EXAMPLE ILLUSTRATING SLIDE RULE ESTIMATES OF FIRE GROWTH

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Example illustrating

Slide Rule Estimates of Fire Growth

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In the November 1985 issue of *Fire Technology*, the authors presented prediction methods for estimating fire growth in compartments. Here they provide an example of the use of those methods.

THIS EXERCISE is designed to provide an example of the use of the predictive methods presented in the November 1985 issue of *Fire Technology*. It is intended as a hypothetical illustration and should not be construed as representative of the hazard associated with the particular items, materials and occupancy configuration selected. The first step in analyzing a fire scenario is to define the problem in terms of information required by the relevant predictive formulae.

PROBLEM

The fire takes place in a hotel room. A fire starts from a cigarette lighter in the center of a bed with a polyurethane foam mattress. The room door is left one-quarter open as the occupant flees the room. Figure 1 shows the plan for the hotel section being studied.

ANALYSIS OF FIRE GROWTH AND CONSEQUENCES

The prediction methods presented earlier are used here to calculate mass loss rate, heat release rate, flame height, ceiling heat flux, temperature rise, ventilation flow rate, visibility, smoke filling, and smoke transport for the sample problem. The data required to make these calculations are provided as

Reference: J. R. Lawson and J. G. Quintiere, "Example illustrating Slide Rule Estimates of Fire Growth," *Fire Technology*, Vol 22, No. 1, February 1986, p. 45.

Key Words: Fire growth, mass loss rate, heat release, radiant flux ventilation, visibility, smoke transfer.

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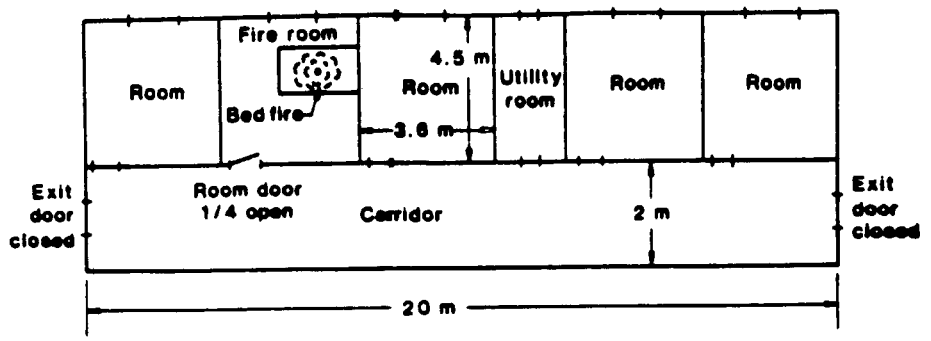

Figure 1. Room fire example. Note: Ceiling height in rooms and corridors 2.4 m. All doors are closed except the fire room door.

well as the assumptions used to simplify the calculation process. Tables of predicted values are presented and selected results are shown graphically.

MASS LOSS RATE

The first step in these predictions of fire growth and hazard conditions is the determination of an expression for the energy generation rate of the fire. Using Equation 3 with $\beta = 0$ yields the following expression for fuel mass loss rate.

$$\dot{m} = \alpha e^{\alpha t} \text{ where } \alpha = 0.03.$$

The solution to this expression is shown in Table 1 and Figure 2 for times up to 250 sec. Mass loss rates for times from 250 sec to 300 sec are calculated using the steady state burning formula for wood cribs:

$$\dot{m}_f = 0.09\, W_o H_0^{3/2}$$

where $W_o = 0.23$,
$H_o = 2$.

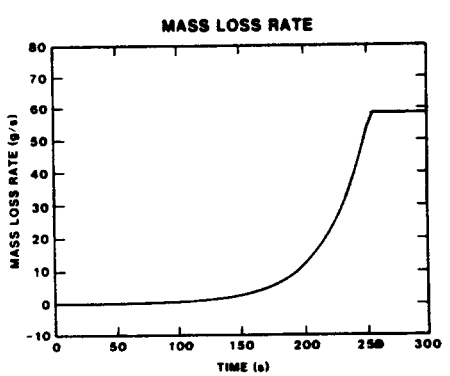

Figure 2. Mass loss rate for fire growth example.

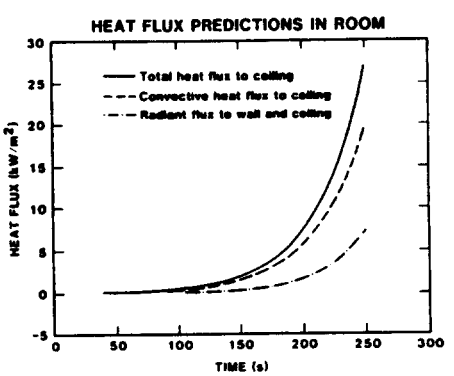

Figure 3. Heat flux predictions in room for fire growth example.

TABLE 1. *Fire growth predictions*

t (sec)	$\dot{m}_f$ (g/sec)	$\dot{Q}$ (kW)	$\dot{q}''_e$ (R_e) (kW/m²)	H_f (m)	H_w (m)	$\dot{q}''$ (0) (kW/m²)	ΔT (°C)	$\dot{m}_c$ (kg/sec)	*Corridor* L_c (m)
0	0.00	0.0	—	—	—	—	—	—	—
10	0.04	0.6	—	—	—	—	—	—	—
20	0.05	0.8	—	—	—	—	—	—	—
30	0.07	1.1	—	—	—	—	—	—	—
40	0.10	1.6	—	0.28	—	0.11	1	0.034	83.6
45	0.12	1.9	—	0.29	—	0.12	7	0.090	67.9
50	0.13	2.0	—	0.30	—	0.13	8	0.095	55.7
55	0.16	2.5	—	0.33	—	0.15	9	0.101	46.1
60	0.18	2.8	—	0.35	—	0.17	10	0.106	38.4
65	0.21	3.3	—	0.37	—	0.19	11	0.111	32.1
70	0.24	3.8	—	0.39	—	0.22	12	0.115	27.1
75	0.28	4.4	—	0.42	—	0.24	14	0.124	22.8
80	0.33	5.2	—	0.44	—	0.28	15	0.128	19.3
85	0.38	6.0	—	0.47	—	0.32	17	0.135	16.4
90	0.45	7.1	—	0.50	—	0.36	19	0.142	14.0
95	0.52	8.2	—	0.53	—	0.41	21	0.149	11.9
100	0.60	9.4	—	0.56	—	0.46	24	0.157	10.2
105	0.70	11.0	0.09	0.60	—	0.52	27	0.164	8.7
110	0.81	12.7	0.11	0.64	—	0.59	29	0.169	7.4
115	0.94	14.8	0.13	0.68	—	0.67	33	0.178	6.4
120	1.10	17.3	0.15	0.72	—	0.76	37	0.186	5.4
125	1.28	20.1	0.17	0.76	—	0.87	41	0.194	4.7
130	1.48	23.2	0.20	0.81	—	0.98	45	0.200	4.0
135	1.72	27.0	0.23	0.86	—	1.11	50	0.208	3.4
140	2.00	31.4	0.27	0.91	—	1.26	56	0.216	3.0
145	2.32	36.4	0.31	0.97	—	1.42	62	0.223	2.5
150	2.70	42.4	0.36	1.03	—	1.61	69	0.231	2.2
155	3.14	49.3	0.42	1.09	—	1.83	77	0.238	1.9
160	3.65	57.3	0.49	1.16	—	2.07	86	0.245	1.6
165	4.24	66.6	0.57	1.23	—	2.35	95	0.251	1.4
170	4.92	77.2	0.66	1.31	—	2.66	106	0.257	1.2
175	5.72	89.8	0.77	1.39	—	3.01	117	0.263	1.0
180	6.64	104.2	0.90	1.48	—	3.41	130	0.267	0.9
185	7.72	121.2	1.04	1.57	—	3.87	145	0.272	0.8
190	8.97	140.8	1.21	1.66	—	4.39	161	0.275	0.7
195	10.42	163.6	1.41	1.77	—	4.97	178	0.278	0.6
200	12.10	190.0	1.63	1.88	0.07	5.63	198	0.279	0.5
205	14.06	220.7	1.90	1.99	0.10	6.38	219	0.280	0.41
210	16.34	256.5	2.20	2.12	0.25	7.23	243	0.279	0.36
215	18.98	298.0	2.56	2.25	0.34	8.19	270	0.278	0.31
220	22.05	346.2	2.98	2.38	0.42	9.28	300	0.288	0.26
225	25.62	402.2	3.46	2.53	0.52	10.52	332	0.293	0.23
230	29.77	467.4	4.02	2.69	0.62	11.92	369	0.297	0.20
235	34.59	543.1	4.67	2.86	0.73	13.51	409	0.300	0.17
240	40.18	630.8	5.42	3.03	0.83	15.30	453	0.301	0.14
245	46.69	733.0	6.31	3.22	0.94	17.34	503	0.301	0.12
250	54.24	851.6	7.32	3.42	1.06	19.65	558	0.300	0.11
255	58.55	Steady state wood crib burning					630		
260	58.55						632		
265	58.55						634		
270	58.55						636		
275	58.55						638		
280	58.55						640		
285	58.55						642		
290	58.55						644		
295	58.55						646		
300	58.55						648		

This represents the ventilation-limited fire case. It is employed at the time when the ratio of fuel mass loss rate to air flow rate to the room exceeds its stoichiometric ratio (Equation 8).

Heat Release Rate

Heat release rate was calculated using the equation:

$$\dot{Q} = \dot{m}\Delta H$$

where $\Delta H = 15.7$ (kJ/g) for the polyurethane foam mattress in the example.

Radiant Flux

From the heat release rate the radiant heat transfer to a nearby surface can be calculated using Equation 7. In this prediction, it is assumed that R_o, the distance from the heat source to the wall is 1.8 m. The χ_r value for polyurethane foam in this example is 0.35. Both values for $\dot{Q}$ and $\dot{q}_o''$ (R_o) are presented in Table 1. The radiant flux $\dot{q}_o''$ (R_o) as a function of time is shown in Figure 3.

Flame Height

The values for flame height, H_f, and ceiling flame impingement length, H_R, in Table 1 and Figure 4 were calculated using Equations 8 and 14, respectively. In Equation 14, the value for H = 1.8 m since the bed height is subtracted from the overall ceiling height, and D was selected as a constant of 0.5 m. (Although the fire is growing, it is not strongly dependent on D.)

Ceiling Heat Flux

Table 1 and Figure 3 also contain predictions for heat flux to the room's ceiling. These results were developed using Equation 15b. The values for ra-

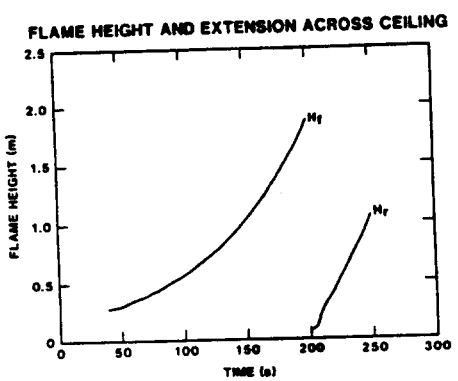

Figure 4. Flame height and extension across ceiling for fire growth example.

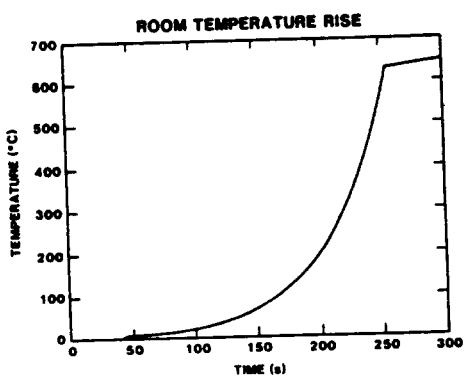

Figure 5. Room temperature rise for fire growth example.

diant flux derived from Equation 7 were added to values from Equation 15b to predict the total heat flux to the ceiling. In this example radiation from the hot gas layer has not been included in the total heat flux to the ceiling. However, an upper limit for radiation to the ceiling from the hot gas layer can be estimated at σT^4 where σ is 5.6697×10^{-8} W/m^2 − K^4.

Temperature Rise

Predictions for gas temperature rise, ΔT, in the room are presented in column 8 of Table 1. Also see Figure 5. These values were generated using Equation 31, but before the various temperatures were calculated thermal penetration times, t_p, for the gypsum walls and plywood floors were determined. The following parameters were used in these calculations:

Gypsum wallboard (walls/ceiling);

t_p = 393 sec,
ϱ = 960 kg/m^3,
c = 1.1 kJ/(kg − K),
k = 1.7×10^{-4} kJ/(m − K),
δ = 0.0159 m.

Plywood (floor);

t_p = 711 sec,
ϱ = 540 kg/m^3,
c = 2.5 kJ/(kg − K),
k = 1.2×10^{-4} kJ/(m − K),
δ = 0.0159 m.

As a result of these calculations, it was found that values for h_k in Equation 31 would be determined using $\sqrt{k\varrho c/t}$ where $t \leq t_p$. At this point, it is important to note that new values for h_k are calculated with each new time in the prediction of ΔT. For $t \leq t_p$, h_k was calculated by

$$h_k = \frac{A_1 h_{k,1} + A_2 h_{k,2}}{A}$$

where

A_1 = 55.08 m^2 area for walls and ceilings,
A_2 = 16.20 m^2 area for floor,
A = 71.28 m^2 total,

and $h_{k,1}$ and $h_{k,2}$ correspond to the gypsum board and plywood respectively. When extended calculations are made for $t > t_p$ for either the walls and ceiling or floor, k/δ should be substituted into the above equation. For ΔT calculations at times greater than the point of flashover, Equation 41 was used. Values for the parameter in Equations 31 and 41 are as follows:

$g = 9.8\ m/sec^2$,
$c_p = 1.046\ kJ/(kg - K)$,
$\varrho_o = 1.25\ kg/m^3$,
$T_o = 293\ K$,
$A_o = 0.46\ m^2$,
$H_o = 2\ m$.

Ventilation Flow Rate

Since both $\dot{Q}$ and ΔT are now available, ventilation flow rate is calculated. In this procedure, Equations 32, 33, 34 and 35 are used to make the predictions. For times down to 220 sec where $\psi \leq 1$, $y_2 = 0.5$ was used in the calculation. For $\psi > 1$, Equation 33 was used to calculate an estimated value of y_2. This was done by substituting the preceding result of $\dot{m}_f$ into the equation. The values of M_o and $\dot{m}_o$ were determined using Equations 32 and 34, and $\dot{m}_f$ results were found with Equation 35. The values used in this calculation were as follows:

$\varrho_o = 1.25\ kg/m^3$,
$g = 9.8\ m/sec^2$,
$W_o = 0.23\ m$,
$H_o = 2\ m$.

It can be seen in Table 1 and Figure 6 that the ventilation starts to drop off at about 220 sec and then starts to rise again. The 220 sec point is where the estimated value for y_2 was started, and it is continued until the ventilation limit condition is reached at a time between 250 and 255 sec. At this point and beyond, the $\dot{m}_f$ value is based on steady state enclosure ventilation limited formula, and the calculation for $\dot{m}_f$ was stopped.

Corridor Visibility

The last column in Table 1 consists of predictions of visibility, L_v, in the

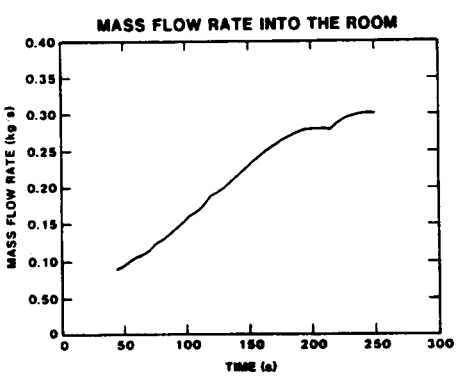

Figure 6. Mass flow rate into the room for fire growth example.

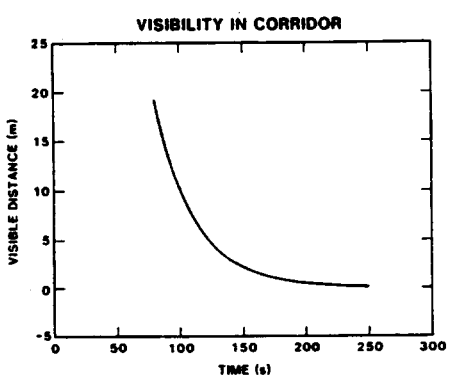

Figure 7. Visibility in corridor for fire growth example.

corridor. Also see Figure 7. The equation used in this prediction was as follows:

$$L_v = \frac{k_v V}{\alpha x}\left(\int_0^t \dot{m}\, dt\right)$$

where

$k_v = 2,$
$V =$ (width) (length) (height) of corridor
(2 m) (20 m) (2.4 m),

and

$\int_0^t \dot{m}\, dt = \int_0^t \alpha e^{\alpha t}\, dt = e^{\alpha t} - 1\Big|_0^t$ for mattress,
$\alpha = 3300\ m^2/kg,$
$x = 0.3$ g smoke particulates/g fuel.

These predictions show that visibility would be about 0.1 m when flashover (based on $\Delta T = 500°$ C) occurs. It should be noted that this calculation assumes a well-mixed gas state in the corridor. But this does not occur until 181 sec approximately. So use of the formulae before this time will over estimate the visibility by the ratio of corridor volume to actual smoke layer volume.

TABLE 2. *Room smoke filling time predictions, steady state fires.*

Time (sec)	*Heat release rate 0.5 kW Smoke layer height* (m)	*Heat release rate 1.0 kW Smoke layer height* (m)	*Heat release rate 10 kW Smoke layer height* (m)	*Heat release rate 100 kW Smoke layer height* (m)
0	0.00	0.00	0.00	0.00
2	2.38	2.37	2.34	2.27
4	2.35	2.34	2.28	2.15
6	2.33	2.32	2.22	2.04
8	2.31	2.29	2.17	1.95
10	2.29	2.26	2.12	
12	2.27	2.24	2.07	Note: 1.99(m)
14	2.25	2.21	2.02	reached
16	2.23	2.19	1.97	@ 7 (sec)
18	2.21	2.16		
20	2.19	2.14	Note: 1.99(m)	
22	2.17	2.11	reached	
24	2.15	2.09	@ 15 (sec)	
26	2.13	2.07		
28	2.11	2.04		
30	2.09	2.02		
32	2.07	2.00		
34	2.06	1.98		
36	2.04			
38	2.02	Note: 1.99(m)		
40	2.00	reached		
42	1.99	@ 33 (sec)		

SMOKE FILLING

Two other tables are presented in this example. Table 2 is a listing of various room smoke filling times based on different steady state heat release rates. Equation 23b was used to calculate these values. The following values were used in these calculations:

$\alpha = 1/5.4,$
$\varrho_\infty = 1.25\ kg/m^3,$
$T_\infty = 293\ K,$
$c_p = 1.046\ kJ/kg - k,$
$g = 9.8\ m/sec^2,$
$H = 2.4\ m,$
$s = 16.2\ m^2.$

These results suggest that combustion products begin to leave the room, i.e., the layer is just below the door soffit (H = 1.99 m) at about 10 to 35 sec.

Table 3 contains additional predictions which provide an order of events for the fire growth example. Smoke filling time for the room was taken from Table 2, and visibility in the corridor was taken from Table 1. The value for smoke filling time in the corridor was generated using Equations 45, 46, and 48. Parameter values used in this calculation were as follows:

$\varrho_u = 1.24\ kg/m^3,$
$g = 9.8\ m/sec^2,$
$H_c = 2.32\ m,$
$\dot{Q} = 100\ kW,$
$L_c = 1.046\ kJ/kg - K,$
$T_u = 293\ K,$
$\tau = 47,$
$A = 40\ m^2.$

The time for the occurrence of flashover and the ventilation limit time was taken from Table 1. The time for flashover is based on a 500° C temper-

TABLE 3. *Summary of critical event predictions.*

Event	*Time* (sec)	*Velocity* (m/sec)
Smoke filling of room	−10-35	
Visibility of 1(m) in corridor	−175	
Smoke filling of corridor	−181	
Occurrence of flashover	−245	
Ventilation limit in room	−250	
Smoke front velocity with ΔT of 10° C		0.44
Smoke transport time to near end of corridor	−9.5	
Smoke transport time to far end of corridor	−35.9	

ature rise, and the ventilation limit is based on the effective fuel-air mass ratio where

$$\gamma = \frac{\Delta H_{air}}{\Delta H_{fuel}} = \frac{3.03 \text{ kJ/g air.}}{15.7 \text{ kJ/g fuel}} = 0.193 \text{ g fuel/g air}.$$

This mass ratio was compared with fuel and air values contained in Table 1.

Smoke Transport

The predictions at the bottom of Table 3 were developed using Equation 42 where

ϱ_c was selected to correspond to the room temperature (T) so that

$$\frac{\varrho_a - \varrho_c}{\varrho_a} = 1 - \frac{T_a}{T}.$$

Parameters used in this calculation were as follows:

$g = 9.8 \text{ m/sec}^2$,
$T_a = 293$ K,
$T = 303$ K,
$H = 2.4$ m.

Smoke transport times to the corridor ends were calculated using Equation 43. Center line distances from the hotel room door were 4.2 m and 15.8 m respectively for the near and far ends of the corridor.

Thus a chronology of significant events and the magnitude of physical fire effects have been estimated for this scenario. Its accuracy is at least good to an order of magnitude and more exact assessments of accuracy must be based on the assumptions and support literature for each of the formulas used.