JOURNAL OF PROPULSION AND POWER
Vol. 18, No. 4, July–August 2002

Heat Release Rates of Burning Items in Fires

Hyeong-Jin Kim* and David G. Lilley†
Lilley and Associates, Stillwater, Oklahoma 74074

Heat release rates of typical items in fires are needed as a prerequisite for estimating fire growth and temperatures in structural fires. That is, these burning rates, in terms of heat release rate vs time, are required to be specified by the user as input to single-room and multiroom structural fire computer codes such as CFAST, FASTLite, FPETool, and HAZARD. Data are given that permit burning items to be specified in a useful modeled way, taking a t^2 fire for the growth and decay periods, with a constant maximum heat release rate between these two periods. By the use of the given data, a user of a fire simulation program can simply and easily specify the initial fire of a typical burning item, rather than having to appeal to the original experimental data. In this way, the user does not need to search for and incorporate a complicated set of numbers into the fire simulation program.

Introduction

COMPUTER codes are available that permit calculations to be made of the effect of a given specified fire on the subsequent environment in a structural fire. Things such as temperature of the smoke layer; its depth from the ceiling downward; its optical density; ceiling, wall, and floor temperatures; floor surface heat flux rate; etc., are calculated a function of time in all of the rooms of a typical multiroom structural fire. However, the accuracy of these calculations is strongly dependent on the correctness of the initial fire specifications.

Heat release rates of typical items in fires are needed as a prerequisite for estimating fire growth and temperatures in structural fires. That is, these burning rates are required to be specified by the user as input to single-room and multiroom structural fire computer codes such as CFAST,[1] FASTLite,[2] FPETool,[3] and HAZARD.[4] Data are given here that permit burning items to be specified in a useful modeled way, taking a t^2 fire for the growth and decay periods, with a constant maximum heat release rate between these two periods. A vast range of many items is considered. Detailed tabulation of the data permits fire modelers to initiate calculations. Further knowledge enables the deduction of when second and subsequent items may become involved, whether flashover may occur, and when conditions may become untenable. Thus, it is clear that many important phenomena that are calculated in fires depend on the quality and accuracy of the initial burn specification.[5–7]

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,[8] Babrauskas and Grayson,[9] Krasny et al.,[10] and DiNenno.[11]) Experimental tests give useful information on the burning rates of many typical household items. These data are used in this paper so as to permit the heat release rate vs time of burning items to be specified in a useful modeled way, taking a t^2 fire for the growth and decay periods, with a constant maximum heat release rate between these two periods. Using the modeled parameterized data given here, a user of a fire simulation program can now simple and easily specify the initial fire of a typical burning item, rather than having to appeal to the original experimental data. In this way, the user does not need to search for and incorporate a complicated set of numbers into the fire simulation program.

t^2-Fire Growth Model

Emphasis is often placed on the growth phase of the fire. Slow, medium, fast, and ultrafast fire growths may be specified by the t^2-fire growth model, where, after an initial incubation period,

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

where α_f is a fire-growth coefficient (kilowatts per second squared) and t_0 is the length of the incubation period (seconds). The coefficient α_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[9] on fire growth rates on single items of furniture (upholstered chairs, beds, etc.) which may be quantified in these terms. Suggested values for the coefficient α_f are also given in Refs. 1–4. The specification there for the fire-growth coefficient α_f is slow 0.002778 kW/s^2, medium 0.011111 kW/s^2, fast 0.044444 kW/s^2, and ultrafast 0.177778 kW/s^2.

These correspond to growth times of the fire from zero size to 1 MW total heat output in slow 600 s, medium 300 s, fast 150 s, and ultrafast 75 s.

Burning Rates of Typical Items

Experimental data are available for a variety of items, giving heat release rate $\dot{Q}$ (kilowatts) vs time (seconds). Each of these graphs is in conformity with several parameters that completely characterize the situation, as given in Fig. 1:

t_d = time at which $\dot{Q}$ decay begins
t_{end} = time at which $\dot{Q}$ equals zero
t_g = growth time, $t_{1\,MW} - t_0$
t_{lo} = level-off time
t_0 = time to the onset of ignition
$t_{1\,MW}$ = time to reach 1 MW

Notice that both the ascent and decent are characterized by t^2-fire activity; where $t = t - t_0$,

$$\dot{Q} = \alpha_g t^2$$

and where $t = t_{end} - t$,

$$\dot{Q} = \alpha_d t^2$$

where α_g and α_d are the fire-growth and fire-decay coefficients (kilowatts per second squared), respectively.

These heat release rates $\dot{Q}$ vs time t (seconds) are active only in the growth ($t_0 \le t \le t_{lo}$) and decay ($t_d \le t \le t_{end}$), respectively. The maximum heat release rate $\dot{Q}_{max}$ occurs when $t_{lo} \le t \le t_d$. The

Presented as Paper 2000-0722 at the AIAA 38th Aerospace Sciences Meeting and Exhibit, Reno, NV, 10–13 January 2000; received 11 December 2000; revision received 3 September 2001; accepted for publication 1 October 2001.

*Research Associate, 7221 Idlewild Acres. Member AIAA.
†Professor, 7221 Idlewild Acres. Fellow AIAA.

Table 1 Heat release rate vs time in t^2-fire characterization of FASTLite data

Code	Description	t_0	$t_{1\,\mathrm{MW}}$	t_{lo}	t_d	t_{end}	$\dot{Q}_{\max}$	t_g	α_g	α_d
Wardrobe 1	$\frac{1}{2}$-in. Plywood wardrobe, clothing on 16 hangers	0	35	60	90	500	2938.8	35	0.816327	0.017482
Wardrobe 2	$\frac{1}{8}$-in. Plywood wardrobe, clothing on 16 hangers	0	40	100	110	140	6250.0	40	0.625000	6.944444
Wardrobe 3	$\frac{1}{8}$-in. Plywood wardrobe, FR paint, clothing on 16 hangers[a]	0	30	70	80	400	5444.4	30	1.111111	0.053168
Wardrobe 4	$\frac{1}{8}$-in. Plywood wardrobe, FR paint, clothing on 16 hangers[a]	0	90	150	160	450	2777.8	90	0.123457	0.033029
Wardrobe 5	$\frac{3}{4}$-in. Particle-board wardrobe, thin plastic coating	0	150	170	670	2000	1284.4	150	0.044444	0.000726
Chair 1	Chair, one-piece wood-reinforced urethane foam	0	1000	650	660	1900	422.5	1000	0.001000	0.000275
Chair 2	Chair, polypropylene foam frame, urethane foam, polyolefin fabric	0	100	140	160	500	1960.0	100	0.100000	0.016955
Chair 3	Chair, thin wood frame, California foam, polyolefin fabric	0	200	175	176	900	765.6	200	0.025000	0.001461
Chair 4	Chair, urethane foam frame, urethane foam, polyolefin fabric	0	60	60	210	430	1000.0	60	0.277778	0.020661
Chair 5	Chair, wood frame, California foam, Haitian cotton fabric	0	350	275	475	1000	617.3	350	0.008163	0.002240
Chair 6	Chair, wood frame, California foam, polyolefin fabric	0	50	70	90	315	1960.0	50	0.400000	0.038716
Chair 7	Chair, wood frame, FR cotton stuffing, Haitian cotton fabric[a]	0	2000	210	310	1000	11.0	2000	0.000250	0.000023
Chair 8	Chair, wood frame, FR cotton stuffing, polyolefin fabric[a]	0	400	275	475	1000	472.7	400	0.006250	0.001715
Chair 9	Chair, wood frame,urethane foam, cotton fabric	0	200	90	310	550	202.5	200	0.025000	0.003516
Chair 10	Chair, wood frame, urethane foam, cotton fabric	0	75	50	250	1250	444.4	75	0.177778	0.000444
Chair 11	Chair, wood frame, urethane foam, cotton fabric, polyester batting	0	425	347	367	1000	666.6	425	0.005536	0.001664
Chair 12	Chair, wood frame, urethane foam, polyolefin fabric	0	80	160	170	420	4000.0	80	0.156250	0.064000
Chair 13	Chair, wood frame, urethane foam, quilted cotton/polyolefin, polyester batting	0	200	187	200	500	874.2	200	0.025000	0.009714
Bed	Innerspring mattress and boxspring, cotton felt/urethane/sisal spring cover	0	1100	680	1080	1300	382.1	1100	0.000826	0.007896
Lounge chair 1	Lounge chair, metal frame, urethane foam, plastic-coated fabric	0	350	170	220	350	235.9	350	0.008163	0.013960
Lounge chair 2	Lounge chair, one-piece molded glass fiber, metal legs	0	120	20	21	150	27.8	120	0.069444	0.001669
Lounge chair 3	Lounge chair, one-piece molded thermoplastic	0	275	230	430	900	699.5	275	0.013223	0.003167
Lounge chair 4	Lounge chair, wood frame, latex foam/cotton stuffing, plastic-coated fabric	0	500	130	140	300	67.6	500	0.004000	0.002641
Loveseat 1	Loveseat, mixed foam and cotton batting stuffing, cotton fabric	0	400	350	400	2000	765.6	400	0.006250	0.000299
Loveseat 2	Loveseat, wood frame, California foam, polyolefin fabric	0	80	130	160	400	2640.6	80	0.156250	0.045844
Loveseat 3	Loveseat, wood frame, urethane foam, plastic-coated fabric	0	350	330	430	1500	889.0	350	0.008163	0.000776
Metal wardrobe 1	Metal wardrobe, clothing on 16 hangers	0	250	125	150	500	250.0	250	0.016000	0.002041
Metal wardrobe 2	Metal wardrobe, clothing on 8 hangers	0	50	40	47	200	640.0	50	0.400000	0.027340
Patient lounge chair	Patient lounge chair, metal frame, urethane foam cushion	0	170	80	90	150	221.5	170	0.034602	0.061515
Sofa 1	Sofa, metal frame, urethane foam, plastic-coated fabric	0	500	260	460	800	270.4	500	0.004000	0.002339
Sofa 2	Sofa, wood frame, California foam, polyolefin fabric	0	100	170	250	430	2890.0	100	0.100000	0.089198
F21 Chair[b]	F21 Chair, wood frame, polyurethane foam, olefin fabric	140	215	250	250	360	2151.1	75	0.177778	0.177778
F31 Loveseat[b]	F31 Loveseat, wood frame, polyurethane foam, olefin fabric	90	165	215	265	390	2777.8	75	0.177778	0.177778
F32 Sofa[b]	F32 Sofa, wood frame, polyurethane foam, olefin fabric	75	150	205	270	400	3004.4	75	0.177778	0.177778

[a]FR = fire/flame retarded. [b]F21, F31, and F32 are original NJST test numbers.

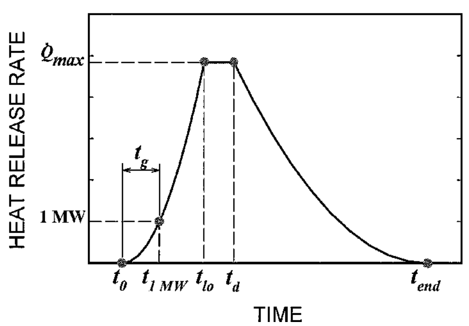

Fig. 1 Heat release rate vs time in t^2-fire characterization.

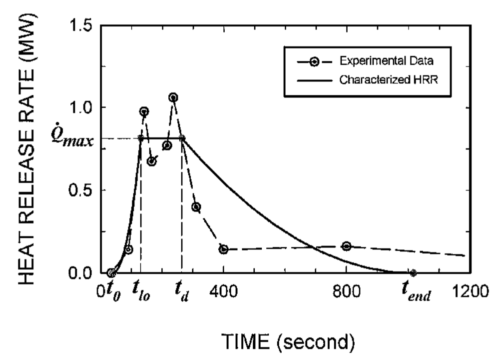

Fig. 2 Example of t^2-fire characterization (chair 5 in Table 2).

growth time to reach 1 MW = 1000 kW of heat release rate $\dot{Q}$ is $t_{1\,\mathrm{MW}} - t_0$, and this is related to the fire-growth parameter α_g via

$$\alpha_g = \frac{1000}{(t_{1\,\mathrm{MW}} - t_0)^2}$$

Similarly the fire-decay parameter α_d is found via

$$\alpha_d = \frac{\dot{Q}_{\max}}{(t_{\mathrm{end}} - t_d)^2}$$

Also note that the maximum heat release rate $\dot{Q}_{\max}$ is related to other parameters via

$$\dot{Q}_{\max} = 1000\left(\frac{t_{\mathrm{lo}} - t_0}{t_{1\,\mathrm{MW}} - t_0}\right)^2$$

To characterize the actual experimental data of heat release rate vs time in this fashion, one proceeds as follows:

1) The values to be taken for the three key parameters $\dot{Q}_{\max}$ (maximum heat release rate), t_{lo} (time to reach $\dot{Q}_{\max}$), and t_d (time to start decay) are decided. Adjustments are made to ensure that the modeled total heat release during the time interval of from t_0 to t_d matches the experiment to within 1% for most items (within 5% for all items).

2) The time to onset of ignition t_0 with associated value of fire-growth parameter α_g is chosen to match the total heat release during the growth phase of from t_0 to t_{lo}. The correspondence of t_0, t_{lo}, and α_g is automatic because a t^2-fire growth is being assumed.

3) The end time t_{end} with associated value of fire-decay parameter α_d is chosen to match the total heat release during the decay phase of from t_d to t_{end}. Again, the correspondence of t_d, t_{end}, and α_d is automatic because a t^2-fire decay is being assumed.

As an example, Fig. 2 shows t^2-fire characterization of an item. Notice that in the fire growth region, excellent agreement is obtained, but that in the decay phase, there is some over- and underrepresentation of the actual burn data.

Modeled data are given for heat release rate $\dot{Q}$ vs time as follows: in Table 1 furniture calorimeter data from FASTLite,[2] in Table 2

Table 2 Heat release rate vs time in t^2-fire characterization of HAZARD data (furniture calorimeter)

Item	Code	Description	Ignition source	t_0	$t_{1\,\mathrm{MW}}$	t_{lo}	t_d	t_{end}	$\dot{Q}_{\max}$	t_g	α_g	α_d
Bed 1	BED001	Double bed, bedding, night table; gypsum board walls; test R1 (85-2998)	Wastebasket and trash, 0.75 kg	169	211	230	230	936	2109.4	42	0.566893	0.004232
Bed 2	BED002	Double bed, bedding, night table; plywood walls; test R5 (85-2998)	Wastebasket and trash0.75 kg	164	239	360	430	998	6829.5	75	0.177778	0.021169
Chair 1 (F21)	UPC001	Upholstered chair, F21, wood frame, polyurethane foam-fr, olefin	Gas burner, 50 kW, 200 s	126	218	260	260	607	2121.5	92	0.118147	0.017619
Chair 2 (F23)	UPC002	Chair, F23, wood frame, fr cotton batting, olefin test 24 (82-2604)	Gas burner, 50 kW, 200 s	0	538	450	450	1932	699.6	538	0.003455	0.000319
Chair 3 (F25)	UPC003	Upholstered chair, F25, wood frame, polyurethane foam, olefin, test 29	Gas burner, 50 kW, 200 s	106	215	260	260	679	1996.1	109	0.084168	0.011370
Chair 4 (F28)	UPC004	Upholstered chair, F28, wood frame, polyurethane/pe/ctn bedding, cotton test 28	Gas burner, 50 kW, 200 s	82	478	420	420	1184	728.5	396	0.006377	0.001248
Chair 5 (F30)	UPC005	Upholstered chair, F30, polyurethane frame, polyurethane foam, olefin, test 30 (82-2604)	Gas burner, 50 kW, 200 s	40	140	130	263	1017	810.0	100	0.100000	0.001425
Chair 6	CHR001	Bean bag chair, vinyl/ps foam beads, c05 nbs tn 1103	Newspaper, 396 g	88	748	545	718	1228	479.5	660	0.002296	0.001843
Chair 7	CHR002	Chair, molded flexible polyurethane frame, polyurethane test 64 (83-2787) cover	Gas burner, 50 kW, 200 s	644	1662	1330	1330	2685	454.1	1018	0.000965	0.000247
Chair 8	CHR003	Easy chair, molded ps foam frame, polyurethane pad and cover, c07, test 48	Gas burner, 50 kW, 200 s	38	245	240	240	883	952.3	207	0.023338	0.002303
Christmas tree	CTR001	Christmas tree, spruce, dry, vtt 285, no. 17	200-ml isopropanol	290	327	320	350	478	657.4	37	0.730460	0.040125
Cooking oil	CKG001	Cooking oil, corn; cottonseed; etc. in 12-in.-pan		0	15	5	1000	1000	111.1	15	4.444444	
Curtain	CUR001	Curtain, Cotton, 0.31 kg/m^2, item 9	5-ml isopropanol	123	229	175	175	411	240.7	106	0.089000	0.004321
Loveseat (F31)	UPS002	Loveseat, F31, wood frame, polyurethane foam(fr), olefin test 37 (82-2604)	Gas burner, 50 kW, 200 s	71	165	229	249	701	2825.3	94	0.113173	0.013829
Mattress 1	MAT001	Mattress, m05, polyurethane foam, rayon ticking, bedding	Wastebasket and 0.72 kg content	269	437	480	480	933	1577.4	168	0.035431	0.007687
Mattress 2	MAT002	Mattress and boxspring (Westchase Hilton) test 67 (83-2787)	Cigarette lighter	144	858	606	980	2233	418.7	714	0.001962	0.000267
Sofa (F32)	UPS001	Upholstered\sofa, F32, wood\frame, polyurethane foam-fr, olefin test 38	Gas burner, 50 kW, 200 s	74	154	211	283	651	2932.7	80	0.156250	0.021655
Trash Bags	TRB001	Trash bags (3), paper		0	100	58	111	517	336.4	100	0.100000	0.002041
Television set	TLV001	Television set, black and white, wood cabinet, exp. 3	100-ml isopropanol	304	984	670	670	1872	289.7	680	0.002163	0.000201
Wardrobe	CLT001	Wardrobe closet, plywood, fr paint nbsir83-2787 test 42	Cardboard box/ paper 0.9 kg	70	113	170	170	358	5408.3	43	0.540833	0.153020
Waste basket	WPB001	Wastepaper basket, polyethylene, milk cartons, exp. 7	10-ml isopropanol	115	2034	350	350	1264	15.0	1919	0.000272	0.000018

furniture calorimeter data from HAZARD,[4,12] in Table 3 furniture calorimeter data from Building and Fire Research Laboratory (see BFRL website), and in Table 4 cone calorimeter data from HAZARD.[4,12]

The data are also given in tables and an extensive set of figures by Kim and Lilley.[13] Finally, $\dot{Q}$ vs t is given by

$$\dot{Q} = 0 \qquad 0 \le t \le t_0$$
$$\dot{Q} = \alpha_g (t - t_0)^2 \qquad t_0 \le t \le t_{\mathrm{lo}}$$
$$\dot{Q} = \alpha_g (t_{\mathrm{lo}} - t_0)^2 \qquad t_{\mathrm{lo}} \le t \le t_d$$
$$\dot{Q} = \alpha_d (t_{\mathrm{end}} - t)^2 \qquad t_d \le t \le t_{\mathrm{end}}$$
$$\dot{Q} = 0 \qquad t_{\mathrm{end}} \le t \le \text{infinity}$$

with the parameters taken directly from Tables 1–4 for the particular item under consideration.

What Happens Next ?

During the course of the burning of the first item of furniture in a room, as specified from data such as that presented in Tables 1–4, one of several things might occur. The preceding section has provided information about the burning rate (heat release rate vs time) of a single specified item in the burn room. What happens next? Either the item burns out without further damage to the surroundings, or one or more nearby items ignite and add fuel to the fire. This can be by direct flame contact (if the second item is judged to be sufficiently close) or, more usually, by radiant heat energy becoming sufficiently large on the surface of the second item. Direct flame contact requires time to pyrolyze the fuel and time to heat the gases produced to their ignition temperature. The radiant flux ignition problem is a very complicated issue and depends on many factors. The radiant energy comes from the flame above the first item, the upper layer,

Table 3 Heat release rate vs time in t^2-fire characterization of building and fire research laboratory data

Code	Description	t_0	$t_{1\,\mathrm{MW}}$	t_{lo}	t_d	t_{end}	$\dot{Q}_{\max}$	t_g	α_g	α_d
Bunk bed	BFRL,[a] Feb. 1996	186	211	240	240	445	4665.6	25	1.600000	0.111020
Koisk	Western Fire Center, summer 1995	817	1129	1230	1230	3300	1752.2	312	0.010273	0.000409
Loveseat		48	222	350	371	866	3012.4	174	0.033029	0.012294
Mattress (center)	BFRL, Feb. 1996	9	173	145	219	959	687.7	164	0.037180	0.001256
Mattress (corner)	BFRL, Feb. 1996	85	294	295	321	484	1009.6	209	0.022893	0.037999
Small dresser	BFRL, Feb. 1996	112	346	423	423	870	1766.4	234	0.018263	0.008840
Sofa		26	222	390	399	931	3449.0	196	0.026031	0.012186
Wooden pallet	BFRL, Feb. 1996	0	467	634	664	1616	1843.1	467	0.004585	0.002034
Workstation (2 panels)	Sponsored by GSA[b] and performed at BFRL, 1991	132	244	280	280	3276	1746.2	112	0.079719	0.000195
Workstation (3 panels)	Sponsored by GSA and performed at BFRL, 1991	283	386	550	550	1142	6719.7	103	0.094260	0.019174

[a]Building and fire research laboratory. [b]General services administration.

Table 4 Heat release rate vs time in t^2-fire characterization of HAZARD data (cone calorimeter)

Item	Code	Description	Material	t_0	$t_{1\,\mathrm{MW}}$[a]	t_{lo}	t_d	t_{end}	$\dot{Q}_{\max}$[b]	t_g	α_g	α_d
Cotton fabric	CTN002	Cotton fabric, fr (test 803a)	Fabric	29	89	45	45	206	71.1	60	0.277778	0.002743
Fir board	DFR003	Douglas fir (828)	Board	2	32	15	15	1502	187.8	30	1.111111	0.000085
Fir plywood board 1	DFP002	Douglas fir plywood, $\frac{1}{2}$ in. thick (435)	Board	74	124	92	604	1193	129.6	50	0.400000	0.000374
Fir plywood board 2	DFP002	Douglas fir plywood, $\frac{1}{2}$ in. thick (446)	Board	0	28	13	309	1829	215.6	28	1.275510	0.000093
Gypsum board 1	GBD002	Gypsum board, $\frac{1}{2}$ in. thick (434)		228	280	243	246	274	83.2	52	0.369822	0.106135
Gypsum board 2	GBD002	Gypsum board, $\frac{1}{2}$ in. thick (448)		6	66	30	30	102	160.0	60	0.277778	0.030864
Mattress composite	MAT001	Mattress ass'y m05, polyurethane foam, rayon ticking (test 296)	Composite	8	44	28	111	164	308.6	36	0.771605	0.109876
Oak board 1	RDO002	Red oak, $\frac{7}{8}$ in. thick (1454)		156	191	166	1684	2310	81.6	35	0.816327	0.000208
Oak board 2	RDO002	Red oak, $\frac{7}{8}$ in. thick (1456)	Board	0	26	11	707	1802	179.0	26	1.479290	0.000149
Oak board 3	RDO002	Red oak, $\frac{7}{8}$ in. thick (1468)	Board	0	28	13	806	1354	215.6	28	1.275510	0.000718
Pine board 1	PIN002	Pine (838)	Board	14	19	16	637	940	160.0	5	40.000000	0.001743
Pine board 2	PIN002	Pine (842)	Board	111	198	137	834	1511	89.3	87	0.132118	0.000195
Pine board 3	PIN002	White pine (wood), 0.75 in. (test 487)	Board	0	8	3	587	4048	140.6	8	15.625000	0.000012
Pine board 4	PIN002	White pine (wood), 0.75 in. (test 493)	Board	40	67	47	1097	4176	67.2	27	1.371742	0.000007
PMMA[c] sheet 1	MMA001	PMMA 1-in. black (cb) w/frame (test 1461)	Sheet	0	123	115	804	1032	874.1	123	0.066098	0.016816
PMMA sheet 2	MMA001	PMMA 1-in. black (cb) w/frame (test 1470)	Sheet	148	218	197	1689	2240	490.0	70	0.204082	0.001614
Polyisocyanurate foam 1	RPI002	Rigid polyisocyanurate foam, 2 in. (test 438)	Foam	0	40	9	9	61	50.6	40	0.625000	0.018722
Polyisocyanurate foam 2	RPI002	Rigid polyisocyanurate foam, 2 in. (test 449)	Foam	0	15	6	6	1127	160.0	15	4.444444	0.000127
Polystyrene foam	PSF004	Polystyrene foam, 2 in. (test 437)	Foam	84	268	201	201	417	404.3	184	0.029537	0.008666
Polyurethane foam 1	FPU007	Flexible polyurethane foam, fr, 2 in. (test 725)	Foam	15	112	80	80	158	449.0	97	0.106281	0.073806
Polyurethane foam 2	RPU001	Rigid polyurethane foam, gm-29/gm-30 (test 257)	Foam	0	33	15	15	260	206.6	33	0.918274	0.003442
Polyurethane foam 3	RPU002	Rigid polyurethane foam, fr, gm-31 (test 258)	Foam	0	36	12	12	115	111.1	36	0.771605	0.010473
Polyvinyl sheet	PVC002	Polyvinyl chloride, 0.5 in. thick (test 333)	Sheet	12	102	37	703	768	77.2	90	0.123457	0.018263
Rayon fabric	RYN001	Rayon fabric (test 804a)	Fabric	26	73	40	40	71	88.7	47	0.452694	0.092329
Wool fabric	WNE001	Wool fabric/neoprene padding (test 722)	Composite	23	62	45	45	167	318.2	39	0.657462	0.021379

[a]Time to reach 1 MW/m^2. [b]Maximum heat release rate in kW/m^2. [c]PMMA = polymethyl methacrylate.

and room surfaces, but simplifying assumptions are sometimes used. As the radiant energy flux rate increases from the first item to the second, often a simple criterion for ignition of the latter is used. A good approximation is that the radiant heat flux (arriving on the surface of the second item) necessary to ignite the second item is 10 kW/m^2 for easily ignitable items, such as thin curtains or loose newsprint; 20 kW/m^2 for normal items, such as upholstered furniture; and 40 kW/m^2 for difficult to ignite items, such as wood of 0.5 in. or greater thickness.

In actuality, ignition is not immediate when the particular level of incident radiant heat flux reaches 10, 20, or 40 kW/m^2, respectively for easy, normal, and difficult to ignite items. These values are used as simple rules of thumb in applied calculations (see Refs. 5–7). Fundamental ignition principles, outlined for example, in Ref. 11, suggest that, for fire initiation, a material has to be heated above its critical heat flux (CHF) value (CHF value is related to the fire point). It was found that, as the surface is exposed to heat flux, initially most of the heat is transferred to the interior of the material. The ignition principles suggest that the rate with which heat is transferred depends on the ignition temperature T_{ig}, ambient temperature T_a, material thermal conductivity k, material specific heat c_p, and the material density ρ. The combined effects are expressed by a parameter defined at the thermal response parameter (TRP) of the material

$$\mathrm{TRP} = \Delta T_{\mathrm{ig}}\sqrt{k\rho c_p}$$

where $\Delta T_{\mathrm{ig}}(=T_{\mathrm{ig}} - T_a)$ is the ignition temperature above ambient in degrees Kelvin, k is in kilowatts per meter degrees Kelvin, ρ is in kilograms per cubic meter, c_p is in kilojoules per kilogram degrees Kelvin, and TRP is in kW-s$^{1/2}$/m^2. The TRP is a very useful parameter for the engineering calculations to assess resistance of ignition and fire propagation in as-yet uninvolved items. The ignition principles suggest that, for thermally thick materials, the inverse of the square root of time to ignition is expected to be a linear function of the difference between the external heat flux and the CHF value

$$\sqrt{\frac{1}{t_{ig}}} = \frac{\sqrt{4/\pi}\,(\dot{q}_e'' - \mathrm{CHF})}{\mathrm{TRP}}$$

where t_{ig} is time to ignition (seconds), $\dot{q}_e''$ is the external heat flux (kilowatts per square meter), and CHF is in kilowatts per square meter. Most commonly used materials behave as thermally thick materials and satisfy this equation.

The CHF and the TRP values for materials derived from the ignition data measured by Scudamore et al.[14] are given by Lilley.[15] He also shows in tables and figures how the ignition time t_{ig} may be determined from the heat flux $\dot{q}''$ and the CHF and TRP. Complete data are given by Lilley[15] to enable the ignitability question to be determined quickly. To see fully how the size and material of a pool fire determines the total heat release $\dot{Q}$, the heat flux $\dot{q}''$ on a target fuel, and the time required for ignition to occur, see Ref. 15.

Flashover

Whether or not flashover occurs during the course of a fire is one of the most important outcomes of a fire calculation. Flashover is characterized by the rapid transition in fire behavior from localized burning of fuel to the involvement of all combustibles in the enclosure. 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). Factors affecting flashover include room size, ceiling and wall conductivity and flammability, and heat- and smoke-producing quality of room contents.

Further research studies relating to specification of the fire, flashover, and spreading of the fire through a structure using the fire specification methodology given here include Kim and Lilley[16–18] and Lilley.[19,20]

Conclusions

The ability to determine fire growth in terms of when the second and subsequent objects may ignite (and their burning rates) and whether or not flashover occurs depends strongly on the initial fire specification. The focus of this paper was to characterize the initial item on fire (in terms of burning rate vs time) to be able to calculate more accurately fire growth, the possible occurrence of flashover, and spreading of the fire through a structure. Heat release rates of typical items in fires are needed as a prerequisite for estimating fire growth and temperatures in structural fires. That is, these burning rates are required to be specified by the user as input to single-room and multiroom structural fire computer codes like CFAST, FASTLite, FPETool, and HAZARD. Burning rates of typical items have been characterized in a consistent fashion, thereby simplifying their direct input into any modeling simulation of a fire in a structure.

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