Name: ______________________________

ID #: ______________________________

University of Saskatchewan
Department of Mechanical Engineering
ME 498 – Introduction to Fire Protection Engineering

December 7, 2002 Final Exam 180 minutes

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150 Points Total

Closed Book Exam - students are permitted to bring two 8.5” x 11” sheets (double-sided) into the exam for formulae and other information; no formulae or other information may be brought into the exam in the memory of programmable calculators or any other electronic storage device

For numerical questions – please show all work in the space provided.
For descriptive questions – please answer each question in a concise and clear fashion in the space provided.

Question	Total Marks	Score
1	30	
2	15	
3	15	
4	15	
5	15	
6	15	
7	15	
8	15	
9	15	
TOTAL	**150**	

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Question 1 (3 points each, 30 points total)

a) What major change is planned for the next edition of Canada's National Building Code? Identify one way in which this change is expected to affect fire protection engineering in Canada.

b) Briefly describe two changes that were made at the World Trade Center as a result of the study of the 1993 evacuation of the twin towers, which helped to substantially increase the number of people who successfully evacuated these buildings on September 11, 2001.

c) Identify two recommendations made by Dr. Kodur and the rest of the team that conducted the preliminary investigation of the collapse of the World Trade Center.

d) Identify two challenges in providing fire protection in big box retail stores, such as those that recently opened in the Preston Crossing complex.

e) Briefly explain one way in which the Canadian Light Source synchrotron could be used to help investigate the performance of different materials in fire.

f) Identify two strategies that could be used for smoke management in the atrium area of the Agriculture Building.

g) Identify two of the major fire safety responsibilities of the Department of Health, Safety and Environment at the University of Saskatchewan.

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h) Use the fire triangle to briefly describe the characteristics of materials that are at risk of undergoing spontaneous ignition.

i) Houses that are built today are better insulated than houses that were built 50 years ago. What effect will this have on the expected time to flashover in a room fire?

j) In your opinion, what are the three most important things you learned during this course?

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Question 2

a) Calculate the adiabatic flame temperature of a stoichiometric mixture of methane and oxygen, initially at 25ºC, assuming that dissociation does not occur. (10 points)

b) How do you expect the adiabatic flame temperature calculated in part (a) to compare with:
   - the adiabatic flame temperature of a stoichiometric mixture of methane and air?
   - the actual flame temperature? (5 points)

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Question 3

A test room used in ISO 9705 full-scale room fire tests is 2.4 m by 3.6 m by 2.4 m high with a single door 0.8 m by 2.0 m high. A 100 kW fire is placed in the back corner of the test room as an ignition source. The ambient temperature is 25ºC. On the center of the ceiling of this test room is a sprinkler that has a temperature rating of 68ºC and a RTI of 100 $m^{1/2}s^{1/2}$.

a) Calculate the activation time for this sprinkler if the ISO 9705 test is run using only the 100 kW ignition source. (10 points)

b) Which sprinkler parameter is used to specify its time response? If the activation time for the sprinkler in this question must be reduced by 50%, what must the value of this sprinkler parameter be changed to? (5 points)

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Question 4

You have been asked to evaluate the fire performance of a piece of an unknown material, which is to be installed on the ceiling of a room. Using the cone calorimeter, you find that this material will ignite in 20 s when subjected to a heat flux of 40 kW/m^2. Your measurements also indicate that the temperature on the surface of this material is 300°C at the time of ignition. Further tests indicate the critical heat flux for this material is 10 kW/m^2. The ambient temperature in your laboratory is 20°C.

You also find data from previous tests, in which the rate of flame spread was measured for a piece of oak, which has the same thickness as the unknown material, and which was installed in the same orientation as you will be testing this unknown material. This data indicates that the flame spread rate for the piece of oak is 0.08 mm/s.

a) What equipment can be used to measure the flame spread rating of the unknown material? (5 points)

b) Based on the data from the cone calorimeter, and the previous test data for oak, estimate the rate of flame spread for the unknown material. (10 points)

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Question 5

Firefighters are called to a fire in an industrial building. When they arrive, they immediately begin to spray water on the outside of one wall of the burning building, which is 10 m high by 50 m wide and completely covered in flames, which project 2.0 m away from the wall. It can be assumed that the temperature of the flames on this wall is equal to a typical temperature in a compartment during a postflashover fire, and that the fire can be treated as a blackbody.

In order to provide the maximum coverage with their hoses, the firefighters wish to stand as close as they can to the center of the base of this exterior wall. However, even with protective clothing, the maximum heat flux that they can be subjected to is 14.0 kW/m^2.

a) Based on this criterion, how close should firefighters stand in front of the center of the base of the wall? (10 points)

b) How do you think that your answer in part (a) would compare to an estimate made by treating the fire as a point source? (5 points)

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Question 6

a) 100 mm thick pieces of polymethylmethacrylate (PMMA) are often used when calibrating the cone calorimeter. Estimate the temperature increase at the surface of a piece of PMMA, and at a depth of 10 mm, after a 280 s exposure to a heat flux of 40 kW/m^2 in the cone calorimeter. (10 points)

b) Briefly explain how you could increase the accuracy of your estimate of the surface temperature. (5 points)

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Question 7

A hotel room is 4 m by 5 m by 2.5 m high, and has a single door, which is 0.7 m by 2.0 m high. The heat release rate density for this room is 500 kW/m^2, while the fire load is 300 MJ/m^2.

Using an appropriate t^2 design fire for this hotel room, sketch the heat release rate curve for the first 10 minutes of this fire, labeling the main stages of the fire. Indicate the maximum heat release rate, and when the maximum heat release rate will be reached for this particular t^2 fire.

(15 points)

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Question 8

In one of our laboratory sessions, we saw a video of a fire test of a Christmas tree, which was conducted by NIST. You wish to use fire protection engineering calculations in order to determine what will happen if a Christmas tree catches fire in a living room in a house. This living room is 3 m by 5 m by 2.5 m high, with a single entrance that is 2.0 m by 2.0 m high. Assume that the walls and ceiling are lined with 16 mm thick gypsum plaster. Assume that the heat release rate density and fire load are 500 kW/m^2 and 300 MJ/m^2, respectively. The initial temperature in the room is 20°C and the fire duration is 10 min.

Use an ultrafast t^2 fire to represent the Christmas tree fire, and assume that the Christmas tree ignites 45 s after a fire starts in a garbage can located beside the tree.

a) Estimate the time from the ignition of the garbage can until flashover occurs in the living room, using McCaffrey's equation. (10 points)

b) Estimate the hot gas layer temperature in the living room 3 min. after the beginning of the garbage can fire. (5 points)

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Question 9

An atrium is 15 m by 20 m by 10 m high. The design fire for this building is a fast t^2 fire in the middle of the atrium, at ground level. The stated fire safety objective for this space is to prevent occupants from being subjected to smoke from the design fire (assume that a clear height of 2 m above the floor level is necessary to prevent all occupants from being subjected to smoke).

A detection model predicts that this fire will be detected 60 s after it begins, while based on evacuation studies, it is estimated that occupants will take 30 s to respond after fire detectors activate.

The smoke control strategy for this space is to let the smoke from the fire fill the atrium, while the occupants leave the building. For this strategy, what is the maximum permitted evacuation time for the atrium, in order to satisfy the stated fire safety objective? (15 points)

Table 1.13 Heats of combustion[a] of selected fuels at 25°C (298 K)

		$-\Delta H_c$ (kJ/mol)	$-\Delta H_c$ (kJ/g)	$-\Delta H_{c,air}$ (kJ/g(air))	$-\Delta H_{c,ox}$ (kJ/g(O_2))
Carbon monoxide	CO	283	10.10	4.10	17.69
Methane	CH_4	800	50.00	2.91	12.54
Ethane	C_2H_6	1423	47.45	2.96	11.21
Ethene	C_2H_4	1411	50.35	3.42	14.74
Ethyne	C_2H_2	1253	48.20	3.65	15.73
Propane	C_3H_8	2044	46.45	2.97	12.80
n-Butane	n-C_4H_{10}	2650	45.69	2.97	12.80
n-Pentane	n-C_5H_{12}	3259	45.27	2.97	12.80
n-Octane	n-C_8H_{18}	5104	44.77	2.97	12.80
c-Hexane	c-C_6H_{12}	3680	43.81	2.97	12.80
Benzene	C_6H_6	3120	40.00	3.03	13.06
Methanol	CH_3OH	635	19.83	3.07	13.22
Ethanol	C_2H_5OH	1232	26.78	2.99	12.88
Acetone	$(CH_3)_2CO$	1786	30.79	3.25	14.00
D-Glucose	$C_6H_{12}O_6$	2772	15.4	3.08	13.27
Cellulose		—	16.09	3.15	13.59
Polyethylene		—	43.28	2.93	12.65
Polypropylene		—	43.31	2.94	12.66
Polystyrene		—	39.85	3.01	12.97
Polyvinylchloride		—	16.43	2.98	12.84
Polymethylmethacrylate		—	24.89	3.01	12.98
Polyacrylonitrile		—	30.80	3.16	13.61
Polyoxymethylene		—	15.46	3.36	14.50
Polyethyleneterephthalate		—	22.00	3.06	13.21
Polycarbonate		—	29.72	3.04	13.12
Nylon 6,6		—	29.58	2.94	12.67

[a] The initial states of the fuels correspond to their natural states at normal temperature and pressure (298°C and 1 atm pressure). All products are taken to be in their gaseous state—thus these are the net heats of combustion.

Table 1.16 Thermal capacities of common gases at 1000 K

	$C_p^{1000\ K}$ (J/mol.K)
Carbon monoxide (CO)	33.2
Carbon dioxide (CO_2)	54.3
Water (vapour) (H_2O)	41.2
Nitrogen (N_2)	32.7
Oxygen (O_2)	34.9
Helium (He)	20.8

Table 2.1 Thermal properties of some common materials[a]

Material	k (W/m.K)	c_p (J/kg.K)	ρ (kg/m^3)	α (m^2/s)	$k\rho c_p$ (W^2.s/m^{4}K^2)
Copper	387	380	8940	1.14×10^{-4}	1.3×10^9
Steel (mild)	45.8	460	7850	1.26×10^{-5}	1.6×10^8
Brick (common)	0.69	840	1600	5.2×10^{-7}	9.3×10^5
Concrete	0.8–1.4	880	1900–2300	5.7×10^{-7}	2×10^6
Glass (plate)	0.76	840	2700	3.3×10^{-7}	1.7×10^6
Gypsum plaster	0.48	840	1440	4.1×10^{-7}	5.8×10^5
PMMA[b]	0.19	1420	1190	1.1×10^{-7}	3.2×10^5
Oak[c]	0.17	2380	800	8.9×10^{-8}	3.2×10^5
Yellow pine[c]	0.14	2850	640	8.3×10^{-8}	2.5×10^5
Asbestos	0.15	1050	577	2.5×10^{-7}	9.1×10^4
Fibre insulating board	0.041	2090	229	8.6×10^{-8}	2.0×10^4
Polyurethane foam[d]	0.034	1400	20	1.2×10^{-6}	9.5×10^2
Air	0.026	1040	1.1	2.2×10^{-5}	—

[a] From Pitts and Sissom (1977) and others. Most values for 0 or 20°C. Figures have been rounded off.

[b] Polymethylmethacrylate. Values of k, c_p and ρ for other plastics are given in Table 1.2.

[c] Properties measured perpendicular to the grain.

[d] Typical values only.

Table 2.2 The error function

x	erf x	erfc x
0	0	1.0
0.05	0.056372	0.943628
0.1	0.112463	0.887537
0.15	0.167996	0.832004
0.2	0.222703	0.777297
0.25	0.276326	0.723674
0.3	0.328627	0.671373
0.35	0.379382	0.620618
0.4	0.428392	0.571608
0.45	0.475482	0.524518
0.5	0.520500	0.479500
0.55	0.563323	0.436677
0.6	0.603856	0.396144
0.65	0.642029	0.357971
0.7	0.677801	0.322199
0.75	0.711156	0.288844
0.8	0.742101	0.257899
0.85	0.770668	0.229332
0.9	0.796908	0.203092
0.95	0.820891	0.179109
1.0	0.842701	0.157299
1.1	0.880205	0.119795
1.2	0.910314	0.09686
1.3	0.934008	0.065992
1.4	0.952285	0.047715
1.5	0.966105	0.033895
1.6	0.976348	0.023652
1.7	0.983790	0.016210
1.8	0.989091	0.010909
1.9	0.992790	0.007210
2.0	0.995322	0.004678
2.1	0.997021	0.002979
2.2	0.998137	0.001863
2.3	0.998857	0.001143
2.4	0.999311	0.000689
2.5	0.999593	0.000407

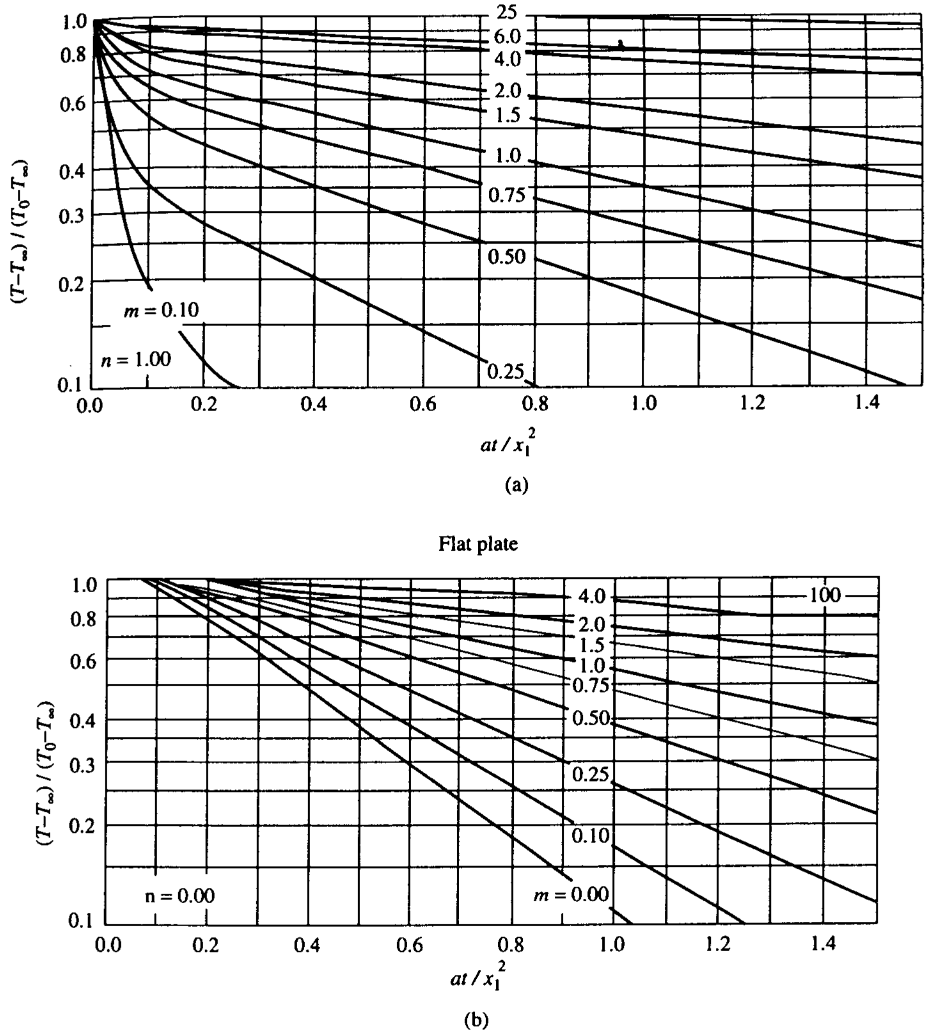

Figure 2.6 Heisler charts for (a) surface temperature and (b) centre temperature of an infinite slab. $n = x/L$ and $m = 1/\mathrm{Bi}$ (Welty *et al.*, 1976). Reproduced by permission of John Wiley & Sons, Inc.

Table 3.1 Flammability data for gases and vapours

	Lower flammability limit $(L)^a$			$\frac{L}{C_{st}}$	Upper flammability limits $(U)^a$		$\frac{U}{C_{st}}$	S_u^b	Minimum ignition energy[b]	Minimum quenching distance[b]
	% Vol	g/m^3	kJ/m^3		% Vol	g/m^3		(m/s)	(mJ)	(mm)
Hydrogen	4.0[c]	3.6	435	0.13	75	67	2.5	3.2	0.01	0.5
Carbon monoxide	12.5	157	1591	0.42	74	932	2.5	0.43	—	—
Methane	5.0	36	1906	0.53	15	126	1.6	0.37	0.26	2.0
Ethane	3.0	41	1952	0.53	12.4	190	2.2	0.44	0.24	1.8
Propane	2.1	42	1951	0.52	9.5	210	2.4	0.42	0.25	1.8
n-Butane	1.8	48	2200	0.58	8.4	240	2.7	0.42	0.26	1.8
n-Pentane	1.4	46	2090	0.55	7.8	270	3.1	0.42	0.22	1.8
n-Hexane	1.2	47	2124	0.56	7.4	310	3.4	0.42	0.23	1.8
n-Heptane	1.05	47	2116	0.56	6.7	320	3.6	0.42	0.24	1.8
n-Octane	0.95	49	2199	0.58	—	—	—	—	—	—
n-Nonane	0.85	49	2194	0.58	—	—	—	—	—	—
n-Decane	0.75	48	2145	0.56	5.6	380	4.2	0.40	—	—
Ethene	2.7	35	1654	0.41	36	700	5.5	>0.69	0.12	1.2
Propene	2.4	46	2110	0.54	11	210	2.5	0.48	0.28	—
Butene-1	1.7	44	1998	0.50	9.7	270	2.9	0.48	—	—
Acetylene	2.5	29	1410		(100)	—	—	1.7	0.02	
Methanol	6.7	103	2141	0.55	36	810	2.9	0.52	0.14	1.5
Ethanol	3.3	70	1948	0.50	19	480	2.9	—	—	—
n-Propanol	2.2	60	1874	0.49	14	420	3.2	0.38	—	—
Acetone	2.6	70	2035	0.52	13	390	2.6	0.50	1.1	—
Methyl ethyl ketone	1.9	62	1974	0.52	10	350	2.7	—	—	—
Diethyl ketone	1.6	63	2121	0.55	—	—	—	—	—	—
Benzene	1.3	47	1910	0.48	7.9	300	2.9	0.45	0.22	1.8

[a] Data from Zabetakis (1965). Mass concentration values are approximate and refer to 0°C ($L(\mathrm{g/m^3}) \approx 0.45\, M_w L$ (vol %)).

[b] Data from various sources including Kanury (1975) and Lees (1996). There is uncertainty with some of these data (Harris, 1983; Lees, 1996).

[c] See Section 3.5.4.

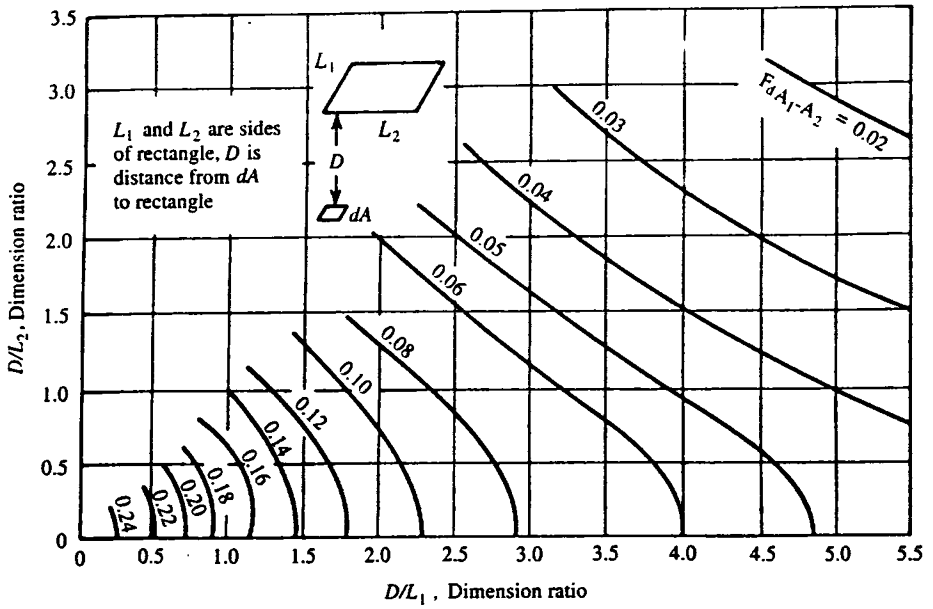

Figure 2.21 Configuration factor ϕ for direct radiation from a rectangle to a parallel small element of surface dA on a perpendicular to one corner (Figure 2.22(a)) (Hottel, 1930). Reproduced by permission of John Wiley & Sons, Inc.

Table 2.7 Values of $\phi(\alpha, S)$ for various values of α and S*

α	$S = 1$	$S = 0.9$	$S = 0.8$	$S = 0.7$	$S = 0.6$	$S = 0.5$	$S = 0.4$	$S = 0.3$	$S = 0.2$	$S = 0.1$
2.0	0.178	0.178	0.177	0.175	0.172	0.167	0.161	0.149	0.132	0.102
1.0	0.139	0.138	0.137	0.136	0.133	0.129	0.123	0.113	0.099	0.075
0.9	0.132	0.132	0.131	0.130	0.127	0.123	0.117	0.108	0.094	0.071
0.8	0.125	0.125	0.124	0.122	0.120	0.116	0.111	0.102	0.089	0.067
0.7	0.117	0.116	0.116	0.115	0.112	0.109	0.104	0.096	0.083	0.063
0.6	0.107	0.107	0.106	0.105	0.103	0.100	0.096	0.088	0.077	0.058
0.5	0.097	0.096	0.096	0.095	0.093	0.090	0.086	0.080	0.070	0.053
0.4	0.084	0.083	0.083	0.082	0.081	0.079	0.075	0.070	0.062	0.048
0.3	0.069	0.068	0.068	0.068	0.067	0.065	0.063	0.059	0.052	0.040
0.2	0.051	0.051	0.050	0.050	0.049	0.048	0.047	0.045	0.040	0.032
0.1	0.028	0.028	0.028	0.028	0.028	0.028	0.027	0.026	0.024	0.021
0.09	0.026	0.026	0.026	0.026	0.025	0.025	0.025	0.024	0.022	0.019
0.08	0.023	0.023	0.023	0.023	0.023	0.023	0.022	0.022	0.020	0.017
0.07	0.021	0.021	0.021	0.021	0.020	0.020	0.020	0.019	0.018	0.016
0.06	0.018	0.018	0.018	0.018	0.018	0.017	0.017	0.017	0.016	0.014
0.05	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.014	0.014	0.013
0.04	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.011	0.010
0.03	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.008
0.02	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
0.01	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003

* $S = L_1/L_2$ and $\alpha = (L_1 \times L_2)/D^2$ (see Figure 2.21). From McGuire (1953). Reproduced by permission of The Controller, HMSO. © Crown copyright.

Table 9.6 Parameters used for 't-squared fires' (Evans. 1995)

Description	Typical scenario	α_f kW/s^2
Slow	Densely packed paper products[a]	0.00293
Medium	Traditional mattress/boxspring[a] Traditional armchair	0.01172
Fast	PU mattress (horizontal)[a] PE pallets, stacked 1 m high	0.0469
Ultrafast	High-rack storage PE rigid foam stacked 5 m high	0.1876

[a] National Fire Protection Association (1993a).

Table 4.1. Typical Fire Growth Constants

t^2 Fire	Growth Time t_g (s)
Slow	600
Medium	300
Fast	150
Ultra Fast	75