, but will mix the smoke and gas present into the entire connected volume.

To illustrate this procedure, an example problem using each of the equations previously described will now be presented.

Hypothetical Example Problem

Assume the subcommittee on educational occupancies is evaluating the hazard of wood storage in a shop on an exit access corridor in a school building. The shop is 8 x 8 meters and has a double door (2.2 m high x 2 m wide) to a corridor 22.9 m long by 4.9 m wide with similar double doors at both ends. The shop doors are chocked open. The ceilings are 3 m high and all surfaces are 6 in concrete.

The fire starts in a stack of 16 oak studs (2 x 4 x 8 ft) piled in an open stack to dry and ignited by a small solvent spill/spark.

1. Find $\dot{Q}_{peak}$ for the stack of wood.

   From table 1, $\dot{q}''$ for oak = 120 kW/m^2

   Each stud has a surface area of 0.61 m^2

   So $\dot{Q}_{peak}$ = 120 (.61) = 73.2 kW per stud or 1171 kW for the stack of 16

2. Find $\dot{M}_{peak}$ to determine radiative spread.

   From eqn. (1), $$\dot{M}_{peak} = \frac{\dot{Q}_{peak}}{\Delta H_c}$$

   $$\dot{Q}_{peak} = 1171 \text{ kW}$$

   From table 1, $$\Delta H_c = 17.78 \text{ kJ/g} = 17.78 \frac{\text{kW-sec}}{\text{g}}$$

   $$\dot{M}_{peak} = \frac{1171}{17.78} = 65.86 \text{ g/sec}$$

Although this is off scale in figure 1, extrapolation of the curves gives critical ignition distances of about 0.6 m for difficult, 1.1 m for normal, and 1.45 for easy to ignite materials.

3. Check for flashover.

The shop has a floor area of 64 m^2 and $A_v \sqrt{h_v}$ for the double door is ~ 6.5

From figure 2, the minimum flashover energy is 1500 kW, so the room will not flashover.

Note: equation (2) gives a minimum flashover energy of 3215.72 kW because figure 2 is very conservative at lower ventilation factors.

4. Estimate upper layer temperature.

From eqn. (3),

$$T_{UL} = 6.85 \left[\frac{\sum_i Q_i^2}{(A_v \sqrt{h_v})(h_k A)} \right]^{1/3} + T_{amb}$$

$$\sum_i Q_i^2 = (1171)^2 = 1.37 \times 10^6$$

$$A_v \sqrt{h_v} = 6.5$$

$$A = 2\ (64) + 4\ (24) = 224\ m^2$$

From table 2 for concrete, $h_k = k/\delta = \frac{1.6 \times 10^{-3}}{.15} = 1.06 \times 10^{-2}$

$$T_{UL} = 6.85 \left[\frac{1.37 \times 10^{6}}{(6.5)(1.06 \times 10^{-2})(224)} \right]^{1/3} + 24$$

$$= 6.85\ (44.6) + 24$$

$$= 330\ °C$$

This is far below the ignition temperature of any materials which might be immersed in the upper layer and will probably not seriously decompose wiring.

5. Estimate filling time.

From figure 3 with a floor area of 64 m^2 and a $\dot{Q}$ of ~ 1000 kW, the filling time is about 3 min.

6. Estimate smoke level.

In step 2 we found that the peak mass loss rate is 65.86 g/s so when the room is filled to the level of the fire, no more than 11,855 g of wood has been burned.

From table 1, $Y_s = 0.013$

Thus the smoke mass = 154 g or 1.54×10^5 mg

The total volume of the shop and corridor is 528.6 m^3

So the mass concentration is 291 mg/m^3

or an optical density of ~ 1 m^{-1}

or a vision distance of ~ 1.38 m (4.5 ft)

This would be difficult to escape through.

7. Estimate toxicity.

In the previous step we found that the fuel mass burned was 11.855×10^6 mg and the volume was 528.6 m^3 (5.286×10^5 ℓ)

So the C_{cp} from eqn. (6) is

$$C_{cp} = 22.4 \text{ mg/}\ell$$

Since the LC_{50} for oak (flaming) is 56.8 mg/ℓ the % Tox = 39.4%, which is safe (using Haber's rule, time to lethality is ~ 76 min).

Therefore, the hazard posed in this scenario at a time of 3 minutes is that of smoke obscuration and upper layer temperature in the room of origin.

8. Estimate escape time needed.

The travel distance in the corridor is 37.5 ft (half the length since there are exits at both ends). Thus travel times will range between 11.25 sec and 22.5 sec after notification. People can move through the double doors at a rate of 2 per second at each end, 4 per second total.

9. Estimate impact of fire protection features.

For an immediate notification (shop occupied), 45 persons can escape in 3 min. With a 60 sec delay (smoke detector) 30 persons can escape in 3 min. Heat detectors and all sprinklers will activate too late, but door closers on the shop doors could extend the safe time in the corridor by preventing smoke flow into the corridor.

Table 1. Material Property Data

	Material/Product	Heat Release (per unit area) $\dot{q}''$ (kW/m^2)	Heats of Combustion ΔH_c (KJ/g)	Smoke Yield Y_s (g/g)	Ignition Temperature T_{ig} (°C)	Toxicity LC_{50} (mg/ℓ) F	NF
NBS Toxicity Test Materials [1,2,3]*	ABS	460	35.3	0.21	575	19.3	30.9
	Douglas Fir	217	21.09	0.010	465	39.8	22.8
	Flexible PU Foam	500	24.64	0.02	370	>40	26.6
	Modacrylic Fabric	--	24.72	--	725	4.4	5.3
	PTFE	--	5.0	0	620	.045	.045
	PVC	70	16.44	0.091	600	17.3	20.0
	Rigid Polystyrene	720	39.7	0.030	490	38.9	>40
	Red Oak	120	17.78	0.013	480	56.8	30.3
	Rigid Polyurethane	221	40.84	0.12	550	13.3	>40
	Wool Fabric	199	20.82	--	650	28.2	25.1
Wire/Cable Insulation [4,5,6]	PTFE	43	3.2	0	660	1.1	
	Silicone	29	25.0	0	573	775	
	XPE/FRXPE	22	28.3	0.22	516	46	
	XPE/Cℓ•S•PE	33	13.9	0.30	600	46	
	PE,PP/FRCℓ•S•PE	36	29.6	0.15	620	46	
	XPE/Neo	34	10.3	0.32	607	46	
	PE/PVC	36	25.1	0.21	620	27	
Mattresses (core/ ticking) [2,3,7]	Polyurethane/PVC	1300	24.9	0.10	400	37.7	
	Polyurethane/PVC (Innerspring)	400	24.8	0.11	400	32.1	
	Cotton/PVC (Innerspring)	30	7.5	0.05	525	42	
	Latex/PVC	1375	28.0	0.20	--	--	
	Polyurethane/Rayon	800	23.0	0.02	400	41	
	Cotton & Polyester/ Polyester	500	11.4	0.04	525	46	
	Cotton/Cotton (Innerspring)	20	5.7	0.005	525	47	
	Neoprene/Cotton	35	9.3	0.12	--	--	
	Polyurethane/ PVC & Nylon	400	22.1	0.10	400	35	
Misc. Materials [5,6]	Cotton	20	18	0.005	525	47	
	Vinyl Floor Tiles	16	18	0.2	470	83	
	Nylon Carpet	350	29	0.1	475	21.6	

*Numbers in brackets refer to the sources of the data presented in each section from the list on the following page.

References for Table 1

1. Levin, B.C. et al., "Further Development of a Test Method for the Assessment of the Acute Inhalation Toxicity of Combustion Products", NBSIR 82-2532, NBS, Gaithersburg, MD 20899 (1982).

2. "Materials Bank Compendium of Fire Property Data", Products Research Committee, Feb. 1980.

3. McKinnon, G., Editor, "Fire Protection Handbook - 15th Edition, NFPA, Quincy, MA 02269, Section 4, Chapter 12.

4. Tewarson, A., "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters", EPRI Report NP-1200, Part 1, Electric Power Research Institute, Palo Alto, CA 94304, Oct. 1979.

5. Matijak-Schaper, M. et al., "Toxicity of Thermal Decomposition Products from Commonly Used Synthetic Polymers", Fire Science and Technology, Vol. 1, No. 1, Oct. 1982.

6. Levin, B.C., unpublished data.

7. Babrauskas, V., "Combustion of Mattresses Exposed to Flaming Ignition Sources, Part II. Bench-Scale Tests and Recommended Standard Test", NBSIR 80-2186, NBS, Gaithersburg, MD 20899, Feb. 1981.

Table 2. Thermal Properties of Room Lining Materials[a]

	Density ρ $\frac{kg}{m^3}$	Specific Heat c $\frac{kJ}{kg.K}$	Thermal Conductivity $k \times 10^3$ $\frac{kW}{m.K}$	$k\rho c$
Aluminum (pure)	2710	.895	206	500
Concrete	2400	.75	1.6	2.88
Asbestos-cement board (heavy)	2100	1.0	1.1	2.31
Brick	2600	0.8	0.8	1.66
Brick/concrete block	1900	.84	.73	1.17
Gypsum board	960	1.1	.17	0.180
Plasterboard	950	.84	.16	0.127
Plywood	540	2.5	.12	0.162
Chipboard	800	1.25	.15	0.150
Aerated concrete	500	.96	.26	0.1248
Cement-asbestos board	658	1.06	.14	0.0976
Calcium silicate board	700	1.12	.11-.14	0.0862
Fibre insulation board	240	1.25	.053	0.0159
Alumina silicate block	260	<1>	.14	0.0464
Glass fibre insulation	60	.8	.037	1.78×10^{-3}
Expanded polystyrene	20	1.5	.034	1.02×10^{-3}

[a]From reference [39].

Source: NBSIR 82-2516

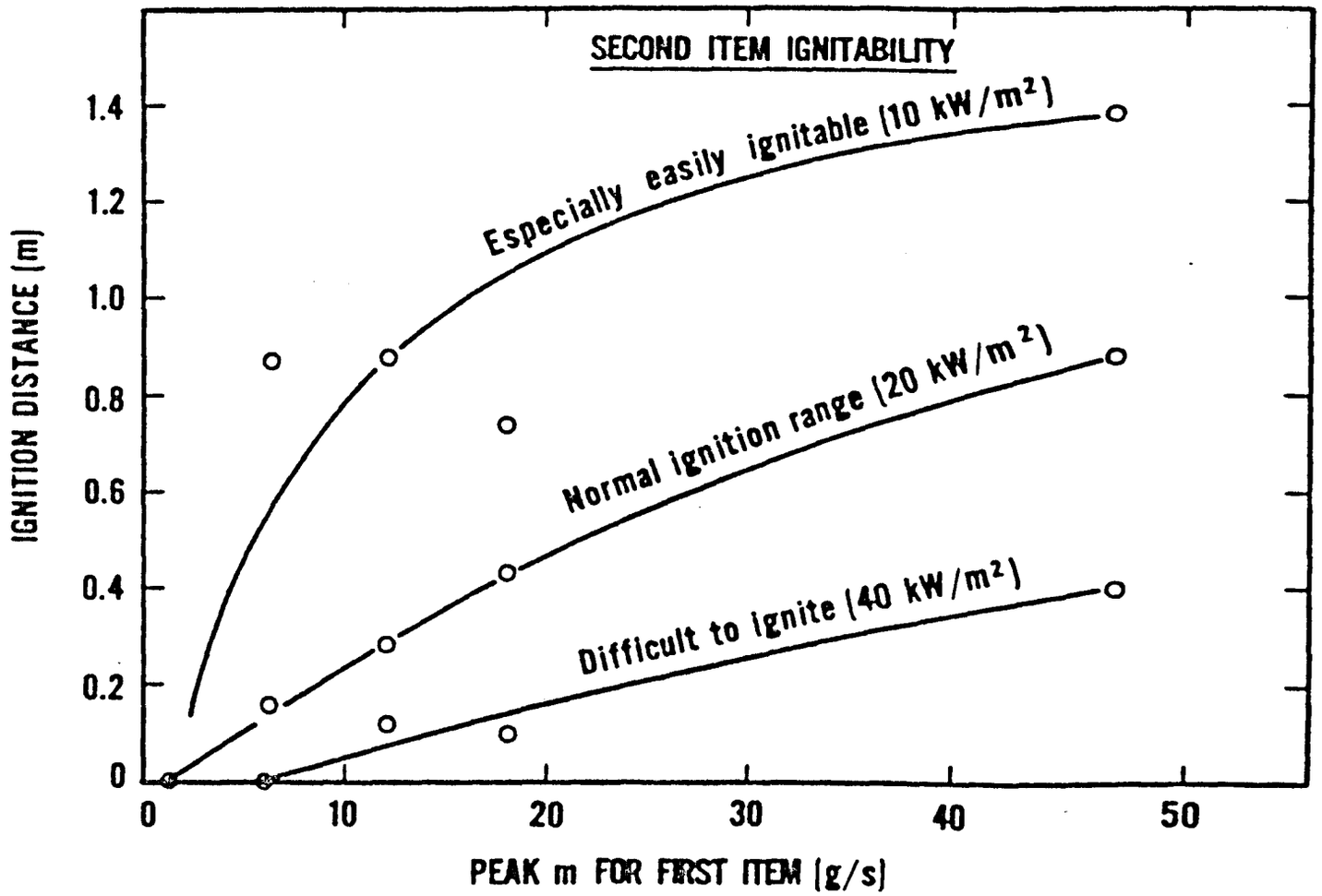


Figure 1 Relationship between peak mass loss rate and ignition distance for various ignitability levels.

Source: NBSIR 81-2271

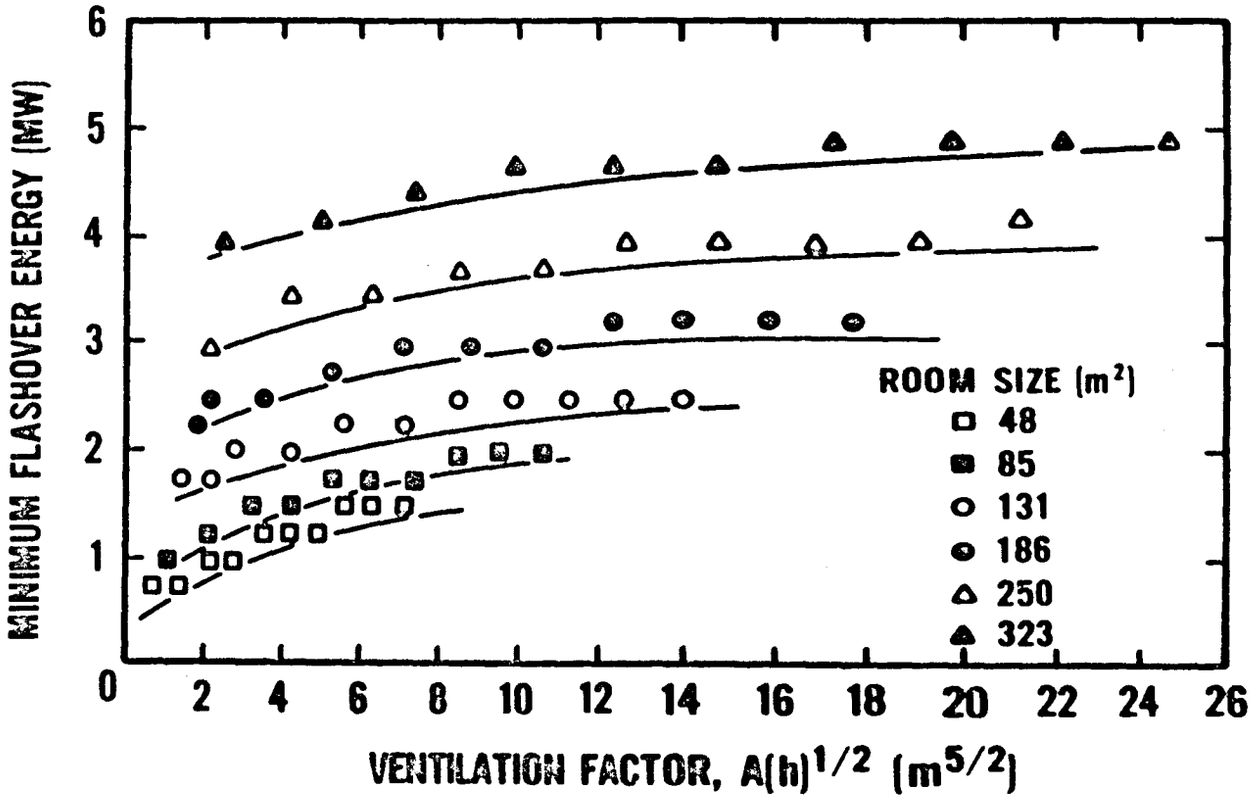
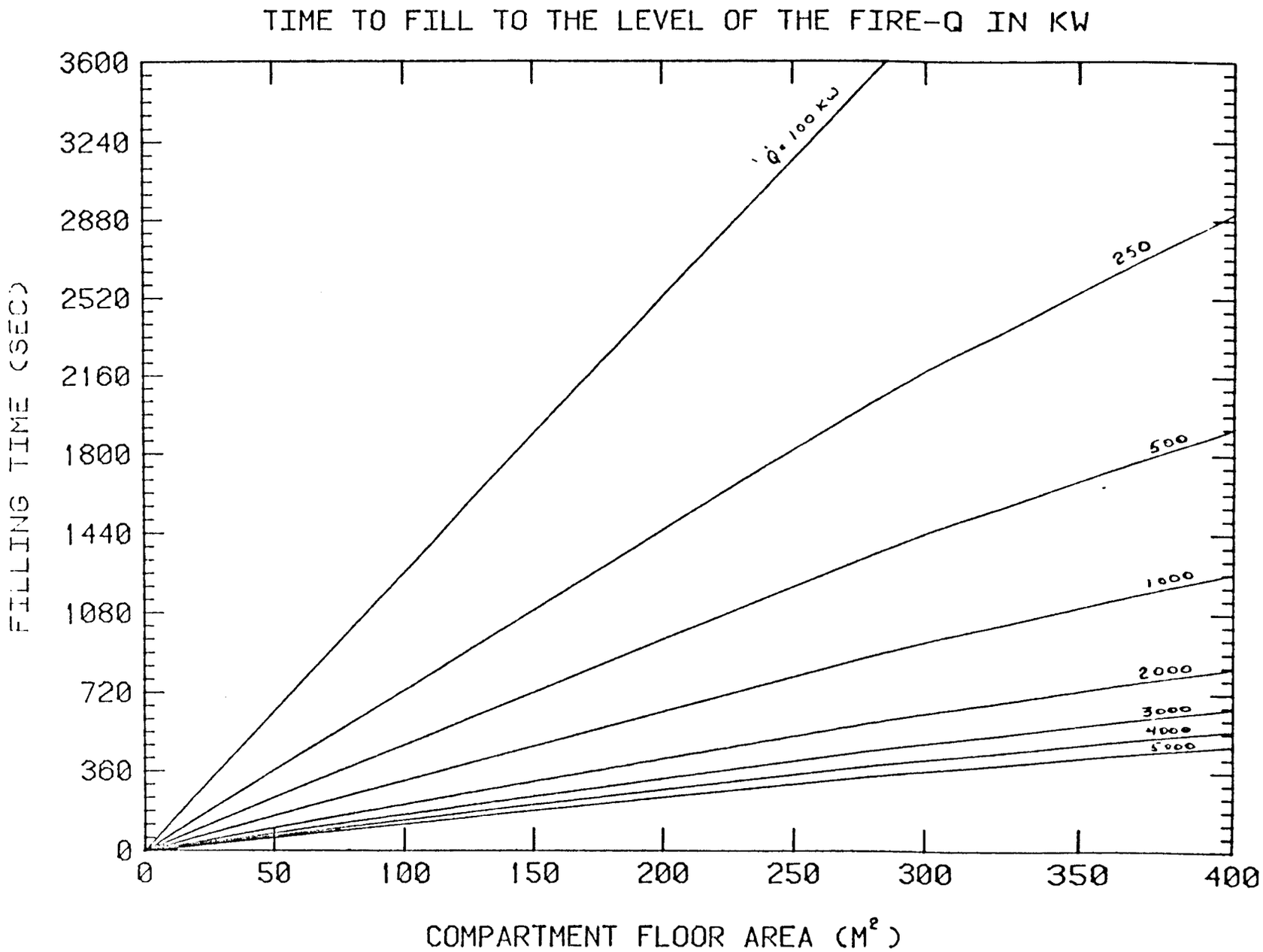


Figure 2. Room Flashover Modeling Prediction for Various Ventilation Factors (Gypsum Wall Lining / 2.4 m Ceiling Height)

Source: NBSIR 82-2516

Figure 3



Source: NBSIR 82-2622
Eqn. 18