NCEES
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PE | Fire Protection

Reference Handbook
Version 1.2

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INTRODUCTION

About the Handbook

The Principles and Practice of Engineering (PE) Fire Protection exam is computer-based, and NCEES will supply all the resource material you can use during the exam. Reviewing the *PE Fire Protection Reference Handbook* before exam day will help you become familiar with the charts, formulas, tables, and other reference information provided. You will not be allowed to bring your personal copy of the *PE Fire Protection Reference Handbook* into the exam room. Instead, the computer-based exam will include a PDF version of the handbook for your use. No printed copies of the handbook will be allowed in the exam room.

The PDF version of the *PE Fire Protection Reference Handbook* that you use on exam day will be very similar to this one. However, pages not needed to solve exam questions—such as the cover and introductory material—may not be included in the exam version. In addition, NCEES will periodically revise and update the handbook, and each PE Fire Protection exam will be administered using the updated version.

The *PE Fire Protection Reference Handbook* does not contain all the information required to answer every question on the exam. Theories, conversions, formulas, and definitions that examinees are expected to know have not been included. The handbook is intended solely for use on the NCEES PE Fire Protection exam.

Other Supplied Exam Material

In addition to the PE Fire Protection Reference Handbook, the exam will include codes and standards for your use. A list of the material that will be included in your exam is shown on the exam specifications. Any additional material required for the solution of a particular exam question will be included in the question itself. You will not be allowed to bring personal copies of any material into the exam room.

Updates on Exam Content and Procedures

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Errata

To report errata in this book, log in to your MyNCEES account and send a message. Examinees are not penalized for any errors in the handbook that affect an exam question.

Contributors

The *PE Fire Protection Reference Handbook* was developed by members of the Society of Fire Protection Engineers and is maintained by NCEES.

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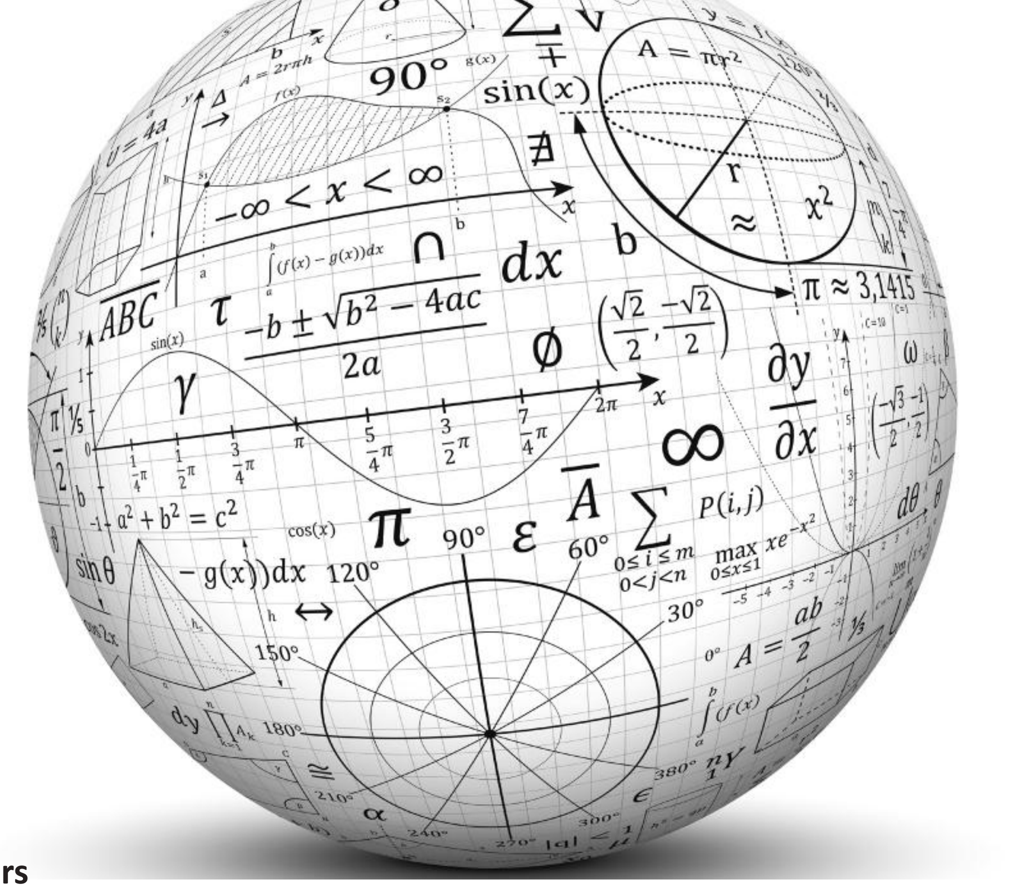

1 GENERAL

1.1 Units and Conversion Factors

1.1.1 Area

Square feet: 1 $ft^2 = 0.092903\ m^2$

1.1.2 Constants

Quantity		Symbol	Value	Units
gravity acceleration (standard)	metric	g	9.807	m/s^2
gravity acceleration (standard)	USCS	g	32.174	ft/sec^2

1.1.3 Flow

1 ft^3/sec = 449 gpm

1.1.4 Pressure

1 ft of water = 1.13 in. of mercury

1 Pa (Pascal) = 1 N/m^2 = 1 J/m^3 = 1 $kg/m \bullet s^2$

ft of water × 0.433 = lb/in^2

lb/in^2 × 2.307 = ft of water

1.1.5 Sound

120 dB = 20 Pa = 1 W/m^2

1.1.6 Temperature

Fahrenheit

$$°\text{F} = 1.8\,(°\text{C}) + 32$$

Celsius

$$°\text{C} = \frac{°\text{F} - 32}{1.8}$$

Rankin

$$°\text{R} = °\text{F} + 459.69$$

Kelvin

$$\text{K} = °\text{C} + 273.15$$

1.1.7 Volume

1 ft^3 = 7.4805 gal

1.1.8 Other Units and Conversion Factors

Multiply	By	To Obtain
acre	43,560	square feet (ft^2)
ampere-hr (A-hr)	3,600	coulomb (C)
ångström (Å)	1×10^{-10}	meter (m)
atmosphere (atm)	76.0	cm, mercury (Hg)
atm, std	29.92	in., mercury (Hg)
atm, std	14.70	lbf/in^2 abs (psia)
atm, std	33.90	ft, water
atm, std	1.013×10^5	pascal (Pa)
bar	1×10^5	Pa
bar	0.987	atm
barrels–oil	42	gallons–oil
Btu	1,055	joule (J)
Btu	2.928×10^{-4}	kilowatt-hr (kWh)
Btu	778	ft-lbf
Btu/hr	3.930×10^{-4}	horsepower (hp)
Btu/hr	0.293	watt (W)
Btu/hr	0.216	ft-lbf/sec
calorie (g-cal)	3.968×10^{-3}	Btu
cal	1.560×10^{-6}	hp-hr
cal	4.184	joule (J)
cal/sec	4.184	watt (W)
centimeter (cm)	3.281×10^{-2}	foot (ft)
cm	0.394	inch (in)
centipoise (cP)	0.001	pascal•sec (Pa•s)
centipoise (cP)	1	g/(m•s)
centipoise (cP)	2.419	lbm/hr-ft
centistoke (cSt)	1×10^{-6}	m^2/sec (m^2/s)
cubic feet/second (cfs)	0.646317	million gallons/day (MGD)
cubic foot (ft^3)	7.481	gallon
cubic meters (m^3)	1,000	liters
electronvolt (eV)	1.602×10^{-19}	joule (J)
foot (ft)	30.48	cm
ft	0.3048	meter (m)
ft of H_2O	0.4332	psi
ft-pound (ft-lbf)	1.285×10^{-3}	Btu
ft-lbf	3.766×10^{-7}	kilowatt-hr (kWh)
ft-lbf	0.324	calorie (g-cal)
ft-lbf	1.356	joule (J)
ft-lbf/sec	1.818×10^{-3}	horsepower (hp)
gallon (U.S. Liq)	3.785	liter (L)
gallon (U.S. Liq)	0.134	ft^3
gallons of water	8.3453	pounds of water
gamma (γ, Γ)	1×10^{-9}	tesla (T)
gauss	1×10^{-4}	T
gram (g)	2.205×10^{-3}	pound (lbm)
hectare	1×10^4	square meters (m^2)
hectare	2.47104	acres
horsepower (hp)	42.4	Btu/min
hp	745.7	watt (W)
hp	33,000	(ft-lbf)/min
hp	550	(ft-lbf)/sec
hp-hr	2,545	Btu
hp-hr	1.98×10^6	ft-lbf
hp-hr	2.68×10^6	joule (J)
hp-hr	0.746	kWh
inch (in.)	2.540	centimeter (cm)
in. of Hg	0.0334	atm
in. of Hg	13.60	in. of H_2O
in. of H_2O	0.0361	lbf/in^2 (psi)
in. of H_2O	0.002458	atm
joule (J)	9.478×10^{-4}	Btu
J	0.7376	ft-lbf
J	1	newton•m (N•m)
J/s	1	watt (W)
kilogram (kg)	2.205	pound-mass (lbm)
kgf	9.8066	newton (N)
kilometer (km)	3,281	feet (ft)
km/hr	0.621	mph
kilopascal (kPa)	0.145	lbf/in^2 (psi)
kilowatt (kW)	1.341	horsepower (hp)
kW	3,413	Btu/hr
kW	737.6	(ft-lbf)/sec
kW-hour (kWh)	3,413	Btu
kWh	1.341	hp-hr
kWh	3.6×10^6	joule (J)
kip (K)	1,000	lbf
K	4,448	newton (N)
liter (L)	61.02	in^3
L	0.264	gal (U.S. Liq)
L	10^{-3}	m^3
L/second (L/s)	2.119	ft^3/min (cfm)
L/s	15.85	gal (U.S.)/min (gpm)
meter (m)	3.281	feet (ft)
m	1.094	yard
m/second (m/s)	196.8	feet/min (ft/min)
mile (statute)	5,280	feet (ft)
mile (statute)	1.609	kilometer (km)
mile/hour (mph)	88.0	ft/min (fpm)
mph	1.609	km/h
mm of Hg	1.316×10^{-3}	atm
mm of H_2O	9.678×10^{-5}	atm
newton (N)	0.225	lbf
newton (N)	1	kg•m/s^2
N•m	0.7376	ft-lbf
N•m	1	joule (J)
pascal (Pa)	9.869×10^{-6}	atmosphere (atm)
Pa	1	newton/m^2 (N/m^2)
Pa•sec (Pa•s)	10	poise (P)
pound (lbm, avdp)	0.454	kilogram (kg)
lbf	4.448	N
lbf-ft	1.356	N•m
lbf/in^2 (psi)	0.068	atm
psi	2.307	ft of H_2O
psi	2.036	in. of Hg
psi	6,895	Pa
radian (rad)	180/π	degree
slug	32.174	pound-mass (lbm)
stokes	1×10^{-4}	m^2/s
tesla	1.0	weber/m^2
therm	1×10^5	Btu
ton (metric)	1,000	kilogram (kg)
ton (short)	2,000	pound-force (lbf)
watt (W)	3.413	Btu/hr
W	1.341×10^{-3}	horsepower (hp)
W	1	joule/s (J/s)
weber/m^2 (Wb/m^2)	10,000	gauss

1.2 Nomenclature

The following is general nomenclature used throughout this handbook. Additional variables are defined within specific sections.

Symbol	Quantity	Units (U.S.)	Units (SI)
a	area	in^2 or ft^2	mm^2 or m^2
a	acceleration	ft/sec^2	m/s^2
bhp	brake horsepower	hp	W (Watt)
C	Hazen-Williams pipe roughness coefficient	dimensionless	
d	diameter	in. or ft	mm
ε	pipe roughness factor	ft	m
f	Darcy friction factor	dimensionless	
F	force	$\text{lb}_\text{f} = \dfrac{\text{slug-ft}}{\text{sec}^2} = \dfrac{\left(\dfrac{\text{lb}_\text{m}}{\text{g}}\right)\text{-ft}}{\text{sec}^2}$	N (Newtons)
g	acceleration due to gravity	ft/sec^2	m/s^2
h	fluid height	ft	m
H	total head	ft	m
L	length of pipe	ft	m
m	mass	lb_m	kg
$\dot{m}$	mass flow rate	$\text{lb}_\text{m}\text{/sec}$	kg/s
n	rotational speed (pumps)	rpm	rpm
Re	Reynolds number	dimensionless	
p	pressure	psi or $\text{lb}_\text{f}/\text{in}^2$	N/m^2 or Pascal
P	power	ft-lb/sec	W
Q	volumetric flow rate	gpm	liter/s
ρ	density	lb/ft^3	g/cm^3
t	time	sec or min	s
v	velocity	ft/sec	m/s
υ	kinematic viscosity	$\text{ft}^2\text{/sec}$	$\text{cm}^2\text{/s}$ (stoke)
V	volume	in^3 or ft^3	liters
w	weight (force)	lb_f	N (or kg_f)
Z	vertical distance	ft	m

1.3 General Formulas

Volume of a pipe:

$$V = 0.25\pi d^2 L$$

Area of a circle/pipe:

$$A = \frac{\pi}{4}d^2$$

Vapor density:

$$\text{Vapor density} = \frac{\text{molecular weight}}{29}$$

Heat:

$$\text{Total heat} = \text{weight} \times H_c$$

where

H_c = heat of combustion (J/kg)

Total heat in J

Weight (kg)

1.4 Engineering Economics

1.4.1 General

Factor Name	Converts	Symbol	Formula
Single Payment, Compound Amount	to F given P	$(F/P, i\%, n)$	$(1+i)^n$
Single Payment, Present Worth	to P given F	$(P/F, i\%, n)$	$(1+i)^{-n}$
Uniform Series, Sinking Fund	to A given F	$(A/F, i\%, n)$	$\frac{i}{(1+i)^n-1}$
Capital Recovery	to A given P	$(A/P, i\%, n)$	$\frac{i(1+i)^n}{(1+i)^n-1}$
Uniform Series, Compound Amount	to F given A	$(F/A, i\%, n)$	$\frac{(1+i)^n-1}{i}$
Uniform Series, Present Worth	to P given A	$(P/A, i\%, n)$	$\frac{(1+i)^n-1}{i(1+i)^n}$
Uniform Gradient, Present Worth	to P given G	$(P/G, i\%, n)$	$\frac{(1+i)^n-1}{i^2(1+i)^n}-\frac{n}{i(1+i)^n}$
Uniform Gradient †, Future Worth	to F given G	$(F/G, i\%, n)$	$\frac{(1+i)^n-1}{i^2}-\frac{n}{i}$
Uniform Gradient, Uniform Series	to A given G	$(A/G, i\%, n)$	$\frac{1}{i}-\frac{n}{(1+i)^n-1}$

Nomenclature and Definitions:

A = Uniform amount per interest period
B = Benefit
BV = Book value
C = Cost
d = Inflation-adjusted interest rate per interest period
D_j = Depreciation in year j
EV = Expected value
F = Future worth, value, or amount
f = General inflation rate per interest period
G = Uniform gradient amount per interest period
i = Interest rate per interest period
i_e = Annual effective interest rate
MARR = Minimum acceptable/attractive rate of return
m = Number of compounding periods per year
n = Number of compounding periods; or the expected life of an asset
P = Present worth, value, or amount
r = Nominal annual interest rate
S_n = Expected salvage value in year n

Subscripts:

j = at time j

n = at time n

$$\dagger = \frac{F}{G} = \frac{\left(\frac{F}{A}\right) - n}{i} = \frac{F}{A} \times \frac{A}{G}$$

1.4.2 Time Value of Money

$$P\left[\frac{1-\left(1+\frac{I}{100}\right)^{-N}}{\frac{I}{100}}\right] + F_v\left(1+\frac{I}{100}\right)^{-N} + P_v = 0$$

where

P = payment

F_v = future value

P_v = present value

I = interest rate (%)

Note: This will yield negative numbers for at least one result due to that number being a value that is paid.

1.4.3 Non-Annual Compounding

$$i_\text{c} = \left(1 + \frac{r}{m}\right)^\text{m} - 1$$

1.4.4 Breakeven Analysis

By altering the value of any one of the variables in a situation, while holding all the other values constant, it is possible to find a value for that variable that makes the two alternatives equally economical. This value is the breakeven point.

The payback period is the period of time required for the profit or other benefits of an investment to equal the cost of the investment.

1.4.5 Inflation

To account for inflation, the dollars are deflated by the general inflation rate per interest period f, and then they are shifted over the time scale using the interest rate per interest period i. Use an inflation-adjusted interest rate per interest period d for computing present worth values P.

$$d = i + f + (i \times f)$$

1.4.6 Depreciation

$$D_j = \frac{C - S_\text{n}}{n}$$

1.4.7 Book Value

$$BV = \textit{initial cost} - \sum D_j$$

1.4.8 Capitalized Costs

Capitalized costs are present worth values using an assumed perpetual period of time.

$$P = \frac{A}{i}$$

1.4.9 Benefit-Cost Analysis

In a benefit-cost analysis, the benefits B of a project should exceed the estimated costs C.

$$B - C \geq 0 \quad \text{or} \quad \frac{B}{C} \geq 1$$

1.4.10 Modified Accelerated Cost Recovery System (MACRS)

$$D_j = (\text{factor})\, C$$

MACRS FACTORS

Year	Recovery Period (Years)			
	3	5	7	10
	Recovery Rate (Percent)			
1	33.33	20.00	14.29	10.00
2	44.45	32.00	24.49	18.00
3	14.81	19.20	17.49	14.40
4	7.41	11.52	12.49	11.52
5		11.52	8.93	9.22
6		5.76	8.92	7.37
7			8.93	6.55
8			4.46	6.55
9				6.56
10				6.55
11				3.28

2 FIRE PROTECTION ANALYSIS

2.1 General Fire Safety

2.1.1 Material Compatibility

Material compatibility is of importance for proper functionality of all systems and equipment. Information on oxidizing chemicals, combustible chemicals, unstable chemicals, water- and air-reactive chemicals, and corrosive chemicals is available in many sources including installation standards.

2.1.2 Acceptable Thresholds

2.1.2.1 Maximum Temperature

Maximum temperatures affect operability of machinery, ignition of flammable vapors or gases (autoignition), and degradation of materials including structural elements.

Temperature thresholds for ignition prevention:

- Autoignition temperature – The minimum temperature required to initiate self-sustained combustion in a substance without any apparent source of ignition.
- Flash-point temperature – The minimum temperature at which the liquid gives off sufficient vapor to form an ignitable mixture with air near the surface of the liquid or within the test vessel used. There are two methods of testing flash point: closed-cup and open-cup.
    - Closed-cup testing involves conditions similar to those in a closed tank. Most flash-point temperatures are given for closed-cup.
    - Open-cup testing is representative of open systems such as open tanks. This value will be indicated with a symbol of *oc*.
    - Generally, there is a difference of 10–20°F between closed-cup and open-cup flash-point temperatures.
    - At flash-point temperatures an ignitable mixture will form but the mixture will not ignite automatically. It is capable of being ignited in the presence of an ignition source.
- Fire point – The lowest temperature of a liquid in an open container at which the vapors evolve fast enough to support continuous combustion. The fire point is not the same as the autoignition temperature. An external ignition source must be present.
- Diluted water-miscible flammable liquids might have a flash point but no fire point. This is a consideration when evaluating protection of storage of heavily diluted water-miscible flammable liquids.

2.1.3 Electrical Fires

2.1.3.1 Ignition Modes Involving Electric Current

Electric sparking or arcing can ignite materials in all phases: gases, liquids, solids, liquid aerosols, and dust clouds. Ignition in gaseous and dust cloud media has been studied extensively. Ignition in bulk liquids is rare, apart from oil-filled transformers and other HV devices. Ignition of liquid sprays, fogs, or aerosols is problematic in some industries, however. Ignition of solids from arcing or sparking is common.

Minimum Ignition Energy (MIE) of Some Common Gases and Vapors

Substance	MIE (mJ)
Acetone	2.15
Acetylene	0.03
Ammonia	680
Benzene	0.91
Butane	0.26
Carbon disulfide	0.039
Cyclohexane	2.65
Ethane	0.42
Ethylene	0.114
Ethylene oxide	0.105
Furan	0.328
Heptane	1.15
Hexane	0.29
Hydrogen	0.03
Hydrogen sulfide	0.077
Iso-octane	2.9
Methane	0.71
Methanol	0.3
Pentane	0.82
Propane	0.5
Propylene	0.418
Toluene	2.5
Vinyl acetylene	0.095
p-Xylene	0.2

From *Ignition Handbook*, used by permission.
Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Minimum Ignition Energy (MIE) for Various Dust Clouds

Substance	MIE (mJ)
Aluminum	50
Aspirin	25–30
Black powder	320
Coal	250
Cocoa	100–180
Coffee	160
Cornstarch	30–60
Cotton linters	1,920
Dextrin	40
Flour, cake	25–80
Grain dust	30
Magnesium	40
Manganese	305
Nitrostarch	40
Nylon	20–30
Paper dust	20–60
Phenol formaldehyde	10–6,000
Polyethylene	70
Polyethylene terephthalate	35
Polystyrene	40–120
Rice	40–120
Silicon	100
Soap powder	60–120
Sugar, powdered	30
Tantalum	120
Tin	80
Titanium	25
TNT	75
Urea formaldehyde	80–1,280
Wheat starch	25–60
Wood flour	30–40
Zinc	960

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Apart from metals and some other rare substances, no combustible solids have an ignition temperature over 1,000°C. The temperature of an electric arc is at least 6,500 K and may be much higher. Yet an electric arc impinging onto a combustible solid is not necessarily assured of igniting it. Two primary factors operate in such cases:

1. The arc impingement may be very brief; many combustible materials can resist enormous heat fluxes if these are sustained only briefly.
2. The material may ablate too rapidly to allow ignition. These mechanisms, however, are understood only qualitatively.

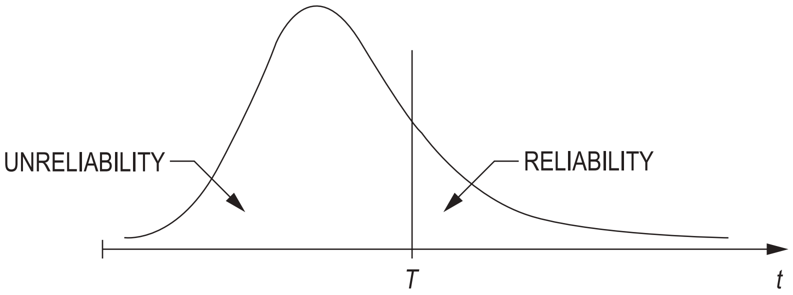
2.2 Risk Analysis

Risk analysis estimates the probability of fire occurring and evaluates its consequences by weighting both fire severity and probability. The results of a risk analysis can be used to estimate the average expected loss and its consequences, the largest possible loss and its consequences, or other parameters. Risk analysis takes fault analysis methodology, extreme value theory, and reliability theory into account in analyzing fire risk of fire safety.

Many methods or techniques may be used to evaluate risk. Examples include failure mode and effects analysis (FMEA), event tree analysis (ETA), hazard and operability analysis (HAZOP), fault tree analysis, criticality analysis, and consequence analysis.

2.2.1 Reliability Analysis

Reliability, represented by the letter R, is the probability of an item functioning after a predefined time, T. This definition introduces the concept of probability in reliability analysis. As such, the time to failure of a system or component is considered a random variable characterized by a probability distribution. The reliability of the system is the area under the probability distribution to the right of time T. Consequently, the unreliability of a system or component, represented by the letter F, is simply $F = 1 - R$. The unreliability will be the area under the curve to the left of time T. The following figure illustrates this concept. The curve in the figure represents the probability distribution characterizing the time to failure:



Conceptual Representation for the Definition of Reliability and Unreliability
Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

The process of conducting a reliability, availability, or maintainability analysis consists of the following general steps:

1. Definition of system boundaries
2. Failure mode analysis
3. Collection of reliability data
4. Selection of appropriate modeling method or technique
5. Quantification
6. Documentation

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2.2.2 Event Tree Analysis

An event tree is a diagram consisting of the sequence of possible states of a system and of corresponding events that lead to those states. By assigning probabilities to the outcomes of the intermediate events, the cumulative probability of consequences can be calculated.

Event tree analysis (ETA) is often used to analyze complex situations with several possible scenarios, where several fire or life safety systems are in place or are being considered. In brief, event trees are developed for a scenario, and probabilities and frequencies for components are applied (see previous discussion on ETA).

One method for quantifying fire risk from multiple fire scenarios is given as

$$\sum Risk_i = \sum \left(Loss_i \times F_i \right)$$

where

$Risk_i$ = risk associated with scenario i

$Loss_i$ = loss associated with scenario i

F_i = frequency of scenario i occurring

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

2.2.3 Criticality Analysis

Criticality analysis estimates the effect of fire prevention measures by assigning probabilities and severities to different possible fire scenarios. This approach is also known as operational risk management.

2.2.4 Building Fire Risk Analysis

Building fire risk analysis is one specific application of risk analysis. In fire safety analysis, the level of building fire safety is complementary to the level of fire risk. The chance of not having a fire is 1 minus the chance of having a fire (risk). Building fire safety analysis may also involve cost-benefit analysis.

To reduce overall risk in an industrial facility, a planned hazardous materials storage area is recommended and sometimes required, depending on the hazardous materials being stored. The location, construction, and level of protection required depend on the level of hazard the stored materials pose. The best option is to have a detached low-value structure that would reduce the risk to the public, nearby structures, or occupants of those nearby structures at risk. If this is not achievable, the next best option is a structure attached to the facility that has no penetrations into the facility that would allow transfer of products of combustion or a material spill from the structure to the facility.

Building fire risk analysis should consider

1. What the fire hazards are and how fires might occur
2. How the unwanted outcomes (consequences) are valued and by whom (including offsetting benefits)
3. What differences in risk perception and valuation exist and how they should be treated (i.e., should high-consequence events be disregarded if the probability of occurrence is very low?)
4. Whether any social or cultural issues may be relevant
5. Any different stakeholder views on the likelihood of fire occurrence and of the resulting consequences
6. Whether uncertainty, variability, and unknowns have been identified and appropriately addressed

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

2.2.5 Limits of Analysis

The limitations of developed models or equations should always be verified and examined when applying them to specific problems.

The factors affecting the reliability of predictions provided by models or equations may be categorized as follows:

- Definition and conceptualization of the assessed problem or scenario
- Formulation of the conceptual model
- Formulation of the computational model
- Estimation of the parameter values
- Data on which the models or equations are based

2.2.6 Percent Error Formula

$$Percentage\ yield = \frac{Actual\ yield}{Theoretical\ yield} \times 100\%$$

2.3 Fire Protection Management

A comprehensive fire protection management program is critical to ensuring the health, safety, and welfare of a building's occupants. To sustain a desired level of life safety, the building components and systems must be managed. In addition, activities occurring within the building must be managed to remain within design limitations.

This topic also includes fire prevention measures such as hot work (welding) permits, housekeeping, security service, maintenance of warehouse aisles and flue spaces, and maintenance of performance-based design parameters.

Three factors are important in managing an adequate level of life safety in an existing facility:

- Capabilities and limitation of design
- Facility system impairments procedures
- Inspection, testing, and maintenance frequencies

The type, quantity, and arrangement of fuel present within a building can significantly affect the magnitude of a fire event. The building design or a prescriptive code requirement may contemplate a specified maximum fuel loading associated with a specific occupancy so that the fire protection systems can perform reliably and efficiently. Elements that can have an impact on this design include

- Size and type of fuel packages
- Maximum quantity of fuel packages within the specified area
- Allowable locations for storage of display of specified fuel packages
- Required spatial separation between fuel packages

2.3.1 Fire Protection System Reliability Prediction

Method to predict the required maintenance interval for a fire protection system that is based on the system's reliability:

$$t_R = \frac{\ln R_R}{-\Lambda}$$

where

$\ln R_R$ = Napierian log of the required reliability, R_R

Λ = inherent failure rate of the system

t_R = required maintenance interval to achieve the required reliability

2.3.2 Reliability of Fire Protection System

$$\Lambda_T = 1 - P_T$$

where

Λ_T = failure rate of the total system

P_T = probability of successful operation for the system, or reliability

The failure rate, Λ, of a system assembled from components having exponential failure rates is computed from the sum of the failure rates of each of the components, Λ_n, from

$$\Lambda = q_1\lambda_1 + q_2\lambda_2 + q_3\lambda_3 + \cdot\cdot\cdot + q_n\lambda_n$$

where

Λ = failure rate of the total system

q_n = quantity of the *n*th component in the system

λ_n = failure rate of the *n*th component in the system

2.4 Fire Protection Analysis—Information Sources

Fire prevention can be defined as the design and monitoring of physical conditions, automated processes, and human activities to minimize the chance of fire. The chance of fire is minimized by controlling fuel, oxidizers, and ignition energy; by taking process fire safety and hazard abatement measures; and by implementing management programs for loss prevention and control. Fire prevention is found in every phase of a facility, from preliminary design through demolition.

2.4.1 Data Interpretation

- Identify and assess the impact of changes (e.g., facility, occupant, content, process/activity)
- Analyze system test results (e.g., fire pump, sprinkler, fire alarm)
- Analyze fire test results

A number of types of fire tests can be analyzed:

- Flame spread over building materials (internal and external)
- Smoke production rates
- Ignitability and flammability of clothing, furniture, drapery, and other similar materials
- Flash point, fire point, and similar tests of liquid flammability
- Warehouse commodity classification
- Dust explosivity and ignitability
- Required extinguishing agent concentrations or densities for specific scenarios
- Susceptibility of liquid to static charge accumulation

2.4.2 Fire Test Methods

Fire tests of entire building component, such as doors or compartments, are known as full-scale tests. Bench tests are smaller-scale tests of representative sample of materials. Fire tests can be grouped into these categories:

- Empirically based bench tests
- Full-scale and component tests
- Research-oriented bench tests

2.4.2.1 Liquid Flammability Tests

The test used to determine the flash points of most liquids is ASTM D56 "Flash Point by Tag Closed Cup Tester." This test is intended for liquids with a flash point of less than 175°F. Flash points determined in an open-cup test can be as much as 50°F higher than when determined using a closed-cup test. The Pensky-Martens test is intended for fuel oils with flash points between 150°F and 230°F.

$$\text{Corrected flash point} = T - 0.033\,(760 - P)$$

where

T = measured closed-cup flash point (°C)

P = ambient atmospheric (barometric)pressure (mm Hg)

Some Values of Closed-Cup Flash Point, Open-Cup Flash Point, and Fire Point Temperatures

	Closed-Cup FP (°C)	Open-Cup FP (°C)	Fire Point (°C)
n-Hexane	–22	[a]	NA
n-Heptane	–4	–1	2
Methanol [b]	12	1.0, 13.5[b]	1.0, 13.5[b]
n-Octane	12	17	18
Ethanol [b]	13	6, 18.0[b]	6, 18.0[b]
s-Butanol	24	NA	29
m-Xylene	25	NA	44
p-Xylene	25	31	44
n-Butanol	29	36	36, 38, 50
n-Nonane	31	37	42
o-Xylene	32	36	42
JP-6	NA	38	43
n-Decane	44	52	61.5, 66
Decalin	NA	57	63
Tetraline	NA	71	74
Bicyclohexyl	NA	74	79
n-Dodecane	74	NA	103
Fuel oil no. 2	124	NA	129
Fuel oil no. 6	146	NA	177
Glycero	160	176	207
Motor oil	216	NA	224

NA = Not available

[a] The open-cup flash point of *n*-hexane is quoted as –26°C in the original *Factory Mutual Handbook* and repeated in Babrauskas. This is incorrect.

[b] Data from Glassman and Dryer. The lower values were obtained with ignition by a pilot flame. The upper values refer to spark ignition.

Unless otherwise stated, these data come from the *Factory Mutual Handbook*, as quoted by Babrauskas.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

2.4.2.2 Smoke and Toxic Gas Release

The type of fuel, mode of burning (flaming/smoldering), heat flux, and ventilation factors have a major effect on smoke development and toxic gas production. Knowledge of smoke development properties is important because smoke inhibits visibility and exposes occupants to toxic gases.

Tests for smoke production include

ASTM E662: "Specific Optical Density of Smoke Generated by Solid Materials"

ASTM D2843: "Density of Smoke from the Burning or Decomposition of Plastics"

ASTM E906: "Heat and Visible Smoke Release Rates for Materials and Products Using a Thermopile Method"

ASTM E1354: "Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter"

2.4.3 ASTM E119 (NFPA 251) Furnace Test Correction Factor

$$C = \frac{2I\left(A - A_S\right)}{3\left(A_S + L\right)}$$

where

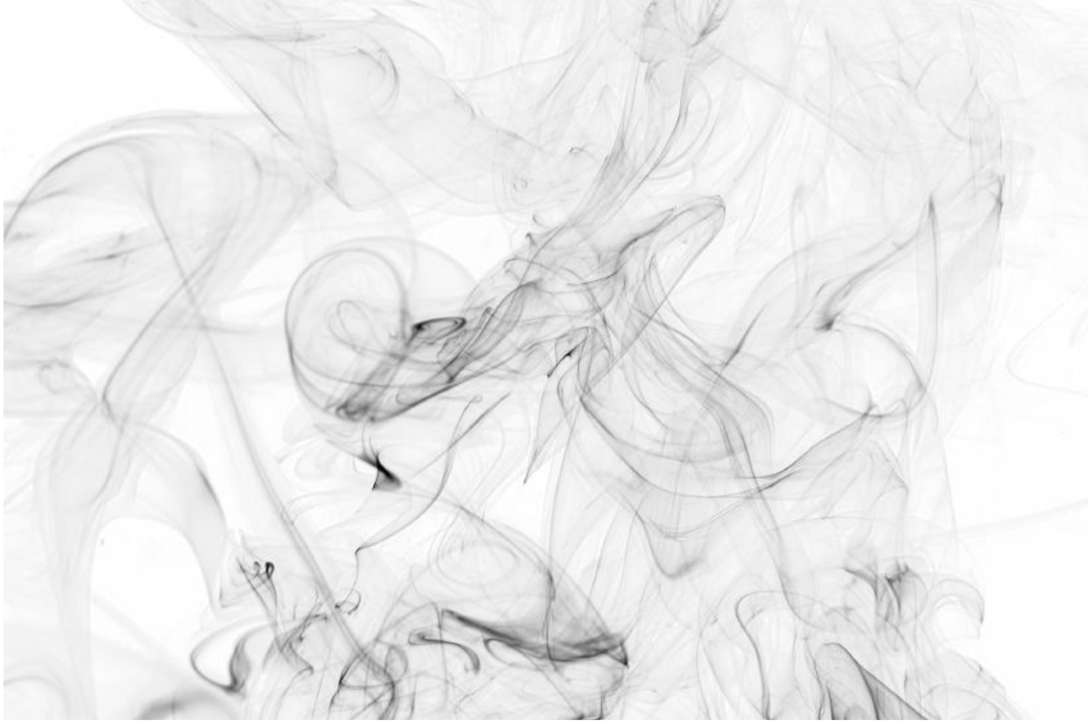
C = correction factor (min or hr)

I = indicated fire resistance period (min or hr)

A = area under the curve of indicated average furnace temperature for the first three-fourths of the indicated period (°F-hr, °C-hr, °F-min, °C-min)

A_S = area under the standard furnace curve for the same part of the indicated period (°F-hr, °C-hr, °F-min, °C-min)

L = lag correction (54°F-hr or 3,240°F-min, 30°C-hr or 1,800°C-min)



3 FIRE DYNAMICS FUNDAMENTALS

3.1 Basics

3.1.1 Combustion

Combustion can be expressed chemically, one example being the balanced chemical equation for the combustion of methane, which is

$CH_4 + 2O_2 = CO_2 + 2H_2O$
(1 mol of methane reacting with 2 mol of oxygen produces 1 mol of carbon dioxide and 2 mol of water)

Heat of reaction = Heat of formation of products – Heat of formation of reactants

Heats of Formation at 25°C (298 K)

Compound	$(\Delta H_f)298$ (kJ/mol)
Hydrogen (atomic)	+218.00
Oxygen (atomic)	+249.17
Hydroxyl (OH)	+38.99
Chlorine (atomic)	+121.29
Carbon monoxide	–110.53
Carbon dioxide	–393.52
Water (liquid)	–285.8
Water (vapor)	–241.83
Hydrogen chloride	–92.31
Hydrogen cyanide (gas)	+135.14
Nitric oxide	+90.29
Nitrogen dioxide	+33.85
Ammonia	–45.90
Methane	–74.87
Ethane	–84.5
Ethene	+52.6

(*continued on next page*)

Compound	$(\Delta H_f)298$ (kJ/mol)
Ethyne (acetylene)	+226.9
Propane	–103.6
n-Butane	–124.3
isobutane*	–131.2
Methanol	–242.1

* Heats of formation of other hydrocarbons are tabulated in Weast.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Complete combustion for a generic hydrocarbon (C_xH_y) burning in air is written as

$$C_xH_y + a\left(O_2 + 3.76N_2\right) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76aN_2$$

where

$$a = x + \frac{y}{4}$$

$$s = \left(\frac{moles\ air}{moles\ fuel}\right)_{\text{stoich}} = \frac{\left(x + \frac{y}{4}\right)}{X_{O_2}}$$

s = molar stoichiometric ratio (both above X_{O_2})

X_{O_2} = mole fraction of oxygen in air $\left(\frac{1}{4.76}\right)$

B-Number Values for Different Fuels

Solids	Formula	B-number
Polypropylene	C_3H_6	1.29
Polyethylene	C_2H_4	1.16
Polystyrene	C_8H_8	1.55
Nylon 6/6	$C_{12}H_{22}N_2O_2$	1.27
Polycarbonate	$C_6H_{14}O_3$	1.41
PMMA	$C_5H_8O_2$	1.78
PVC	C_2H_3Cl	1.15
Fir wood	$C_{4.8}H_8O_4$	1.75
α-cellulose	$C_6H_{10}O_5$	6.96
Polyoxymethylene	CH_2O	1.47

Liquids	Formula	B-number
Methanol	CH_3OH	2.53
Ethanol	C_2H_5OH	2.89
Propanol	C_3H_7OH	3.29
Butanol	C_4H_8OH	3.35
n-Pentane	C_5H_{12}	7.63
n-Hexane	C_6H_{14}	6.67
n-Heptane	C_7H_{16}	5.92
n-Octane (gasoline)	C_8H_{18}	5.42
iso-Octane	C_8H_{18}	6.59
n-Nonane	C_9H_{20}	4.89
n-Decane	$C_{10}H_{22}$	4.61
n-Undecane	$C_{11}H_{24}$	4.43
n-Dodecane (kerosene)	$C_{12}H_{26}$	4.13
Acetone	C_3H_2O	7.28

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.1.2 Stoichiometric Combustion

If the combustion process is stoichiometric, air or oxygen is being supplied at exactly the rate required to consume the fuel as it is being made available. The stoichiometric air-to-fuel ratio, r, is defined as

$$r = \frac{rate\ of\ supply\ of\ air}{rate\ of\ supply\ of\ fuel} = \frac{\dot{m}_{\text{air}}}{\dot{m}_{\text{fuel}}}$$

The combustion process is rarely complete. The efficiency of the combustion process can be assessed using the equivalence ratio, ϕ.

$$\phi = \frac{\left(\frac{fuel}{air}\right)_{\text{actual}}}{\left(\frac{fuel}{air}\right)_{\text{stoich}}} = \frac{\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air}}}\right)_{\text{actual}}}{\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air}}}\right)_{\text{stoich}}} = r\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air}}}\right)_{\text{actual}}$$

If $\phi < 1$, the combustion will be fuel lean. If $\phi > 1$, it will be fuel rich. Fuel-rich conditions can lead to incomplete combustion.

3.1.3 Heats of Combustion

The heat of combustion of a fuel is defined as the amount of heat released when unit quantity is oxidized completely to yield stable end products. Tables for a variety of products can be found in Sections 11.3 and 11.4 of this document.

3.1.4 Heats of Formation

The most stable compounds (CO_2 and H_2O) have the largest negative values, while positive values tend to indicate an instability with respect to the parent elements. This can indicate high chemical reactivity, and indeed heats of formation have been used in preliminary hazard assessment to provide an indication of the risks associated with new processes in the chemical industry. (See table on page 17.)

3.1.5 Specific Heat

Heat Capacities of Selected Gases at Constant Pressure (101.1 kN/m^2)

***Cp* (J/m•K)**					
Species	**Temperature (K)**				
	298	**500**	**1,000**	**1,500**	**2,000**
CO	29.14	29.79	33.18	35.22	36.25
CO_2	37.129	44.626	54.308	58.379	60.350
$H_2O(g)$	33.577	35.208	41.217	46.999	51.103
N_2	29.125	29.577	32.698	34.852	35.987
O_2	29.372	31.091	34.878	36.560	37.777
He	20.786	20.786	20.786	20.786	20.786
CH_4	35.639	46.342	71.797	86.559	94.399

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Thermal Capacity of the Products of Combustion of a Stoichiometric Propane/Air Mixture

Species	No. of Moles	Thermal Capacity at 1,000 K	
		J/mol•K	J/K
CO_2	3	54.3	162.9
H_2O	4	41.2	164.8
N_2	18.8	32.7	614.8
Total thermal capacity (per mole of propane) =			942.5

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.1.6 Ignition

Methods to predict the ignition of solid materials involve the following properties:

- Specific heat (c_p)
- Thermal conductivity (k)
- Density (ρ)

The product of these properties ($k\rho c$) is called thermal inertia. Selected information can be found in Sections 11.7 and 11.13 of this document.

3.1.7 Ignition of Thermally Thin Material

When the external heat flux is much larger than the losses, estimation of the time to ignition can be made using the following equation:

$$t_{ig} = \frac{\bar{\rho}_s \bar{C}_s L\left(T_{ig} - T_0\right)}{\dot{q}_e''}$$

where

t_{ig} = time to ignition (s)

$\bar{\rho}_s$ = density (kg/m^3)

$\bar{C}_s$ = specific heat (kJ/kg-K)

L = material thickness (m)

T_{ig} = ignition temperature (°C)

T_0 = initial temperature (°C)

$\dot{q}_e''$ = external heat flux (kW/m^2)

It applies to a material of thickness d heated on one side and insulated on the other, or a material of thickness $2d$ heated symmetrically.

The physical thickness, d, of the material must be less than the thermal penetration depth, δ_T, for it to be considered thermally thin. Typically, items with a thickness of less than about 1 mm can be treated as thermally thin.

The equation for thermal penetration depth is given as (*Fundamentals of Fire Phenomena* by J. Quintiere, equation 7.20a)

$$d \ll \delta_T \approx \sqrt{\alpha\, t} \approx \frac{k\left(T_s - T_0\right)}{\dot{q}''}$$

or

$$Bi \equiv \frac{dh_c}{k} \ll \frac{h_c\left(T_s - T_0\right)}{\dot{q}''}$$

where

d = material thickness (m)

δ_T = thermal penetration depth (m)

α = thermal diffusivity (m^2/s)

t = time (s)

k = thermal conductivity (W/m-K)

T_s = temperature of solid (°C)

T_0 = initial temperature (°C)

$\dot{q}''$ = heat flux (kW/m^2)

Bi = Biot number (dimensionless)

h_c = heat transfer coefficient (W/m^2-K)

3.1.8 Ignition of Thermally Thick Material

Different equations are applicable to materials with high- and low-incident heat fluxes. The solution using these equations is an iterative process requiring a comparison of the ignition time to a characteristic time.

The characteristic time, t_c, is determined as follows

$$t_c = \frac{\overline{k}\,\overline{\rho}_s\overline{C}_s}{\left(h_T\right)^2}$$

where

t_c = characteristic time (s)

$\overline{k}$ = thermal conductivity (kW/m-K)

$\overline{p}_s$ = density (kg/m^3)

$\overline{C}_s$ = specific heat (kJ/kg-K)

h_T = total heat-transfer coefficient (kW/m^2-K)

It incorporates both convective and radiative heat losses.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.1.8.1 High-Incident Heat Flux

Where $t_{ig} \ll t_c$:

$$t_{ig} = \frac{\pi}{4}\bar{k}\,\bar{\rho}_s\,\bar{C}_s\left(\frac{T_{ig} - T_0}{\dot{q}_e''}\right)^2$$

where

t_{ig} = time to ignition (s)

$\bar{k}$ = thermal conductivity (kW/m-K)

$\bar{\rho}_s$ = density (kg/m^3)

$\bar{C}_s$ = specific heat (kJ/kg-K)

T_{ig} = ignition temperature (°C)

T_0 = initial temperature (°C)

$\dot{q}_e''$ = external heat flux (kW/m^2)

The heat-loss term is not included, implying that it holds true where the heat-flux term is large.

Thermal response parameter, *TRP*, is defined as

$$TRP = \Delta T_{ig}\sqrt{\bar{k}\,\bar{\rho}_s\,\bar{C}_s\,\frac{\pi}{4}}$$

where

TRP = thermal response parameter (kW-s$^{1/2}$/m^2)

ΔT_{ig} = ignition temperature above ambient (K)

$\bar{k}$ = thermal conductivity (kW/m-K)

$\bar{\rho}_s$ = density (kg/m^3)

$\bar{C}_s$ = specific heat (kJ/kg-K)

For fire initiation, a material must be heated above its *CHF* value. And substitution into the high-incident heat-flux equation results in the following

$$\frac{1}{\sqrt{t_{ig}}} = \frac{\left(\dot{q}_e'' - CHF\right)}{TRP}$$

where

t_{ig} = time to ignition (s)

$\dot{q}_e''$ = external heat flux (kW/m^2)

TRP = thermal response parameter (kW-s$^{1/2}$/m^2)

CHF = critical heat flux (kW/m^2)

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.1.8.2 Low-Incident Heat Flux

Where $t_{ig} > t_c$:

$$\frac{1}{\sqrt{t_{ig}}} = \frac{\sqrt{\pi}\,h_T}{\sqrt{\bar{k}_s \bar{\rho}_s \bar{C}_s}} \left[1 - \frac{h_T\left(T_{ig} - T_\infty\right)}{\dot{q}_e''}\right]$$

See Section 3.1.8.1 for variables and units.

3.1.9 Gas Flame Temperature

Adiabatic Flame Temperature of Lower-Limiting Hydrocarbon Air Mixtures

Gas	Adiabatic Flame Temperature at Lower Flammability Limit (K)
Methane	1,446
Ethane	1,502
Propane	1,554
n-Butane	1,612
n-Pentane	1,564
n-Heptane	1,692
n-Octane	1,632

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.1.10 Combustion Efficiency

Combustion efficiency is likely to vary from around 0.3–0.4 for heavily fire-retarded materials to 0.9 or higher in the case of oxygen-containing products.

The combustion efficiency, χ_{ch} (dimensionless), can be described as the ratio of the effective heat of combustion and the net heat of combustion:

$$\chi_{ch} = \frac{\Delta H_{ch}}{\Delta H_T}$$

or

$$\chi_{ch} = \frac{\Delta h_c}{\Delta h_c^{1}}$$

where

ΔH_{ch} = effective heat of complete combustion per unit of fuel vaporized (mJ/kg)

ΔH_T = net heat of complete combustion per unit of fuel vaporized (mJ/kg)

Δh_c = effective heat of combustion (MJ/kg)

Δh_c^{1} = net heat of combustion (MJ/kg)

3.1.11 Virtual Origin

The virtual origin is defined as the point source from which the plume above the flame appears to originate.

3.1.11.1 Virtual Origin for Pool Fires

$$z_0 = -1.02D + 0.083\dot{Q}^{2/5}$$

where

z_0 = virtual origin (m)

D = effective diameter (m)

$\dot{Q}$ = total heat-release rate (kW)

If the pool is not circular

$$D = \left(\frac{4A}{\pi}\right)^{1/2}$$

where

A = area of the pool (m^2)

3.1.11.2 Virtual Origin of Other Fire Types

$$z_0 = L - 0.175\dot{Q}_c^{2/5}$$

where

z_0 = virtual origin (m)

L = flame height (m)

$\dot{Q}_c$ = convective heat-release rate (kW)

3.2 Fire Growth and Heat Release Rates

3.2.1 Heat Release Rate—General

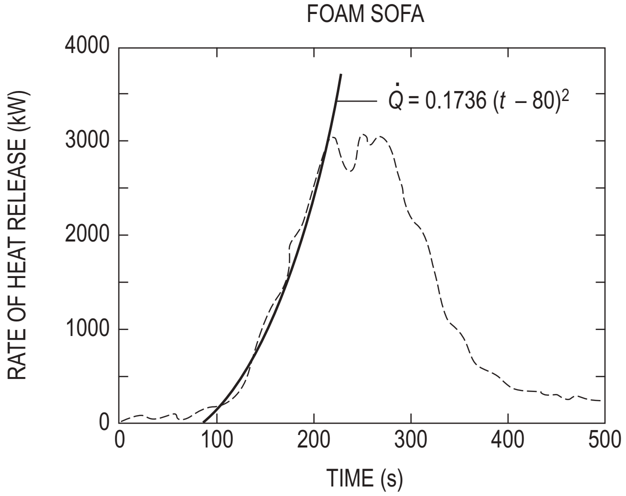
$$\dot{Q} = \dot{m}_{\text{fuel}} \times \Delta H_C$$

$\dot{m}_{\text{fuel}}$ = mass burning rate (kg/s)

ΔH_C = heat of combustion (kJ/kg)

3.2.2 Heat Release Rates—Example Fire Test

Following is an example of a heat-release-rate graph for a burning foam sofa based on fire test data:



Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.2.3 Total Heat Release

Since the energy released by a fire is transported primarily through convection and radiation, the total heat-release rate can be defined as:

$$\dot{Q} = \dot{Q}_c + \dot{Q}_r$$

3.2.4 Rate of Heat Release Within a Compartment

To calculate the heat release rate within the compartment, it is assumed that the fire is ventilation controlled and that all combustion takes place within the compartment:

$$\dot{Q} = \dot{m}_{air} \times \Delta H_c(\text{air})$$

where

$\dot{Q}$ = portion of the heat-release rate (kW)

$\dot{m}_{air}$ = mass flow rate of air into the compartment (kg/s)

$\Delta H_c(\text{air})$ = heat of combustion (kJ/kg) per unit mass of air consumed (3,000 kJ/kg)

$$\dot{m}_{air} = 0.52 A_0 H_0^{1/2}$$

where

A_0 = effective area of ventilation (m^2)

H_0 = height of the ventilation opening (m)

3.2.5 Rate of Heat Release for Pallets

The general heat-release rate for a standard pallet, 1.22 m × 1.22 m, can be determined using the following equation:*

$$\dot{Q} = 1{,}368\,(1 + 2.14h_{\text{p}})(1 - 0.03M)$$

where

$\dot{Q}$ = heat release rate (kW)

h_{p} = stack height (m)

M = moisture (%) with an assumed net heat of combustion of 12×10^3 kJ•kg^{-1}

* equation not appropriate for stacks less than 0.5 m in height

The general heat-release rate for a nonstandard pallet per-unit-pallet-floor-area can be determined using the following equation:

$$\dot{Q}'' = 919\,(1 + 2.14h_{\text{p}})(1 - 0.03M)$$

where

$\dot{Q}''$ = heat release rate per unit area (kW/m^2)

h_{p} = stack height (m)

M = moisture (%) with an assumed net heat of combustion of 12×10^3 kJ•kg^{-1}

* equation not appropriate for stacks less than 0.5 m in height

3.2.6 Power-Law Fire Growth

These growth models do not model fire decay. The most common power-law growth model is the t^2 model:

$$\dot{Q} = \alpha\left(t - t_{\text{i}}\right)^{\text{p}}$$

where

$\dot{Q}$ = heat release rate of fire at time t (kW)

α = fire growth coefficient (kW/s$^{\text{p}}$)

t = time measured into the fire at which the heat release is being calculated (s)

t_{i} = ignition reference time (incorporates time to ignition and incubation period) (s)

p = power (characterizing heat-release rate increase)

3.2.7 t^2 Fire Growth Rates

$$\alpha = \frac{1{,}055}{t_{\text{g}}^2}$$

Slow $t_{\text{g}} = 600$

Medium $t_{\text{g}} = 300$

Fast $t_{\text{g}} = 150$

Ultra Fast $t_{\text{g}} = 75$

where

t_g = time for fire to grow to 1,055 kw

3.2.8 Heat-Release Rates for t^2 Fires with Standard Growth Rates

The t^2 fire growth can be depicted as curves at various α values. These are curves that present liquid fuel fires with liquid-phase and gas-phase flame spread.

3.2.9 t^2 Fires—with Fuel Constant

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

where

$\dot{Q}$ = heat release rate (kW)

α = fire growth coefficient (kW/s^2)

t = time after burning occurs (sec)

These fire heat-release rates curves are chosen to be representative of actual fires involving different commodities and geometric storage arrangements:

Slow	$\dot{Q} = 0.00293t^2$
Medium	$\dot{Q} = 0.01172t^2$
Fast	$\dot{Q} = 0.0469t^2$
Ultrafast	$\dot{Q} = 0.1876t^2$

where

$\dot{Q}$ is in kW

t^2 is in sec

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.2.10 t^2 Fires – with Fire Growth Time

$$\dot{Q}(t) = \left(\frac{1{,}055}{t_{\mathrm{g}}^2}\right) \times t^2$$

where

$\dot{Q}(t)$ = total heat-release rate at time t (kW)

t = time (sec)

t_{g} = time (sec) for a fire to grow from first appearance of flame to 1,055 kW

3.3 Heat Transfer

Methods for calculating the heat transferred by conduction, convection, and radiation.

3.3.1 Conduction

Conduction is the gradual spreading of heat through materials, molecule by molecule. The heat flux is related to the temperature differential as follows:

$$\dot{q}'' = \frac{\Delta T}{\left(\frac{t}{k}\right)}$$

where

$\dot{q}''$ = heat flux at material surface(kW/m^2)

t = thickness (m)

k = thermal conductivity (kW/m-K)

ΔT = change in temperature (K)

3.3.1.1 Rate of Heat Transfer Through a Solid

The rate that heat is transferred through a solid is directly proportional to the difference in temperature, as given by Fourier's law. Many thermal properties of materials are time-dependent (i.e., thermal conductivity and specific heat). Average values that span the range of temperatures under consideration are often used.

$$\dot{Q} = -kA\frac{dT}{dx}$$

where

$\dot{Q}$ = rate of heat transfer (kW)

k = thermal conductivity (kW/m-K)

A = surface area perpendicular to direction of heat transfer (m^2)

T = temperature (K)

x = spatial location within the solid (m)

For heat-transfer rate per unit area:

$$\dot{q}'' = -k\frac{dT}{dx} = -k\left(\frac{T_2 - T_1}{x}\right)$$

where

$\dot{q}''$ = heat-transfer rate per unit area (kW/m^2)

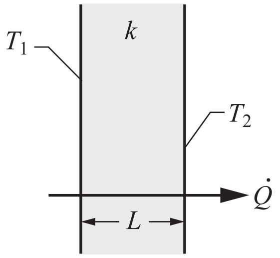
k = thermal conductivity (kW/m-K)

T_1 = temperature (K)

T_2 = temperature (K)

x = spatial location within the solid (m)

3.3.1.2 Conduction Through a Plane Wall



$$\dot{Q} = \frac{-kA\left(T_2 - T_1\right)}{L}$$

where

$\dot{Q}$ = rate of heat transfer (kW)

k = thermal conductivity (kW/m-K)

A = wall surface area normal to heat flow (m^2)

L = wall thickness (m)

T_1 = temperature of one surface of the wall (K)

T_2 = temperature of the other surface of the wall (K)

3.3.1.3 Thermal Resistance

$$\dot{Q} = \frac{\Delta T}{R_{\text{total}}}$$

where

$\dot{Q}$ = rate of heat transfer (kW)

$\dot{\alpha}$ = rate of heat transfer (kW)

ΔT = change in temperature (K)

R_{total} = sum of resistances (K/kW)

Resistances in series are added:

$$R_{\text{total}} = \Sigma R$$

For plane wall conduction resistance (K/kW)

$$R = \frac{L}{kA}$$

where

L = wall thickness

k = thermal conductivity (kW/m-K)

A = wall surface area normal to heat flow (m^2)

For cylindrical wall conduction resistance (K/kW)

$$R = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi kL}$$

where

L = cylinder length

k = thermal conductivity (kW/m-K)

r_1 = cylinder inside radius (m)

r_2 = cylinder outside radius (m)

For convection resistance (K/kW)

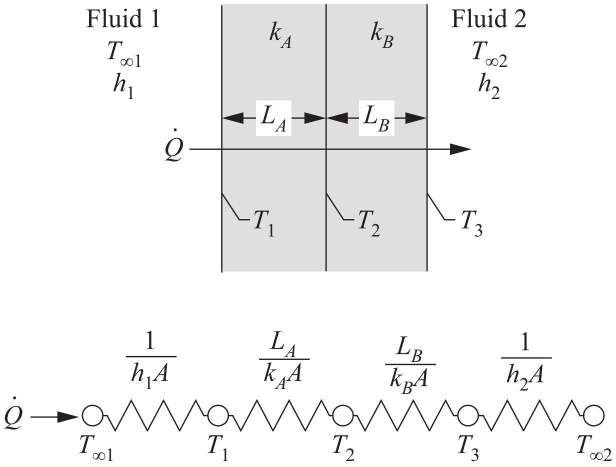
$$R = \frac{1}{hA}$$

where

h = convective heat-transfer coefficient (which depends on the material characteristics, geometry of the solid, and property of the fluid, including fluid parameters) (kW/m^2-K)

A = surface area (m^2)

Composite Plane Wall



To evaluate surface or intermediate temperatures:

$$\dot{Q} = \frac{T_1 - T_2}{R_\mathrm{A}} = \frac{T_2 - T_3}{R_\mathrm{B}}$$

where

$\dot{Q}$ = rate of heat transfer (kW)

$T_1, T_2 \ldots$ = temperature at surface (K)

$R_\mathrm{A}, R_\mathrm{B} \ldots$ = resistance (K/kW)

3.3.2 Convection

Convection is the effect of conduction with the motion of heated fluids. Convection is a significant part of heat transfer through turbulent plumes associated with most fires. The basic convective heat-release rate (per unit area) equation is

$$\dot{q}'' = h\Delta T$$

where

$\dot{q}''$ = convective heat-release rate per unit surface area (kW/m^2)

h = convective heat-transfer coefficient (which depends on the material characteristics, geometry of the solid, and property of the fluid, including fluid parameters) (kW/m^2-K)

ΔT = temperature difference between the fluid and the surface area (K)

3.3.3 Radiation

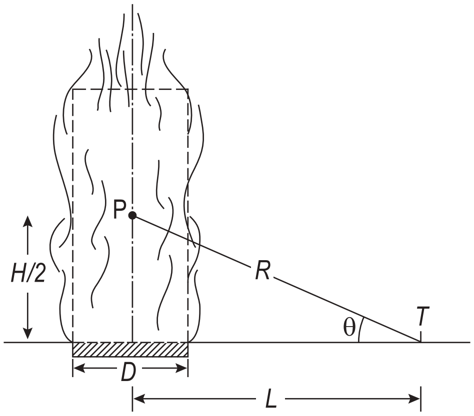
Variations in the predicted versus measured heat fluxes vary considerably between methods. The following table is a summary of methods:

Method	Range of Use (kW/m^2)	Preferred Methods (kW/m^2)
Shokri and Beyler correlation	All heat fluxes, ground level only	--
Point source model	0–5	≤ 5
Shokri and Beyler model	≥ 5	≥ 5
Mudan model	All heat fluxes	--

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.3.3.1 Point-Source Radiation

This model is the simplest configuration of a radiant source and models the flame by a point source located at the center of the real flame. This model assumes a vertical target and θ is the angle between the target's normal and the line of sight from the target to the point-source location:



Nomenclature for Use with the Point-Source Model

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

The heat flux on a target for the point-source model (Drysdale) is given by the equation

$$\dot{q}''_{\mathrm{r}} = \frac{\dot{Q}_{\mathrm{r}} \cos\theta}{4\pi r^2}$$

where

$\dot{q}''_{\mathrm{r}}$ = heat flux on a target perpendicular to radius from the point source (kW/m^2)

$\dot{Q}_{\mathrm{r}}$ = radiative heat release from the fire (typically 20–30% of Q_{total}) (kW)

r = distance from plume center at $H/2$ to the target (m)

θ = angle between the normal to the target and the line of sight from the target to the point-source location (degrees) (The worst case is that $\cos\theta = 1$ and this factor is ignored.)

3.3.3.2 Incident Heat Flux—Shokri and Beyler Correlation

This method assumes that the pool is circular or nearly circular. It also assumes that the target is vertical and located at ground level. Radiant heat flux is maximized near the mid-height of the radiating source. A target facing the center of radiation will give the maximum heat flux at a given location. At heights above ground level, the radiant heat flux is expected to exceed that given by this equation:

$$\dot{q}'' = 15.4\left(\frac{L}{D}\right)^{-1.59}$$

where

$\dot{q}''$ = incident radiant heat flux (kW/m^2)

D = diameter of pool fire (m)

L = distance from center of pool fire to target edge (m)

(The edge of a circular pool has a value of $\frac{L}{D}$ of 0.5.)

The equivalent diameter for noncircular pools is given as

$$D = \sqrt{\frac{4A}{\pi}}$$

where

A = surface area of noncircular pool (m)

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.3.3.3 Radiative Energy Output

$$\dot{Q}_\mathrm{r} = \chi_\mathrm{r}\dot{Q} = (0.21 - 0.0034D)\dot{Q}$$

where

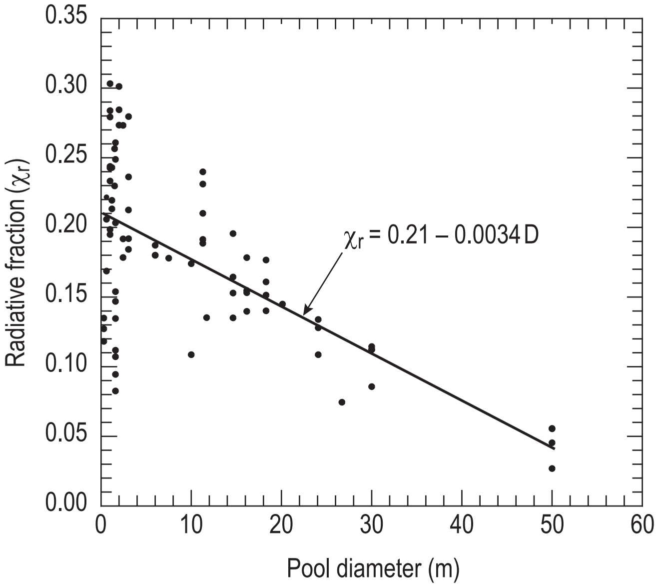
$\dot{Q}_\mathrm{r}$ = total radiative energy output (kW)

χ_r = radiative fraction (dimensionless)

$\dot{Q}$ = total heat release (kW)

D = pool diameter (m)

3.3.3.4 Radiative Fraction (χ_r) as a Function of Pool Diameter



The Solid Line Is a Curve Fit to the Data

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

χ_r = radiative fraction (dimensionless)

D = pool diameter (m)

3.3.3.5 Energy Absorbed (Heat Transfer)

$$E = \varepsilon \times q'' \times A \times t$$

where

E = energy absorbed (kJ)

ε = emissivity (dimensionless)

q'' = heat flux (kW/m^2)

A = exposed area (m^2)

t = time (sec)

3.3.3.6 Emissivity

$$q = \varepsilon \sigma T^4$$

where

q = flame emissive power (W/m^2)

ε = emissivity (1.0 for a black body) (dimensionless)

σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^2–K^4)

T = temperature (K)

3.3.3.7 Emissivity—with Configuration Factor

For targets very near the fire, other methods that account for configuration (shape) factors are required.

Computing shape factors based on the algebraic formulae would take too long in the exam format; therefore, the shape factor will likely be given or read off a graph. It is important to understand the relationship of the source to the target when selecting shape factors. It is also important to understand when shape factors are mathematically combined.

If the emissive power from a surface is known, then it is possible to calculate the intensity of radiation falling at a point at a known distance from the surface by incorporating a configuration or shape factor, Φ:

$$\dot{q}'' = \Phi \varepsilon \sigma T^4$$

where

$\dot{q}''$ = heat flux (W/m^2)

Φ = configuration factor (dimensionless)

ε = emissivity (dimensionless)

σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^2–K^4)

T = temperature (K)

Under steady-state conditions, Kirchhoff's law stipulates that the absorptivity of a surface is equal to its emissivity. Thus, under steady-state conditions, given a known incident heat flux and surface emissivity, the total energy absorbed by the surface can be calculated. In this case the total energy absorbed is also equal to the total energy emitted (i.e., steady state).

$$\dot{q}'' = \left(\sum F\right) \varepsilon \sigma T^4$$

where

$\dot{q}''$ = flame emissive power (kW/m^2)

ε = emissivity (1.0 for a black body) (dimensionless)

σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^2–K^4)

T = absolute temperature (K)

$\sum F$ = sum of configuration factors

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.3.3.8 Net Energy Exchange by Radiation Between Two Bodies

Body small compared to its surroundings:

$$\dot{Q}_{12} = \varepsilon \sigma A \left(T_1^4 - T_2^4\right)$$

where

$\dot{Q}_{12}$ = net heat-transfer rate from the body (W)

ε = emissivity of the body (1.0 for a black body) (dimensionless)

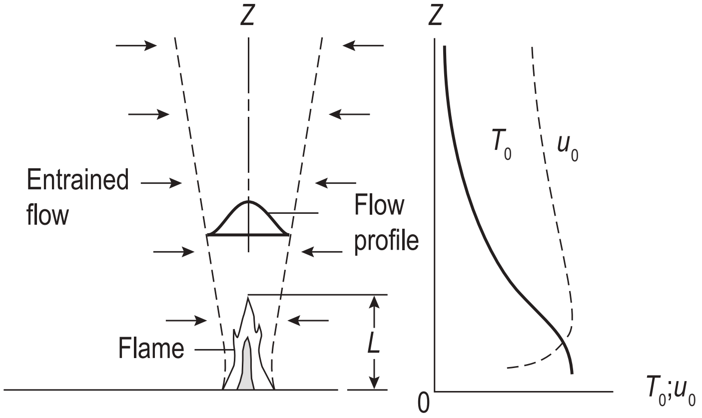
σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^2–K^4)

A = body surface area (m^2)

T_1 = temperature (K) of the body surface

T_2 = temperature (K) of the surroundings

3.4 Plumes and Flames



Features of a Turbulent Fire Plume, Including Axial Variations on the Centerline of Mean Excess Temperature, ΔT_0, and Mean Velocity, u_0

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.4.1 Mean Flame Height

The mean flame height, L, is the distance above the fire source where the intermittency has declined to 0.5. This height marks the level at which the combustion reactions are essentially complete and the inert plume can be considered to begin.

Under normal atmospheric conditions and for most gaseous and liquid fuels:

$$L = H = -1.02D + 0.235\dot{Q}^{2/5}$$

where

L = flame height (m)

H = flame height (m)

D = diameter (m)

$\dot{Q}$ = heat release rate of the pool fire (kW)

The equivalent diameter for noncircular pools is given as

$$D = \sqrt{\frac{4A}{\pi}}$$

where

A = surface area of noncircular pool

However, if the actual lower heat of combustion (H_c) and the actual mass stoichiometric ratio of air to volatiles (r) are known or if atmospheric conditions deviate significantly from normal, the following equation should be used:

$$L = -1.02D + A\dot{Q}^{2/5}$$

where

$$A = 15.6\left[\frac{c_p T_\infty}{g\rho_\infty^2\left(\frac{H_c}{r}\right)^3}\right]^{1/5}$$

where

D = diameter (m)

g = gravity = 9.81 (m/s^2)

c_p = specific heat of air at constant pressure = 1 kJ/kg-K

T_∞ = ambient temperature (K)

ρ_∞ = ambient density = 1.2 (kg/m^3)

H_c = actual lower heat of combustion (kJ/kg)

r = actual mass stoichiometric ratio (dimensionless)

$$Q = 37(L + 1.02D)^{5/2}$$

Note: 0.235 is an average applicable to many gaseous and liquid fuels under normal atmospheric conditions (H_C/r within the range of 2,900–3,200 kJ/kg).

3.4.1.1 Entrained Flow

$\dot{m}_{ent}$ = entrained mass flow rate in plume (kg/s)

$\dot{m}_{ent,L}$ = $\dot{m}_{ent}$ at mean flame height

$\dot{Q}_c$ = convective heat-release rate (kW)

z = height above fire (m)

At the mean flame height, $L(\Delta T_L = 500\text{ K})$:

$$\dot{m}_{ent,L}(\text{kg/s}) = 0.0058\dot{Q}_c(\text{kW})$$

At and below the mean flame height, L, for fire source diameters of 0.3 m and greater:

$$\dot{m}_{ent}(\text{kg/s}) = 0.0058\dot{Q}_c(\text{kW}) \bullet \frac{z}{L}$$

3.4.2 Temperature of Smoke Layer

$$T = T_\infty + \frac{\dot{Q}_c}{Mc_p}$$

where

T = temperature of smoke in plume (K)

T_∞ = ambient temperature (K)

$\dot{Q}_c$ = convective heat-release rate (kW)

M = mass flow rate of plume (kg/s)

c_p = specific heat of air at constant pressure (1 kJ/kg-K)

3.4.3 Plume Centerline Temperature Rise

$$\Delta T_0 = 9.1\left(\frac{T_\infty}{g c_\mathrm{p}^2 \rho_\infty^2}\right)^{1/3} \dot{Q}_\mathrm{c}^{2/3}\left(z - z_0\right)^{-5/3}$$

$$z_0 = -1.02D + 0.083Q^{2/5}$$

where

$\Delta T_0 = T_0 - T_\infty$

ΔT_0 = temperature rise on centerline (K)

T_0 = centerline temperature (K)

T_∞ = ambient temperature (K)

g = gravity = 9.81 (m/s^2)

c_p = specific heat of air at constant pressure (1 kJ/kg-K)

ρ_∞ = ambient density (1.2 kg/m^3)

$\dot{Q}_\mathrm{c}$ = convective heat-release rate (kW)

z = elevation of interest (m)

z_0 = virtual origin (m)

D = effective diameter (m)

Q = total heat-release rate (kW)

$$D = \sqrt{\frac{4A}{\pi}}$$

3.4.4 Plume Radius to Point Where Temperature Rise Has Declined to 0.5 ΔT_0

$$b_{\Delta \mathrm{T}} = 0.12\left(\frac{T_0}{T_\infty}\right)^{1/2}\left(z - z_0\right)$$

where

$b_{\Delta \mathrm{T}}$ = plume radius (m)

T_0 = centerline temperature (K)

T_∞ = ambient temperature (K)

z = elevation above fire source (m)

z_0 = elevation of virtual origin (m)

Plume Centerline Velocity

$$u_0 = 3.4\left(\frac{g}{c_\rho \rho_\infty T_\infty}\right)^{1/3} \dot{Q}_\mathrm{c}^{1/3}\left(z - z_0\right)^{-1/3}$$

where

$\dot{Q}_c$ = convective heat-release rate (kW)

g = gravity (9.81 m/s^2)

T_∞ = ambient temperature (K)

c_p = specific heat of air at constant pressure (1 kJ/kg-K)

ρ_∞ = ambient density (1.2 kg/m^3)

z_0 = virtual origin (m)

z = elevation of interest (m)

3.4.5 Weak Plume Relations for Point Sources

The plume radius and centerline values for mean excess temperature and mean velocity follow these equations:

$$b_{\Delta T} = 0.12\left(\frac{T_0}{T_\infty}\right)^{1/2}\left(z - z_0\right)$$

$$\Delta T_0 = 9.1\left(\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right)^{1/3} \dot{Q}_c^{2/3}\left(z - z_0\right)^{-5/3}$$

$$u_0 = 3.4\left(\frac{g}{c_p \rho_\infty T_\infty}\right)^{1/3} \dot{Q}_c^{1/3}\left(z - z_0\right)^{-1/3}$$

where

$b_{\Delta T}$ = plume radius to the point where the temperature ruse has declined to 0.5 ΔT_0 (m)

ΔT_0 = centerline temperature (K)

$\dot{Q}_c$ = convective heat-release rate (kW)

z = elevation above the fire source (m)

z_0 = virtual origin (m)

u_0 = mean axial velocity on centerline (m/s)

T_∞ = ambient temperature (K)

g = gravity = 9.81 (m/s^2)

c_p = specific heat of air at constant pressure (1 kJ/kg-K)

ρ_∞ = ambient density (1.2 kg/m^3)

At standard temperature and pressure:

The factor $9.1\left(\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right)^{1/3}$ has a value of 25.0 K m$^{5/3}$kW$^{-2/3}$

The factor $3.4\left(\frac{g}{c_p \rho_\infty T_\infty}\right)^{1/3}$ has a value of 1.03 m$^{4/3}$s^{-1}kW$^{-1/3}$

3.4.6 Smoldering Combustion

The core of any combustion process is a global exothermic reaction that results in the release of heat and both gaseous and solid products. Whether smoldering or flaming will be the dominant mode is dictated by which chemical species is oxidized. If the oxidation takes place in the solid phase, smoldering is dominant; if the oxidation takes place in the gas phase, then flaming dominates.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.4.6.1 General Characteristics of Smoldering Combustion

The characteristic temperature, spread rate, and power of smoldering combustion are low compared to flaming combustion. Typical peak temperatures for smoldering are in the range of 450°C to 700°C, although very energetic and dense fuels such as coal can reach peaks at around 1,000°C. The effective heat of combustion taking into account the combustion efficiency is in the range of 6 to 12 kJ/g. These are much lower compared to typical values of around 1,500°C and 16–30 kJ/g, respectively, for flaming combustion. The heat-release rate per unit area of burning front is low and ranges from 10 to 30 kW/m^2. Because of these characteristics and despite the considerable variation in the chemical nature of smoldering fuels, smoldering spreads in a creeping fashion, typically around 1 mm/min, which is two orders of magnitude slower than flame spread.

Forward propagation occurs when the oxygen supply is moving in the direction of the smolder front. Opposed propagation (also called reverse) occurs when the oxygen supply is moving opposite to the smolder front. In general, real smoldering fires are multidimensional and cannot be classified into a single mode.

Forward smolder is faster than opposed, under the same fuel and oxidizer supply, and allows for more complete combustion of the fuel.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.4.6.2 Suppression of Smoldering Combustion

A smoldering fire can be extraordinarily difficult to suppress. Experiments on heaps of coal show that smoldering requires large amounts of water. For example, the amount of water required to suppress smoldering coal was measured to be in the range from 1 to 2 L of water per kg of burning fuel. Moreover, smoldering requires lower oxygen concentration to be smothered, around 10% O_2, compared to 16% O_2 for flaming.

The CO/CO_2 ratio, which can be thought of as an index of the incompleteness of combustion, is ~0.4 in smoldering but ~0.1 in flaming combustion.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.4.6.3 Gas Emissions

The mean particle size of the aerosol in smoldering cellulose was measured to be in the range of 2 to 3 μm; this is about 50–200 times larger than the sooty particulates produced by flaming combustion.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.4.7 Opposed-Flow Flame Spread

ϕ is a parameter that can be quantified with bench scale testing:

$$V_p \asymp \frac{\phi}{k\rho c\left(T_{ig} - T_0\right)^2}$$

where

V_p = flame spread velocity (m/s)

k = conductivity [W/(m°C)]

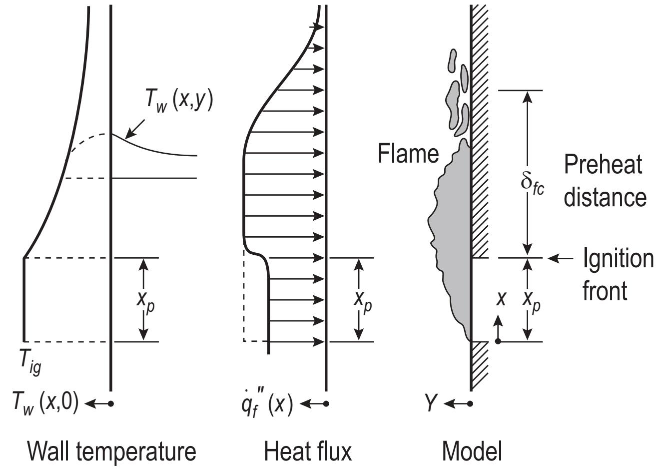
ρ = density (kg/m^3)

c = specific heat [J/(kg°C)]

T_{ig} = temperature at ignition (°C)

T_0 = initial temperature (°C)

3.4.8 Wind-Aided Flame Spread Velocity on Thermally Thick Solid



Upward Wall Flame Spread

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

The flame spread occurs in two manners: advancement of the flame front and advancement of the ignition front of the solid surface. The location of the ignition front is identified as the location where the surface temperature has reached the ignition temperature.

$$V_p = \frac{4\dot{q}''^{2}_{fc}\delta_{fc}}{\pi k \rho c\left(T_{ig} - T_0\right)^2} = \frac{\left(x_{fc} - x_p\right)}{t^*_{ig}}$$

$$t^*_{ig} = \frac{\pi k \rho c\left(T_{ig} - T_0\right)^2}{4\dot{q}''^{2}_{fc}}$$

where

V_p = characteristic steady-flame spread velocity (m/s)

x_{fc} = characteristic flame height (m)

$$x_{fc} = x_p + \delta_{fc}$$

x_p = pyrolysis front length (m)

t^*_{ig} = characteristic time to ignition (sec)

δ_{fc} = characteristic preheat distance, essentially the distance between the flame front and the ignition front

k = thermal conductivity (kW/m-K)

ρ = density (kg/m^3)

c = heat capacity (kJ/kg-K)

T_{ig} = ignition temperature of the material (K)

T_0 = initial surface temperature (K)

$\dot{q}''_{fc}$ = characteristic flame heat flux (kW/m^2)

3.5 Flammable and Combustible Liquids Fires

3.5.1 Pool Fires Mass Loss Rate

$$\dot{m}'' = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right)$$

where

$\dot{m}''$ = mass loss rate per unit area (kg/m^2–s)

$\dot{m}''_{\infty}$ = mass loss rate per unit area for an infinite pool diameter (kg/m^2–s)

D = pool diameter (m)

$k\beta$ = extinction absorption coefficient (m^{-1})

3.5.2 Liquid Fuel Flame Height (Mean Flame Height)

See Section 3.4.1

3.5.3 Burning Duration of Pool Fire

3.5.3.1 Actual Burning Duration

$$t_{\text{b,a}} = \frac{\text{Mass of liquid}}{\text{Mass burning rate}} \bullet \frac{V_{\rho}}{A\dot{m}''} = \frac{m}{A\dot{m}''} = \frac{4m}{\pi D^2 \dot{m}''}$$

where

$t_{\text{b,a}}$ = actual burning duration (sec)

m = mass of liquid (kg)

V = volume of liquid (m^3)

$\dot{m}''$ = mass loss rate per unit area (kg/m^2–s)

ρ = density of liquid (kg/m^3)

A = burning surface area (m^2)

D = burning surface diameter (m)

3.5.3.2 Idealized Burning Duration

$$t_{\text{b,I}} = \frac{\text{Mass of liquid}}{\text{Mass burning rate}} \bullet \frac{V_{\rho}}{A\dot{m}''_{\infty}} = \frac{m}{A\dot{m}''_{\infty}} = \frac{4m}{\pi D^2 \dot{m}''_{\infty}}$$

where

$t_{b,I}$ = idealize burning duration (s)

m = mass of liquid (kg)

V = volume of liquid (m^3)

$\dot{m}''_{\infty}$ = mass loss rate per unit area (kg/m^2–s)

= peak mass burning rate of the fuel per unit area (kg/m^2–s)

D = burning surface diameter (m)

ρ = density of liquid (kg/m^3)

A = burning surface area (m^2)

3.5.4 HRR from Liquid Pool Fire

The empirical relationship for predicting the heat-release rate from liquid pool fires is

$$\dot{q} = \Delta h_c \dot{m}''_\infty \left(1 - e^{-k\beta D}\right) A$$

where

$\dot{q}$ = heat release rate (kW)

D = pool diameter (m)

$\dot{m}''_\infty$ = mass loss rate per unit area for an infinite pool diameter (kg/m^2/s)

$-k\beta$ = extinction-absorption coefficient (m^{-1})

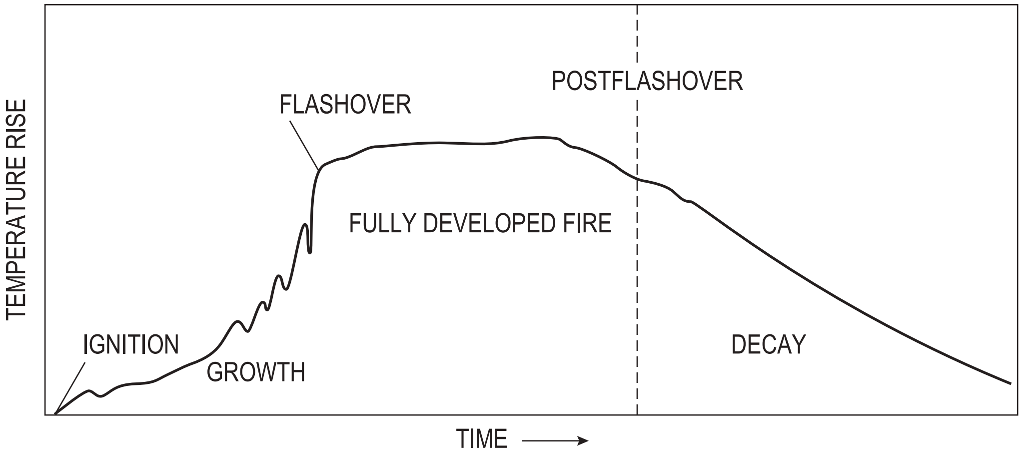
Δh_c = net heat of combustion (kJ/kg)

A = area of pool (m^2)

3.6 Compartment Fires

Compartment fires are often discussed in terms of growth stages:

- Ignition
- Growth
- Flashover
- Fully developed
- Decay



Temperature Rise Over Time of a Typical Room Fire in the Absence of Fire Control

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

The following is taken from this source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

The total surface area of a compartment is calculated as

$$A_T = A_{floor} + A_{walls} + A_{ceiling} - A_{openings}$$

3.6.1 Ventilation Factor

The ventilation factor is defined as

$$A_O\sqrt{H_O}$$

where

A_O = area of opening (m^2)

H_O = height of opening (m)

3.6.2 Preflashover Compartment Temperatures—with Mechanical Ventilation

The following is an equation for forced ventilation fires based on the method of Foote et al:

$$\frac{\Delta T_g}{T_\infty} = 0.63\left(\frac{\dot{Q}}{m_g T_\infty c_p}\right)^{0.72}\left(\frac{h_k A_T}{m_g c_p}\right)^{-0.36}$$

where

$\Delta T_g = T_g - T_\infty$

ΔT_g = upper gas temperature rise above ambient (K)

T_g = upper gas temperature (K)

T_∞ = ambient gas temperature (K)

$\dot{Q}$ = total heat release rate (kW)

h_k = effective heat-transfer coefficient (kW/m^2-K)

A_T = total area of compartment enclosing surfaces (m^2)

c_p = specific heat of gas (kJ/kg-K)

m_g = compartment mass ventilation rate (kg/s)

$$m_g = \dot{V} = \left(1.18\ \mathrm{kg/m^3}\right)$$

where

$\dot{V}$ = ventilation flow rate (m^3/s)

Note: 1 cfm = .00047 m^3/s

3.6.3 Preflashover Compartment Temperatures—with Natural Ventilation

$$\Delta T_g = 480\left[\frac{\dot{Q}}{\sqrt{g}\left(c_p\rho_\infty T_\infty A_O\right)\sqrt{H_O}}\right]^{2/3}\left[\frac{h_k A_T}{\sqrt{g}\left(c_p\rho_\infty A_O\right)\sqrt{H_O}}\right]^{-1/3}$$

where

$\Delta T_g = T_g - T_\infty$

ΔT_g = upper gas temperature rise above ambient (K)

T_g = upper gas temperature (K)

T_∞ = ambient gas temperature (K)

$\dot{Q}$ = total heat-release rate (kW)

h_k = effective heat-transfer coefficient (kW/m^2-K)

A_T = total area of compartment enclosing surfaces (m^2)

A_O = area of opening (m^2)

H_O = height of opening (m)

g = 9.81 (m/s^2)

c_p = 1.0 kJ/kg-K (specific heat)

ρ_∞ = 1.2 kg/m^3 (ambient air density)

T_∞ = 295 K

3.6.4 Preflashover Compartment Temperatures—with Natural Ventilation at Standard Temperature and Pressure

The following is a simplified equation for naturally ventilated fire assuming typical values for ambient conditions, based on the method of McCaffrey et al:

$$\Delta T_g = 6.85\left(\frac{Q^2}{h_k A_T A_O \sqrt{H_O}}\right)^{1/3}$$

where

$\Delta T_g = T_g - T_\infty$

ΔT_g = upper gas temperature rise above ambient (K)

T_g = upper gas temperature (K)

T_∞ = ambient gas temperature (K)

Q = total heat-release rate (kW)

h_k = effective heat-transfer coefficient (kW/m^2-K) [see Section 3.6.5 for calculation of h_k]

A_T = total area of compartment enclosing surfaces (m^2)

A_O = area of opening (m^2)

H_O = height of opening (m)

3.6.5 McCaffrey Flashover Heat-Release Equations

$$Q_{fl} = 610\left(h_k A_T A_O \sqrt{H_O}\right)^{1/2}$$

where

Q_{fl} = heat-release rate required for flashover (kW)

h_k = effective heat-transfer coefficient (kW/m^2-K)

A_T = total area of compartment surfaces (m^2)

A_O = area of opening (m^2)

H_O = height of opening (m)

Determine thermal penetration time (t_p):

$$t_p = \left(\frac{\rho c}{k}\right)\left(\frac{\delta}{2}\right)^2$$

where time of exposure (t) > thermal penetration time (t_p)

$$h_k = \frac{k}{\delta}$$

where $t \le t_p$

$$h_k = \left(\frac{k\rho c}{t}\right)^{1/2}$$

k = thermal conductivity of wall material (kW/m-K)

δ = thickness (m)

where

ρ = density of compartment surface (kg/m^3)

c = specific heat of compartment surface material (kJ/m-K)

k = thermal conductivity of compartment surface (kW/m-K)

d = thickness of compartment surface (m)

3.6.6 Flashover References

Flashover is at 20 kW/m^2 or 500–600°C.

3.6.7 Heat Release Rate Needed for Flashover

This is a simplified method for predicting the heat-release rate needed to cause flashover, using the Babrauskas method:

$$\dot{Q} = 750 A_O \sqrt{H_O}$$

Using the Thomas method, the equation is as follows:

$$\dot{Q} = 7.8 A_T + 378 A_O \left(H_O\right)^{1/2}$$

where

A_T = total area of the compartment enclosing surfaces (m^2)

A_O = area of opening (m^2)

$\dot{Q}$ = heat-release rate required to cause flashover (kW)

H_O = height of opening (m)

3.6.8 Post-Flashover Compartment Temperature

Use Law's formula to calculate post-flashover compartment fire temperatures:

$$T_{g(\max)} = 6{,}000\frac{\left(1 - e^{-0.1\Omega}\right)}{\sqrt{\Omega}}$$

$$\Omega = \frac{\left(A_T - A_O\right)}{A_O\sqrt{H_O}}$$

where

A_T = total area of compartment enclosing surfaces (m^2)

A_O = area of opening (m^2)

H_O = height of opening (m)

$T_g = T_{g(max)}\left(1 - e^{-0.05\Psi}\right)$

where

T_g = average temperature in the compartment (°C)

$$\Psi = \frac{L}{\left[A_O\,(A_T - A_O)\right]^{1/2}}$$

where

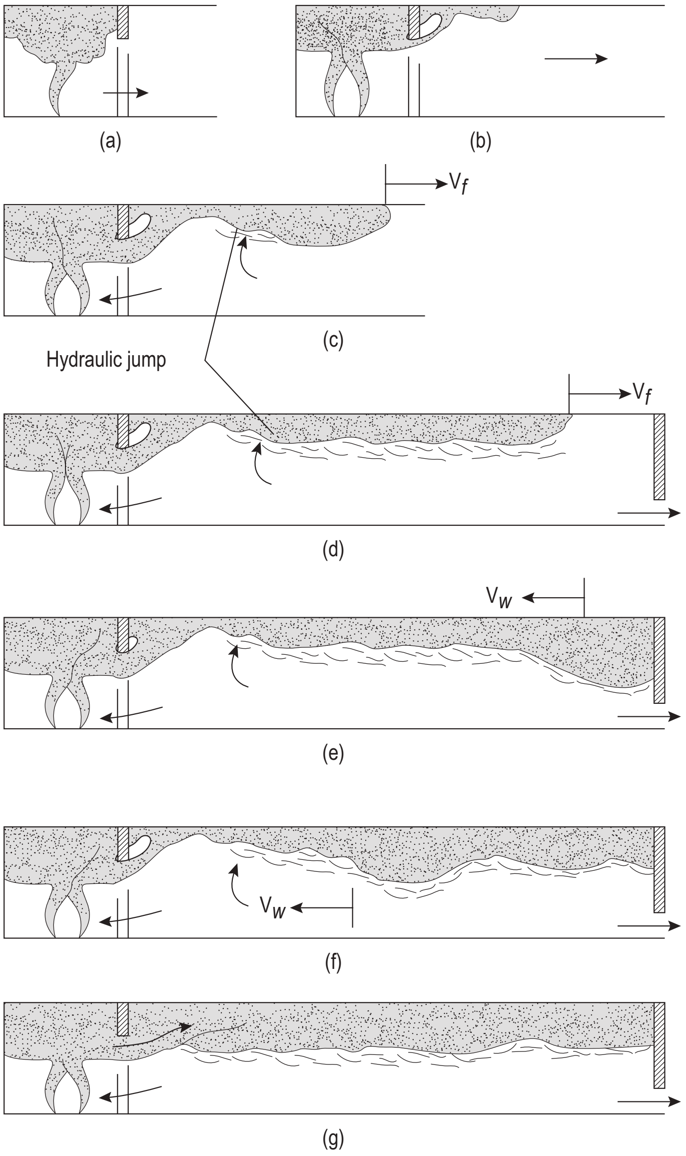
L = fire load equivalent to wood (kg)

A_T = total area of compartment enclosing surfaces (m^2)

A_O = area of opening (m^2)

Ψ fire-loading calculation can be assumed 1 where only upper layer temperature is requested.

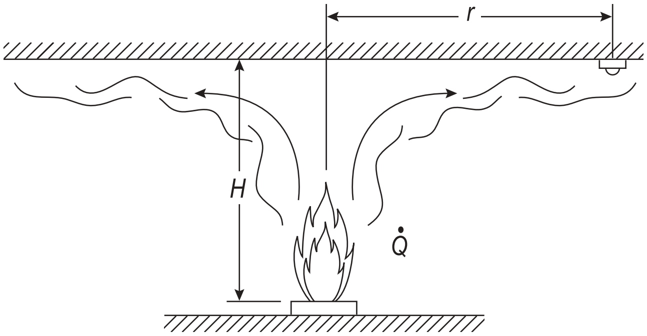
3.6.9 Transient Ceiling Jet Flow in a Room



Transient Ceiling Jet Flow in a Room and Corridor

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.6.10 Ceiling Jet Flow Beneath an Unconfined Ceiling



Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Equations below are for axisymmetric fires, where the fire source is away from the enclosure walls. These correlations were developed for data where the fire source was at a distance from the enclosure walls of at least 1.8 times the ceiling height. Where the fire source is against a flat wall, use $2\dot{Q}$ instead of $\dot{Q}$. Where the fire source is in a 90° corner, use $4\dot{Q}$ instead of $\dot{Q}$.

3.6.10.1 Weak Plume-Driven Temperature of Ceiling Jet (Alpert)

$$T_{\max} - T_\infty = 16.9\frac{\dot{Q}^{2/3}}{H^{5/3}} \text{ for } \frac{r}{H} \le 0.18$$

$$T_{\max} - T_\infty = 5.38\frac{\left(\dfrac{\dot{Q}^{2/3}}{H^{5/3}}\right)}{\left(\dfrac{r}{H}\right)^{2/3}} \text{ for } \frac{r}{H} > 0.18$$

where

$T_{\max}$ = maximum temperature (°C)

T_∞ = ambient temperature (°C)

$\dot{Q}$ = total heat-release rate (kW)

H = distance from fire source to ceiling (m)

r = radial distance from plume centerline (m)

3.6.10.2 Weak Plume-Driven Velocity of Ceiling Jet (Alpert)

$$U = 0.947\left(\frac{\dot{Q}}{H}\right)^{1/3} \text{ for } \frac{r}{H} \le 0.15$$

$$U = 0.197\frac{\left(\dfrac{\dot{Q}}{H}\right)^{1/3}}{\left(\dfrac{r}{H}\right)^{5/6}} \text{ for } \frac{r}{H} > 0.15$$

where

U = maximum ceiling-jet gas velocity (m/s)

$\dot{Q}$ = total heat-release rate (kW)

H = distance from fire source to the ceiling (m)

r = radial distance from plume centerline (m)

Many of the correlations described hereafter were developed from tests involving heat-release rates that ranged from 600 kW to 98 MW and total ceiling heights that ranged from 4.6 m to 18 m. These data should be considered limitations when using the correlations.

3.6.10.3 Strong Plume-Driven Plume Fields

When the flame height is comparable to the ceiling height above the burning fuel, the resulting ceiling jet is driven by a strong plume.

$$b_{\Delta T} = 0.12\left(\frac{T_0}{T_\infty}\right)^{1/2}\left(z - z_0\right)$$

$$\Delta T_0 = 9.1\left(\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right)^{1/3}\dot{Q}_{\mathrm{c}}^{2/3}\left(z - z_0\right)^{-5/3}$$

$$u_0 = 3.4\left(\frac{g}{c_p \rho_\infty T_\infty}\right)^{1/3}\dot{Q}_{\mathrm{c}}^{1/3}\left(z - z_0\right)^{-1/3}$$

where

$b_{\mathrm{D}T}$ = plume radius to the point where the temperature rise has declined to 0.5 $\Delta T_{0\,\mathrm{(m)}}$

T_0 = centerline temperature (K)

T_∞ = ambient temperature (K)

z = elevation above the fire source (m)

z_0 = elevation of the virtual origin (see Section 3.1.11.1)

g = acceleration of gravity (m/s^2)

c_{p} = specific heat of air at constant pressure (kJ/kg-K)

ρ_∞ = ambient density (kg/m^3)

$\dot{Q}_c$ = convective heat-release rate (kW/m^2-K)

u_0 = mean velocity (m/s)

3.6.11 Vent Flows

Two-layer method:

$$\text{Outflow } u_{\mathrm{u}} = \left(2g\,\frac{\rho_{\mathrm{a}} - \rho}{\rho}\,y\right)^{1/2}$$

where

u_{u} = velocity of upper layer (m/s)

y = distance above neutral plane (m)

ρ_{a} = atmospheric air density (kg/m^3)

ρ = upper layer air density (kg/m^3)

$$\dot{m}_\text{u} = \frac{2}{3} Cb \sqrt{2g\rho(\rho_\text{a} - \rho)} \left(h_\text{v} - h_\text{n}\right)^{3/2}$$

where

$\dot{m}_\text{u}$ = mass flow rate of upper layer (kg/s)

b = width of vent (m)

C = experimentally determined flow coefficient (0.68)

h_v = height of vent (m)

h_n = height of neutral plane (m)

ρ_a = atmospheric air density (kg/m^3)

ρ = upper layer air density (kg/m^3)

Mass conservation:

$$\frac{d}{dt}(\rho V_\text{R}) = \sum\left(-\dot{m}_{ij} + \dot{m}_{ji}\right)$$

Heat conservation:

$$c_\text{p} \frac{d}{dt}\left(\rho V_\text{R} T\right) = \dot{Q} - \dot{Q}_\text{h} + c_\text{p} \sum\left(-\dot{m}_{ij} T + \dot{m}_{ji} T_j\right)$$

Ideal gas law:

$$\rho T = \frac{Mp}{R}$$

where

c_p = specific heat at constant pressure (kJ/kg-K)

M = average molecular weight of flowing gas (kg/kg or mol)

p = pressure (Pa)

R = universal gas constant = 8.314 J/K-mol

ρ = density (kg/m^3)

T = temperature (K)

j = index of adjacent room connected by vents with the room considered

V, V_R = volume of the room (m^3)

$\dot{m}_{ij}$ = mass outflow rate from room i to an adjacent room j (kg/s)

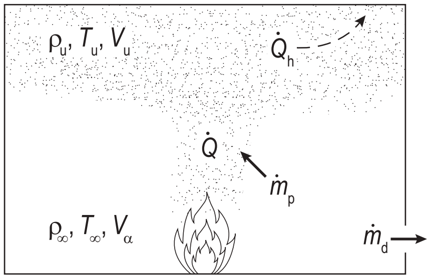
$\dot{m}_{ji}$ = mass inflow rate to room i from an adjacent room j (kg/s)

$\dot{Q}$ = heat-release rate of fire source (kW)

$\dot{Q}_\text{h}$ = heat loss from the room gas due to heat transfer (kW)

$\sum$ = summation with respect to all the vents between all the adjacent rooms

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.



Fire Room at the Stage of Smoke Layer Filling
Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Mass inflow and outflow rates through the vent, $\dot{m}_d$ and $\dot{m}_u$, are given as a function of the neutral plane height, h_n:

$$\dot{m}_d = \frac{\sqrt{2}}{3} Cb\sqrt{2g\rho_a\left(\rho_a - \rho\right)}\,h_n^{3/2} \qquad \text{(inflow)}$$

$$\dot{m}_u = \frac{\sqrt{2}}{3} Cb\sqrt{2g\rho_a\left(\rho_a - \rho\right)}\left(h_v - h_n\right)^{3/2} \qquad \text{(outflow)}$$

$$h_n = \frac{h_v}{1 + \left(\dfrac{\rho_a}{\rho}\right)^{1/3}} = \frac{h_v}{1 + \left(\dfrac{T}{T_a}\right)^{1/3}}$$

where

g = gravity constant (m/s^2)

b = width (m)

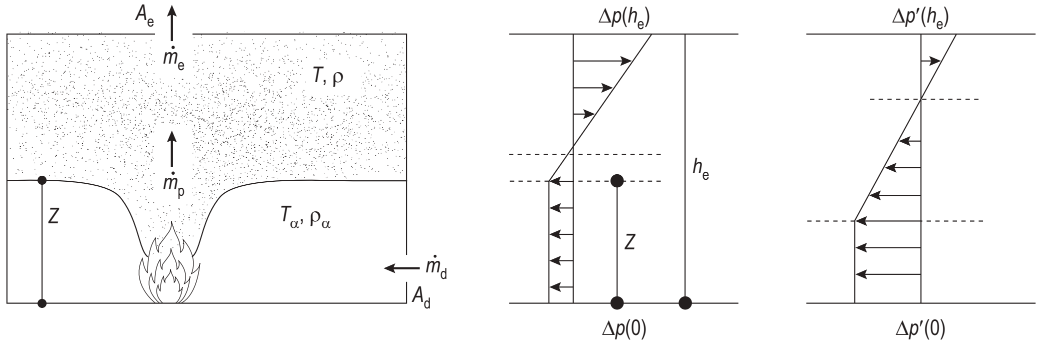
h_v = ventilation opening height (m)

h_n = neutral plane height (m)

ρ_a = density of the cold (lower) layer (kg/m^3)

ρ = density of the hot (upper) layer (kg/m^3)

3.6.12 Required Smoke Vent Area



(a) NATURAL SMOKE VENTING CONFIGURATION

(b) PRESSURE DIFFERENCE PROFILE FOR LARGE A_d

(c) PRESSURE DIFFERENCE PROFILE FOR SMALL A_d

Configuration and Pressure Profile of Natural Smoke Venting
Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

1. Calculate the plume flow rate $(\dot{m})$at layer interface height y_c:

$$\dot{m} = 0.08\dot{Q}^{1/3} y_c^{5/3}$$

where

y_c = layer interface height (m)

$\dot{m}$ = plume mass flow rate (kg/s)

$\dot{Q}$ = heat release rate (kW)

2. Calculate the smoke layer temperature (T):

$$T = T_a + \frac{\dot{Q}}{c_p m + a_k A_w}$$

where

$\dot{Q}$ = heat release rate (kW)

a_k = effective heat-transfer coefficient (kW/m^2-K)

T = smoke layer temperature (K)

T_a = room ambient air temperature (K)

A_w = boundary wall area exposed to heat transfer from smoke layer (m^2)

m = mass (kg)

c_p = specific heat at constant pressure (kJ/kg-K)

3. Calculate the smoke layer density (ρ):

$$\rho = \frac{352.8}{T}$$

where

ρ = smoke layer density (kg/m^3)

T = smoke layer temperature (K)

4. Calculate the pressure Δ[$\Delta p(0)$] at floor level:

$$\Delta p(0) = \frac{\dot{m}^2}{2\rho_a (CA_d)^2}$$

where

$\dot{m}$ = plume mass flow rate (kg/s)

ρ_a = air density (kg/m^3)

C = experimentally determined flow coefficient (0.68)

A_d = area of inflow vent near floor (m^2)

5. Calculate the pressure at the smoke vent [$\Delta p(h_c)$] :

$$\Delta p(h_e) = -\Delta p(0) + (\rho_a - \rho) g (h_e - y_c)$$

h_e = smoke vent height (m)

y_c = layer interface height (m)

ρ_a = air density (kg/m^3)

p = smoke layer density (kg/m^3)

$\Delta p(0)$ = pressure at floor level (ρ_a)

6. Calculate the smoke vent area, A_e:

$$A_e = \frac{\dot{m}}{C\sqrt{2\rho\left[\Delta p\left(h_e\right)\right]}}$$

where

A_e = area (m^2)

h_e = smoke vent height (m)

y_c = layer interface height (m)

ρ_a = air density (kg/m^3)

p = smoke layer density (kg/m^3)

$\Delta p(0)$ = pressure at floor level (ρ_a)

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.6.13 Smoke Characterization and Damage Potentials

The governing mode of smoke deposition is primarily dependent on whether the transport flow is turbulent or laminar and on the particle size. The flow type can be classified by the magnitude of the particle Reynolds number:

$$Re_p = \frac{\rho_g d_p V}{\eta}$$

where

ρ_g = gas density (kg/m^3)

d_p = particle diameter (m)

V = particle velocity (m/s)

η = gas viscosity (kg/s-m)

Laminar flow occurs when the Reynolds number is less than 1 ($Re_p < 1$).

Turbulent flow occurs when the Reynolds number is greater than 1 ($Re_p > 1$).

3.6.13.1 Laminar Flow—Smoke Particles > 1 µm

The following equation applies for smoke particles > 1µm:

$$V_{TS} = \frac{\rho_p d_p^2 g}{18\eta}$$

where

ρ_g= particle density (kg/m^3)

d_p = particle aerodynamic equivalent diameter (m)

g = gravitational acceleration (9.81 m/s^2)

V_{TS} = particle terminal settling velocity (m/s)

3.6.13.2 Laminar Flow—Smoke Particles < 1 μm

The following equation for slip correction applies for smoke particles < 1μm:

$$C_c = 1 + \frac{2.52\Lambda}{d_p}$$

where

C_c = slip correction factor (dimensionless)

Λ = mean free path (μm), which is 0.066 μm for air at 1 atm and 20°C

d_p = particle diameter (μm)

This slip correction factor applies to the right-hand side of the equation for Laminar Flow – Smoke Particles > 1 μm, increasing the terminal settling velocity.

3.6.13.3 Turbulent Flow—Smoke Particles > 1 μm

$$V_{\text{TS}} = \left(\frac{4\rho_p d_p g}{3C_D \rho_g}\right)^{1/2}$$

where

V_{TS} = particle terminal settling velocity (m/s)

C_D = drag coefficient (dimensionless)

ρ_p = particle density (kg/m^3)

d_p = particle diameter (m)

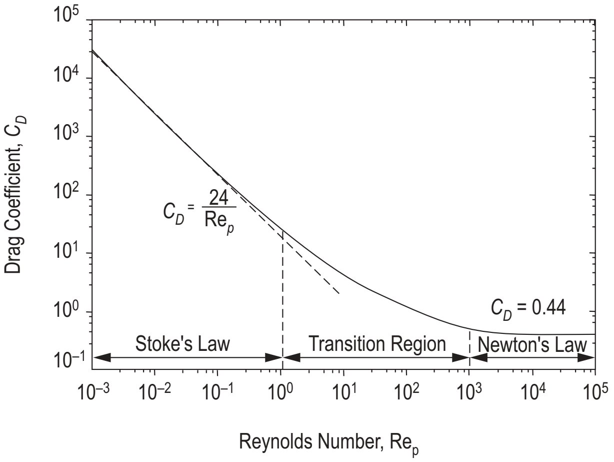
g = gravity constant (m/s^2)

ρ_g = gas density (kg/m^3)

3.6.13.4 For Reynolds Number Greater than 1 and Less than 1,000 (1 < Re_p < 1,000)

$$C_D = \frac{24}{Re_p}\left(1 + 0.15\,Re_p^{0.687}\right)$$

3.6.13.5 Turbulent Flow—Smoke Particles < 1 µm



Drag Coefficient Versus Particle Reynolds Number

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

$$D = \frac{k_\beta T C_c}{3\pi\eta d_p}$$

where

D = particles' diffusion coefficient (m^2/s)

k_β = Boltzmann constant = 1.380649×10^{-23} J/K

T = temperature (K)

C_c = slip correction factor (dimensionless)

η = gas viscosity (Pa-s)

d_p = particle diameter (m)

3.6.14 Light Transmission Through Smoke

$$\frac{I}{I_0} = \exp\left(-OD_\lambda l\right)$$

where

I = transmitted intensity (cd)

I_0 = initial intensity (cd)

OD_λ = optical density (m^{-1})

l = optical path length (m)

$$f_v = \frac{OD_\lambda \lambda}{c}$$

where

OD_λ = optical density (m^{-1})

f_v = smoke volume fraction

λ = incident wavelength (m)

c = average coefficient of smoke extinction (dimensionless)

3.6.15 Smoke Mass Concentration

$$C_s = \rho_s f_v = \frac{\rho_s OD_\lambda \lambda}{c}$$

where

C_s = smoke mass concentration (kg/m^3)

f_v = smoke volume fraction

ρ_s = smoke particle density (kg/m^3)

OD_λ = optical density (m^{-1})

λ = incident wavelength (m)

c = average coefficient of smoke extinction (dimensionless)

Terminal settling velocity is

$$V_{TS} = \frac{\rho_0 d_a^2 g}{18\eta}$$

where

V_{TS} = terminal settling velocity (m/s)

ρ_0 = standard particle density (kg/m^3)

d_a = aerodynamic equivalent diameter (m)

g = gravitational acceleration (m/s^2)

η = gas viscosity (kg/s-m)

Aerodynamic Mass Mean Diameter of Smoke from Flaming Plastics

Material	d_{ag} (μm)	σ_g	Environment
Nylon	0.4	2.0	1.0 m^3 smoke box
Polycarbonate	3.0	3.4	1.0 m^3 smoke box
Polyethylene	1.0	2.5	1,200 m^3 enclosure
Polymethylmethacrylate	2.3	4.4	1,200 m^3 enclosure
	0.7–1.0	NR	0.37 m^2 duct [28]
Polypropylene	1.2	2.0	1,200 m^3 enclosure
Polyurethane	2.0	1.8	0.18 m^2 duct [29]
Polyvinylchloride	1.1	1.8	1.0 m^3 smoke box
Polystyrene	2.0	2.6	1.0 m^3 smoke box
	2.4	2.1	1,200 m^3 enclosure
	1.5–2.5	NR	0.37 m^2 duct [28]

NR Not reported

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.6.16 Mass Burning Rate

The formula to estimate the mass burning rate of the fuel can be given as

$$\dot{m}_{\mathrm{f}} = \frac{qA}{L}$$

where

$\dot{m}_{\mathrm{f}}$ = mass burning rate of the fuel (kg/s)

q = heat flux to the fuel surface (kW/m^2)

A = surface area of the fuel (m^2)

L = heat of gasification (kJ/kg)

The rate of energy release is equal to the mass loss rate of the fuel times the heat of combustion of the fuel:

$$\dot{Q} = \dot{m}_{\mathrm{f}} \Delta h_{\mathrm{c}}$$

where

$\dot{Q}$ = energy release rate of the fire (kW)

$\dot{m}_{\mathrm{f}}$ = mass burning rate of the fuel (kg/s)

Δh_{c} = effective heat of combustion of the fuel (kJ/kg)

3.6.17 Heat-Release Rate

$$\dot{Q} = \dot{m}_{\mathrm{g}} c_{\mathrm{p}} \left(T_{\mathrm{g}} - T_{\infty} \right) + q_{\mathrm{loss}}$$

where

$\dot{Q}$ = energy-release rate of the fire (kW)

$\dot{m}_{\mathrm{g}}$ = gas flow-rate out of the opening (kg/s)

c_{p} = specific heat of gas (kJ/kg-K)

T_{g} = temperature of the upper gas layer (K)

T_{∞} = ambient temperature (K)

q_{loss} = net radiative and convective heat transfer from the upper gas layer (kW)

3.6.18 Rate of Heat Transfer to Surfaces

The rate of heat transfer to the surfaces is approximated by

$$q_{\mathrm{loss}} = h_{\mathrm{k}} A_{\mathrm{T}} \left(T_{\mathrm{g}} - T_{\infty} \right)$$

where

h_{k} = effective heat-transfer coefficient (kW/m^2-K)

A_{T} = total area of the compartment enclosing surfaces (m^2)

T_{g} = temperature of the upper gas layer (K)

T_{∞} = ambient temperature (K)

3.6.19 Heat-Release Rate with Natural Ventilation

$$\dot{Q} = 610\left(h_k A_T A_O \sqrt{H_O}\right)^{1/2}$$

where

h_k = effective heat-transfer coefficient (kW/m^2-K)

A_T = total area of compartment enclosing surfaces (m^2)

A_O = area of opening (m^2)

H_O = height of opening (m)

Alternatively, the equation is sometimes expressed using a coefficient of 620 (instead of 610). This is based on a difference in the value used for the specific heat of air. The use of either 610 or 620 is acceptable within the accuracy of the expression.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

3.6.20 Fire-Generated Environmental Conditions

$$\rho Y_i = \frac{\left(\frac{Q_f}{V}\right)}{\left(\frac{\Delta H_c}{f_i}\right)}$$

where

ρY_i = mass concentration of species i (kg$_i$/m^3)

$\left(Q_f / V\right)$ = fire heat-release per unit volume of the control volume (kJ/m^3)

$\left(\Delta H_c / f_i\right)$ = species heat of combustion (kJ/kg$_i$)

$$\Delta T_{g,\lim} = \frac{\Delta H_c}{r_{air}} \frac{\chi_{O_2,\lim}\left(1 - \chi_1\right)}{c_p}$$

where

$\Delta T_{g,\lim}$ = upper gas temperature rise above ambient (K)

ΔH_c = fuel heat of combustion (kJ/kg)

$\chi_{O_2,\lim}$ = fraction of oxygen that can be consumed before extinction (dimensionless)

χ_1 = heat loss factor (dimensionless)

r_{air} = air stoichiometric ratio (kg air/kg fuel)

c_p = specific heat at constant pressure (kJ/kg-K)

$$K = K_m \rho Y_{soot}$$

where

K_m = specific light-extinction coefficient (m^2/kg)
Suggested: 7,600 m^2/kg for flaming combustion; 4,400 m^2/kg for smoke produced by pyrolysis; and 8,700 m^2/kg for flaming combustion of wood and plastic fuels

ρY_{soot} = soot mass concentration (kg_{soot}/m^3)

K = light-extinction coefficient (m^{-1})

$$\frac{I}{I_0} = e^{-KL}$$

where

$\frac{I}{I_0}$ = light attenuation

I = intensity of incident light (cd)

I_0 = intensity of light through smoke (cd)

K = light-extinction coefficient (m^{-1})

L = light path length (m)

$$S = \frac{C}{K}$$

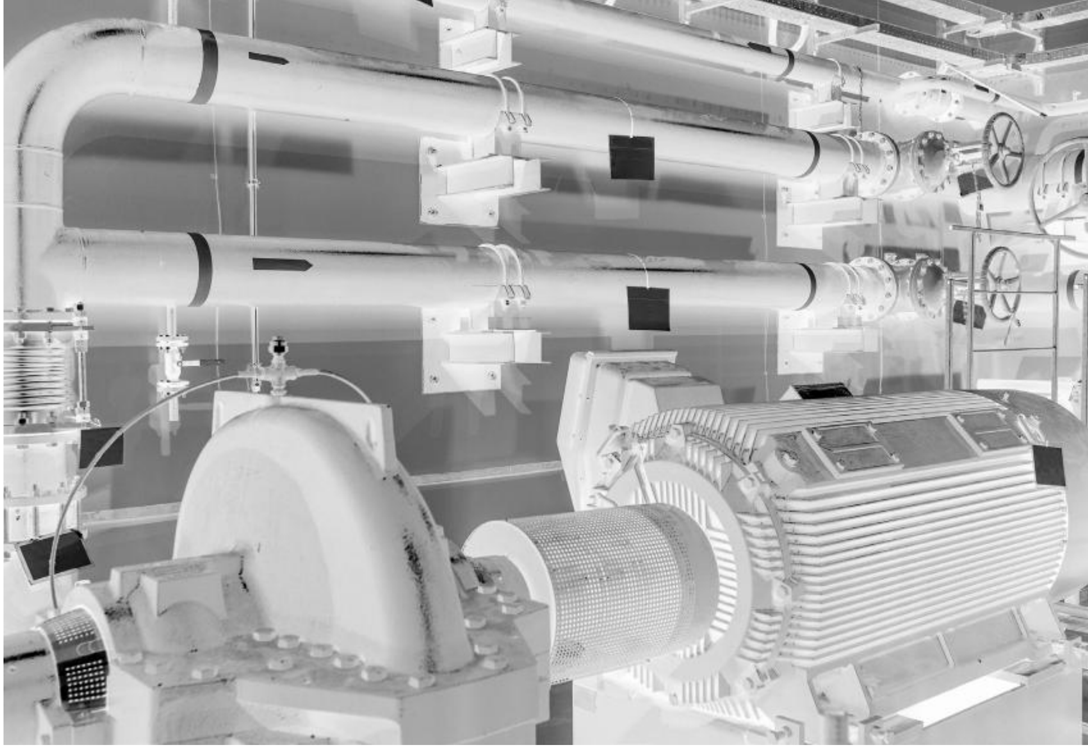
where

S = visibility distance (m)

C = nondimensional constant associated with the object being viewed through smoke (dimensionless)
Suggested: 8 for light-emitting signs; 3 for light-reflecting signs

K = light-extinction coefficient (m^{-1})

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.



4 WATER-BASED EXTINGUISHING SYSTEMS

4.1 Fluid Mechanics

4.1.1 Density, Specific Volume, Specific Weight, and Specific Gravity

The definitions of density, specific weight, and specific gravity follow:

$$\rho = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V}$$

$$\gamma = \lim_{\Delta V \to 0} \frac{\Delta W}{\Delta V}$$

$$\gamma = \lim_{\Delta V \to 0} \frac{g \bullet \Delta m}{\Delta V} = \rho g$$

Also $SG = \dfrac{\gamma}{\gamma_w} = \dfrac{\rho}{\rho_w}$

where

ρ = density (also called mass density)

Δm = mass of infinitesimal volume

ΔV = volume of infinitesimal object considered

γ = specific weight = ρg

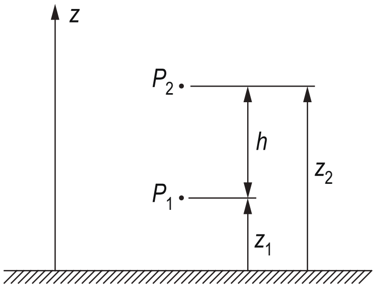
ΔW = weight of an infinitesimal volume

SG = specific gravity

ρ_w = density of water at standard conditions = 1,000 kg/m^3 (62.4 lbm/ft^3)

γ_w = specific weight of water at standard conditions = 9,810 N/m^3 (62.4 lbf/ft^3) = 9,810 $kg/m^2 \bullet s^2$

4.1.2 Characteristic of a Static Liquid



The Pressure Field in a Static Liquid
Bober, W., and R.A. Kenyon, *Fluid Mechanics*, Wiley, 1980. .

The difference in pressure between two different points is

$$P_2 - P_1 = -\gamma\,(z_2 - z_1) = -\gamma h = -\rho g h$$

Absolute pressure = atmospheric pressure + gauge pressure reading

Absolute pressure = atmospheric pressure – vacuum-gauge pressure reading

4.1.3 Principles of One-Dimensional Fluid Flow

Continuity Equation

As long as the flow Q is continuous, the *continuity equation*, as applied to one-dimensional flows, states that the flow passing two points (1 and 2) in a stream is equal at each point, $A_1 v_1 = A_2 v_2$.

$$Q = Av$$
$$\dot{m} = \rho Q = \rho A v$$

where

Q = volumetric flow rate

$\dot{m}$ = mass flow rate

A = cross-sectional area of flow

v = average flow velocity

ρ = fluid density

For steady, one-dimensional flow, $\dot{m}$ is a constant. If, in addition, the density is constant, then Q is constant.

Bernoulli Equation

The field equation is derived when the energy equation is applied to one-dimensional flows. Assuming no friction losses and that no pump or turbine exists between sections 1 and 2 in the system:

$$\frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2 = \frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1$$

or

$$\frac{P_2}{\rho} + \frac{v_2^2}{2} + z_2\,g = \frac{P_1}{\rho} + \frac{v_1^2}{2} + z_1\,g$$

where

P_1, P_2 = pressure at sections 1 and 2

v_1, v_2 = average velocity of the fluid at the sections

z_1, z_2 = vertical distance from a datum to the sections (the potential energy)

γ = specific weight of the fluid (ρg)

g = acceleration of gravity

ρ = fluid density

Conservation Equation

$$p_T = p + \frac{\rho V^2}{2} + \rho g Z$$

where

p_T = total pressure (psi)

p = normal pressure (psi)

ρ = fluid density (lb/ft^3)

V = fluid velocity (ft/sec)

g = gravitational constant ($32.2\ ft/s^2$)

Z = vertical distance from an arbitrary elevation

Hydraulic Gradient (Grade Line)

Hydraulic grade line is the line connecting the sum of pressure and elevation heads at different points in conveyance systems. If piezometers were placed at intervals along the pipe, the grade line would join the water levels in the piezometer water columns.

Energy Line (Bernoulli Equation)

The Bernoulli equation states that the sum of the pressure, velocity, and elevation heads is constant. The energy line is this sum or the "total head line" above a horizontal datum. The difference between the hydraulic grade line and the energy line is the $v^2/2g$ term.

4.1.4 Fluid Flow Characterization

Reynolds Number

$$Re = \frac{vD\rho}{\mu} = \frac{vD}{\nu}$$

$$Re' = \frac{v^{(2-n)} D^n \rho}{K\left(\frac{3n+1}{4n}\right)^n 8^{(n-1)}}$$

where

v = fluid velocity (m/s)

ρ = mass density (kg/m^3)

D = diameter of the pipe, dimension of the fluid streamline, or characteristic length (m)

μ = dynamic viscosity (kg/m•s)

ν = kinematic viscosity (m^2/s)

Re = Reynolds number (Newtonian fluid)

Re' = Reynolds number (Power law fluid)

K = consistency index (dimensionless)

n = power law index (dimensionless)

The critical Reynolds number, Re_c, is defined to be the minimum Reynolds number at which a flow will turn turbulent.

Flow through a pipe is generally characterized as laminar for $Re < 2{,}100$, fully turbulent for $Re > 10{,}000$, and transitional flow for $2{,}100 < Re < 10{,}000$.

The velocity distribution for *laminar flow* in circular tubes or between planes is

$$v(r) = v_{\max}\left[1-\left(\frac{r}{R}\right)^2\right]$$

where

r = distance from the centerline (m)

R = radius of the tube or half the distance between the parallel planes (m)

v = local velocity at r (m/s)

$v_{\max}$ = velocity at the centerline of the duct (m/s)

$v_{\max} = 1.18\overline{v}$, for fully turbulent flow

$v_{\max} = 2\overline{v}$, for circular tubes in laminar flow

$v_{\max} = 1.5\overline{v}$, for parallel planes in laminar flow

where $\overline{v}$ = average velocity in the duct (m/s)

The shear stress distribution is

$$\frac{\tau}{\tau_w} = \frac{r}{R}$$

where τ and τ_w are the shear stresses at radii r and R, respectively

4.1.5 Consequences of Fluid Flow

Drag Force

The drag force F_D on objects immersed in a large body of flowing fluid or objects moving through a stagnant fluid is

$$F_D = \frac{C_D \rho v^2 A}{2}$$

where

C_D = drag coefficient

v = velocity of the flowing fluid or moving object (m/s)

A = projected area of blunt objects such as spheres, ellipsoids, disks, and plates, cylinders, ellipses, and air foils with axes perpendicular to the flow (m^2)

ρ = fluid density (kg/m^3)

For flat plates placed parallel with the flow:

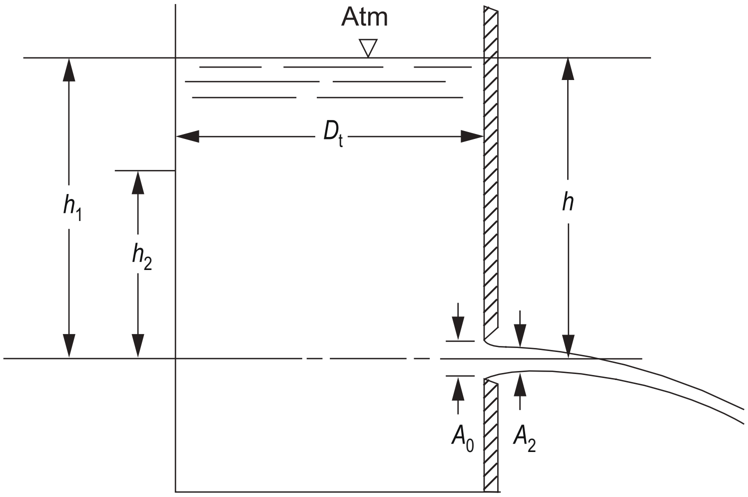
$$C_D = \frac{1.33}{Re^{0.5}} \qquad (10^4 < Re < 5 \times 10^5)$$

$$C_D = \frac{0.031}{Re^{1/7}} \qquad (10^6 < Re < 10^9)$$

The characteristic length in the Reynolds number (*Re*) is the length of the plate parallel with the flow. For blunt objects, the characteristic length is the largest linear dimension (diameter of cylinder, sphere, disk, etc.) that is perpendicular to the flow.

4.2 General Water Flow

Orifice discharging freely into the atmosphere:



Vennard, J.K., *Elementary Fluid Mechanics*, 6th ed., J.K. Vennard, 1954.

$$Q = CA_0 \sqrt{2gh}$$

in which h is measured from liquid surface to centroid of orifice opening

where

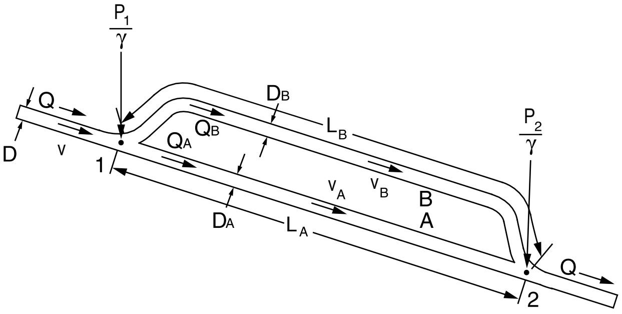
Q = volumetric flow (gpm)

A_0 = cross-sectional area of flow (ft^2)

g = acceleration of gravity (ft/sec^2)

h = height of fluid above orifice (ft)

4.2.1 Multipath Pipeline Problems



Vennard, J.K., *Elementary Fluid Mechanics*, 6th ed., J.K. Vennard, 1954.

$$h_L = f_A \frac{L_A}{D_A}\frac{v_A^2}{2g} = f_B \frac{L_B}{D_B}\frac{v_B^2}{2g}$$

$$\left(\frac{\pi D^2}{4}\right)v = \left(\frac{\pi D_A^2}{4}\right)v_A + \left(\frac{\pi D_B^2}{4}\right)v_B$$

4.2.2 Pitot Tube

From the stagnation pressure equation for an incompressible fluid,

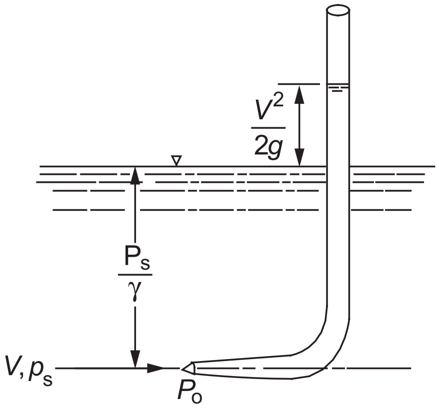
$$v = \sqrt{\left(\frac{2}{p}\right)\left(P_0 - P_S\right)} = \sqrt{\frac{2g\left(P_0 - P_S\right)}{\gamma}}$$

where

v = velocity of the fluid (ft/sec)

P_0 = stagnation pressure (psi)

P_S = static pressure of the fluid at the elevation where the measurement is taken (psi)



Vennard, J.K., *Elementary Fluid Mechanics*, 6th ed., J.K. Vennard, 1954.

For a compressible fluid, use the above incompressible fluid equation if the Mach number ≤0.3.

4.3 Fire Hydrants

4.3.1 Hydrant Flow Test

$$Q_2 = Q_1 \frac{(S-R_2)^{0.54}}{(S-R_1)^{0.54}}$$

where

Q = flow (gpm)

S = static pressure (psi)

R = residual pressure (psi): R_1 = test residual; R_2 = desired residual

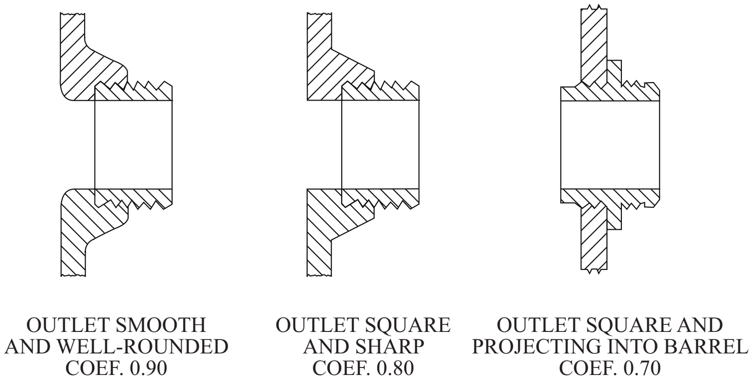
$$Q = 29.84cd^2\sqrt{\text{pitot}}$$

where

c = constant based upon hydrant outlet (0.9, 0.8, 0.7)

d = diameter of opening (in.)

pitot = velocity pressure of water exiting hydrant (psi)



NFPA Standard 291, *Recommended Practice for Fire Flow Testing and Marking of Hydrants*, Section 4.10.1.2.
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Pressure available at water supply (P):

$$P = (P_R - P_S)\left(\frac{Q}{Q_R}\right)^{1.85} + P_S$$

where

P_S = static pressure from test (psi)

P_R = res. pressure from test (psi)

Q = flow at which you want to know pressure (gpm)

Q_R = flow at P_R (gpm)

4.4 Fire Sprinkler Systems

The area of sprinkler coverage is taken as twice the maximum coverage in one direction times twice the maximum coverage in the other direction.

The area of coverage for each sprinkler is determined by the following steps:

1. Consider the distance to the next sprinkler or twice the distance to the wall in one direction. Whichever is greater is given the dimension S.
2. Consider the distance to the next sprinkler or twice the distance to the wall in the perpendicular direction to step 1. Whichever distance is greater is given the dimension L.
3. The area of coverage for a sprinkler is determined by multiplying S × L.

4.4.1 Sprinkler Flow Using Sprinkler K-Factor

$$Q = k\sqrt{p}$$

where

k = nominal orifice coefficient with different k-factors available in traditional U.S. and Metric units

Q = system flow (gpm or Lpm)

p = system pressure (psi or bar)

4.4.2 Sprinkler Flow Normal Pressure

$$P_n = P_t - P_v$$

where

P_n = normal pressure (psi)

P_t = total pressure (psi)

P_v = velocity pressure (psi)

4.4.3 Sprinkler Flow Velocity Pressure

$$P_v = \frac{0.001123Q^2}{d^4}$$

where

P_v = velocity pressure (psi)

Q = flow prior to orifice (gpm)

d = inside diameter of pipe prior to orifice (in.)

4.4.4 Dry Pipe Valve Trip Time

Time to trip a dry pipe sprinkler system, per FM Global Research:

$$t = 0.0352\frac{V_T}{A_n T_0^{1/2}}\ln\left(\frac{p_{a0}}{p_a}\right)$$

where

t = time (sec)

V_T = dry volume of sprinkler system (ft^3)

T_0 = air temperature (°R)

A_n = flow area of open sprinklers (ft^2)

p_{a0} = initial air pressure (absolute)

p_a = trip pressure (absolute)

4.5 Hydraulic Calculations

4.5.1 Pressure Due to Elevation

$$P = 0.433H$$

where

P = pressure (psi)

H = height (ft)

4.5.2 Hazen-Williams Pressure Loss

US Customary Units

$$p = \frac{4.52Q^{1.85}}{C^{1.85}d_i^{4.87}}$$

where

p = pressure loss per foot of pipe (psi/ft)

Q = flow rate (gpm)

C = pipe roughness coefficient

d_i = internal pipe diameter (in.)

SI Units

$$P = \frac{6.05Q^{1.85}}{C^{1.85}D^{4.87}} \times 10^5$$

where

P = pressure loss per meter of pipe (bars)

Q = flow (L/min)

D = pipe diameter (mm)

Values of Hazen-Williams Coefficient *C* for Underground Pipe

Pipe Material	*C*
Asbestos – Cement	140
Brick Sewers	100
Cast Iron (Lined)	140
Cast iron (Unlined)—new	130
Cast iron (Unlined)—5 yr old	120
Cast iron (Unlined)—20 yr old	100
Concrete	130
Copper	150
Ductile Iron (Lined)	140
Ductile Iron (Unlined)	100
Plastic	150
Steel—galvanized or black—dry pipe system with air in piping	100
Steel—galvanized or black—dry pipe system with nitrogen in piping	120
Steel—galvanized or black—deluge system	120
Steel—galvanized or black—preaction system with air in piping	100
Steel—galvanized or black—preaction system with nitrogen in piping	120
Steel—galvanized or black—wet-pipe system	120
Steel—riveted	110
Wood stave	120

Note: Other values for above-ground piping are available within the provided reference standards.

4.5.3 Pipe Schedule Correction Factor

$$Correction\ factor = \left(\frac{d_{\text{actual}}}{d_{\text{sched40}}}\right)^{4.87}$$

where

d_{actual} = pipe diameter for schedule pipe being used (in.)

d_{sched40} = pipe diameter for schedule 40 pipe (in.)

4.5.4 Darcy-Weisbach Friction Loss

$$h_L = f\frac{Lv^2}{2Dg}$$

where

h_L = friction loss over a length of pipe (ft)

f = friction factor

L = length of pipe (ft)

v = fluid velocity (ft/sec)

D = pipe diameter (ft)

g = gravitational constant (ft/sec^2)

For laminar flow ($Re < 2{,}000$):

$f = \frac{64}{Re}$ or Moody Diagram

where Re = Reynolds number

For hydraulically smooth or turbulent smooth flow:

$$\frac{1}{\sqrt{f}} = -0.86 \ln\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right)^{-2}$$

or

$$f = \left[1.14 - 2\log\left(\frac{\varepsilon}{D} + \frac{9.35}{\mathrm{Re}\sqrt{f}}\right)\right]^{-2}$$

A chart that gives f versus Re for various values of $\frac{\varepsilon}{D}$, known as the Moody diagram, is available in this section.

Values of Absolute Roughness of Commercial Pipes

Type of pipe or tubing	ε in ft × 10^{-6}		Probable maximum variation of f from design (%)
	Range	Design	
New clean pipe			
Asphalted cast iron	400	400	–5 to +5
Brass and copper	5	5	–5 to +5
Concrete	1,000–10,000	4,000	–35 to +50
Cast iron	850	850	–10 to +15
Galvanized iron	500	500	0 to +10
Wrought iron	150	150	–5 to +10
Steel	150	150	–5 to +10
Riveted steel	3,000–30,000	6,000	–25 to +75
Wood stave	600–3,000	2,000	–35 to +20
Aged pipe			
Steel, dry system		1,250	
Steel, wet system		333	
Plastic		7	
Copper		7	

Notes:
For ε values in meters, multiply the above numbers by 0.3048. For ε values in inches, multiply the above numbers by 12.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

$$Re = \frac{D_e v \rho}{\mu}$$

where

D_e = equivalent flow diameter

ρ = density

μ = absolute (dynamic) viscosity

$D_e = 4r_h$

where r_h = hydraulic radius (area in flow divided by the wetted perimeter)

For fluids:

$$h = \frac{0.000216 f \rho Q^2}{D^5}$$

where

h = friction loss over a unit length of pipe

Q = flow rate

For water at 68°F:

$$h = \frac{0.0135 f l Q^2}{D^5}$$

where l = length of pipe

Alternate terms:

$$\Delta P = 0.000216 f \, \frac{l \rho Q^2}{d^5} \qquad Re = 50.6 \frac{Q\rho}{d\mu}$$

where

ΔP = friction loss (psi)

Q = flow (gpm)

d = internal diameter of the pipe (in.)

μ = viscosity (cP)

4.5.5 Piping Loops

$$A = \sum_{i=1}^{x} \left[\frac{L_i}{c_i^{1.85} d_i^{4.87}} \right] \text{for Leg 1 of the loop}$$

$$B = \sum_{j=1}^{y} \left[\frac{L_j}{c_j^{1.85} d_j^{4.87}} \right] \text{for Leg 2 of the loop}$$

$$Q_1 = Q_3 \left[\frac{B^{0.54}}{\left(A^{0.54} + B^{0.54}\right)} \right]$$

$$Q_2 = Q_3 - Q_1$$

where

L = length of pipe (ft)

d = pipe diameter (in.)

c = pipe C-factor

Q = pipe flow (gpm)

Equivalent pipe:

Series: $\text{FLC}_e = \text{FLC}_1 + \text{FLC}_2 + \text{FLC}_3 + \ldots.$

Parallel: $\left(\frac{1}{\text{FLC}_e}\right)^{0.54} = \left(\frac{1}{\text{FLC}_1}\right)^{0.54} + \left(\frac{1}{\text{FLC}_2}\right)^{0.54} + \left(\frac{1}{\text{FLC}_3}\right)^{0.54} + \ldots.$

$$\text{FLC}_e = \frac{4.52 L_e}{C_e^{1.85} D_e^{4.87}}$$

where

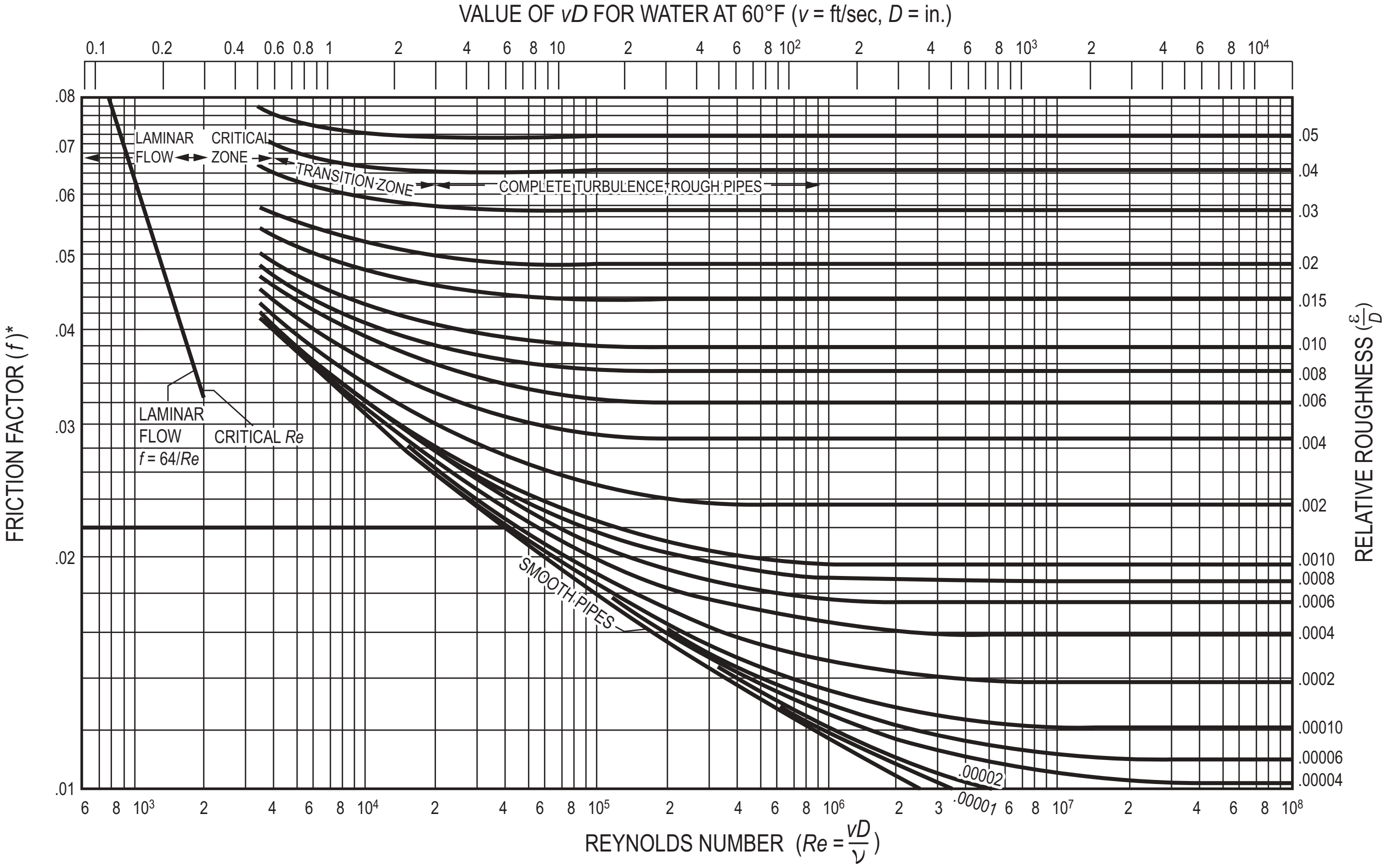
L_e = equivalent length of pipe (ft)

D_e = equivalent pipe diameter (in.)

C_e = equivalent pipe C-factor

FLC_e = equivalent pipe flow (gpm)

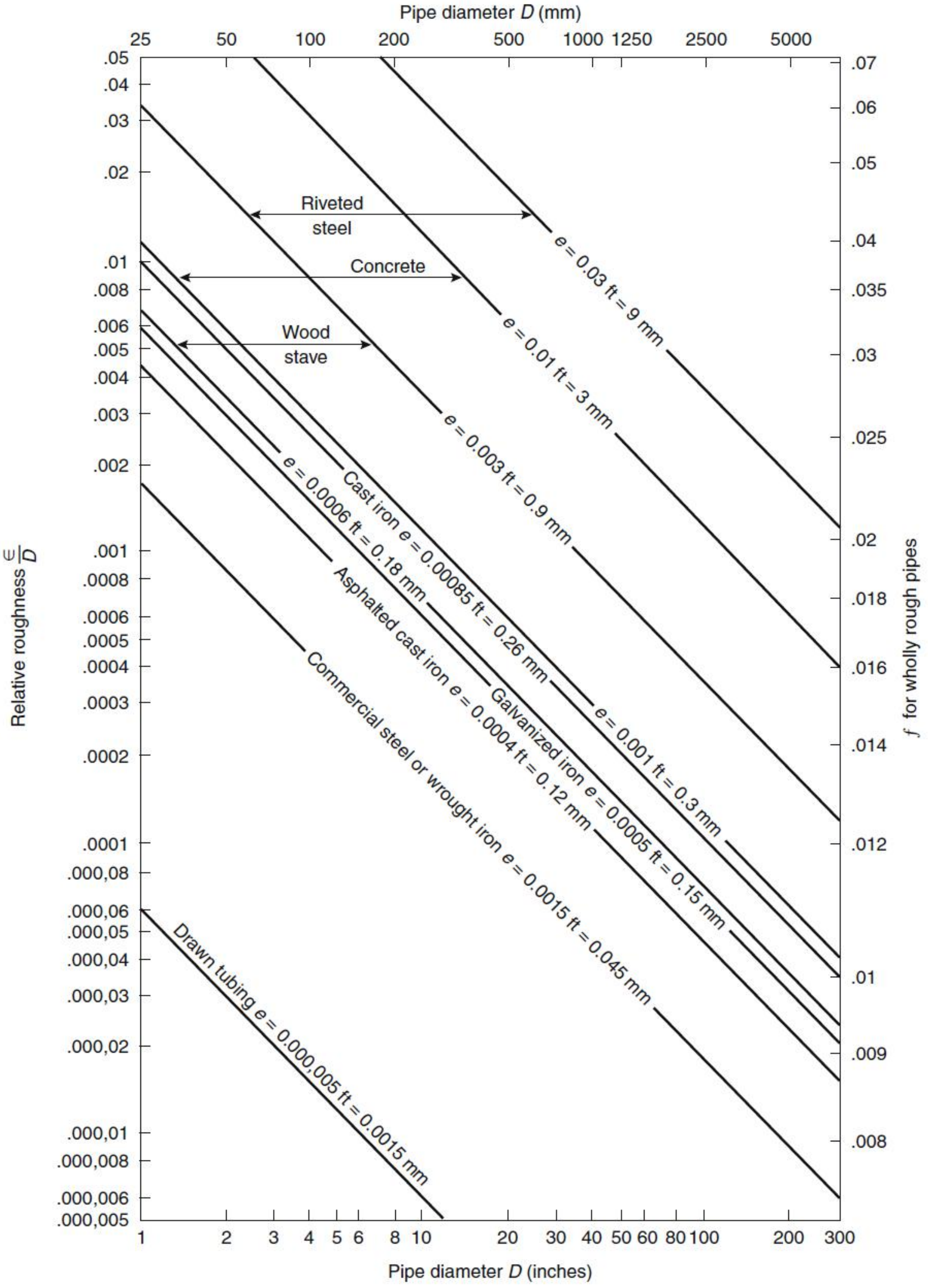
4.5.6 Moody, Darcy, or Stanton Friction Factor Diagram



Flow in Closed Conduits

* The Fanning Friction is this factor divided by 4

4.5.7 Relative Roughness Chart



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4.6 Water Hammer

Water hammer in a pipeline is caused by a sudden stoppage of flow and is characterized by loud noise and vibration. The formula expressing the relationship between pressure and volume for water hammer is

$$\Delta p = -E\frac{\Delta V}{V_0}$$

where

Δp = change in pressure (psi)

E = bulk modulus of elasticity

ΔV = change in volume

V_0 = initial volume

Pressure shocks in fluids of infinite extent travel at a velocity given by

$$c^* = \sqrt{\frac{KE}{\rho}}$$

where

c^* = celerity (velocity) of the shock wave

KE = kinetic energy of the fluid

ρ = fluid density

For a system composed of fluid and pipe:

$$\frac{1}{E_c} = \frac{1}{E} + \frac{D}{E_p w}$$

where

E_c = modulus of elasticity of a system composed of fluid and pipe

E_p = modulus of elasticity of the pipe material

D = pipe diameter

w = thickness of pipe wall

Modulus of Elasticity E_p of Various Pipe Materials

Pipe Material	E_p		
	psi	lb/ft^2	kg/m^2
Lead	0.045×10^6	6.48×10^6	31.64×10^6
Lucite (at 73°F)	0.4×10^6	57.6×10^6	281.23×10^6
Rubber (vulcanized)	2×10^6	288×10^6	$1{,}406 \times 10^6$
Aluminum	10×10^6	$1{,}440 \times 10^6$	$7{,}030 \times 10^6$
Glass (silica)	10×10^6	$1{,}440 \times 10^6$	$7{,}030 \times 10^6$
Brass, bronze	13×10^6	$1{,}872 \times 10^6$	$8{,}489 \times 10^6$
Copper	14×10^6	2.016×10^6	$9{,}842 \times 10^6$
Cast iron, gray	16×10^6	$2{,}304 \times 10^6$	$11{,}249 \times 10^6$
Cast iron, malleable	23×10^6	$3{,}312 \times 10^6$	$16{,}170 \times 10^6$
Steel	28×10^6	$4{,}023 \times 10^6$	$19{,}685 \times 10^6$

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Shock wave in a pipe system of finite extent:

$$\frac{c}{c^*} = \frac{1}{\sqrt{1 + \frac{ED}{E_P w}}}$$

Time for a shock to be absorbed into a larger energy field:

$$t = \frac{L}{c}$$

where

L = distance from the energy reservoir to shock-wave point of origin

t = time

t, L, and c can be any set of consistent units. For example, if c is in m/s, then L would be m and t would be s.

Time period that the initial shock acts on a valve:

$$T = 2t = \frac{2L}{c}$$

Theoretical magnitude of the pressure shock at instantaneous valve closure:

$$p^* = \rho c \Delta v$$

The pressure will oscillate in the pipe within the range $p = p_0 \pm p^*$.

4.7 Pressures

4.7.1 Velocity Head

$$h_V = \frac{Q^2}{891 d^4}$$

where

h_v = velocity head (psi)

Q = flow rate (gpm)

d = pipe inside diameter (in.)

4.7.2 Net Positive Suction Head (NPSH)

$$\text{NPSH}_\text{A} = P_\text{atm} + P_\text{static} - f - P_\text{vapor}$$

where

NPSH_A = net positive suction head available (psi)

P_atm = atmospheric pressure (psi)

P_static = pressure tank pressure – elevation pressure (psi)

f = friction loss in line (psi)

P_vapor = vapor pressure (psig) adjusted for temperature and altitude (0.256 psia represents water at 20°C)

4.8 Fire Pumps

4.8.1 Pump Affinity Laws

Law 1 – Constant Diameter

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad \frac{H_1}{H_2} = \frac{N_1^2}{N_2^2} \qquad \frac{P_1}{P_2} = \frac{N_1^3}{N_2^3}$$

Law 2 – Constant Speed

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \qquad \frac{H_1}{H_2} = \frac{D_1^2}{D_2^2} \qquad \frac{P_1}{P_2} = \frac{D_1^3}{D_2^3}$$

where

Q = volumetric flow rate (gpm or L/min)

N = rotational speed (rpm)

H = developed head (ft, psi, or m)

P = power (hp or kW)

D = impeller diameter (in., cm, or mm)

4.8.2 Fire Pump Total Head

$$H = h_\text{d} + h_\text{Vd} - h_\text{s} - h_\text{Vs}$$

where

H = total head (ft)

h_d = discharge head (ft)

h_Vd = discharge velocity head (ft)

$$= \frac{V_\text{d}^2}{2g}$$

V = velocity discharge or suction velocity (ft/sec)

$$= \frac{Q}{A} = \text{gpm} \times \frac{1\,\text{ft}^3}{7.48\text{ gal}} \times \frac{1\text{ min}}{60\text{ s}} \times \frac{1}{A}$$

g = acceleration due to gravity (32.2 ft/sec^2)

h_s = suction head (ft)

h_{Vs} = suction velocity head (ft)

$$= \frac{V_s^2}{2g}$$

4.8.3 Pump Power Equation

$$\dot{W} = \frac{Q\gamma h}{\eta_t} = \frac{Q\rho g h}{\eta_t}$$

where

$\dot{W}$ = power (ft-lbf/sec or kg•m^2/s^3)

Q = volumetric flow (cfs or m^3/s)

h = head the fluid has to be lifted (ft or m)

η_t = total efficiency ($\eta_{pump} \times \eta_{motor}$)

4.8.4 Water Horsepower

$$\text{WHP} = \frac{Qh}{3{,}960}$$

where

WHP = water horsepower

Q = flow (gpm)

h = total dynamic head (ft)

using the specific weight, γ, for water at 68°F (20°C)

4.8.5 Pump Brake Horsepower

$$H = \frac{P \times 600 \times E}{Q}$$

where

P = brake horsepower (kW)

Q = pump discharge (L/min)

H = pump discharge head (bar)

E = combined efficiency of the motor and gear drives $\left(\eta_d \times \eta_m\right)$

$$\text{bhp} = \frac{QP}{1{,}710E}$$

where

bhp = brake horsepower

hp = hydraulic horsepower = $QP/1{,}710$

Q = flow (gpm)

P = total pressure (psi) = total head × 0.433

E = pump efficiency (decimal); usually 60 to 75%

Deratings for altitude and temperature:

Altitude: 3% for every 1,000 ft above 300 ft

Temperature: 1% for every 10°F above 77°F

4.8.6 Diesel Fuel Tank Capacity

When a diesel fuel tank is needed to support the fire pump, the tank must be able to accommodate 1 gal/bhp plus 5% for expansion and 5% for sump.

4.9 Water-Mist Fire Suppression Systems

Water-mist fire protection systems refer to water sprays with no drops larger than 1.0 mm, or 1,000 µm (micrometers or microns). Extinguishing mechanisms apply to extinguishment of Class B liquid-fuel fires as well as Class A solid fuels. Water-mist systems can control or extinguish a fire by reducing the oxygen concentration below the limiting oxygen concentration (LOC), wetting/cooling the fuel surface, or reducing radiant-heat flux through radiation attenuation.

Water-mist systems can be categorized based on several distinguishing factors. From a systems engineering perspective, the four most important are

1. Mode of application of the mist
2. Method of spray generation
3. Pressure regime
4. Means of providing the necessary system flow and pressure

There are several subcategories of systems, each with its own specific technical features, such as single-fluid and twin-fluid systems, and constant-pressure versus decaying-pressure discharges. The mode of application refers to how the system is intended to develop and deploy the mist within a given space or environment and includes total compartment application (TCA), local application (LA), and zoned application (ZA) systems.

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4.9.1 Water-Mist System Definitions

Engineered Water-Mist System

This system is designed in the same manner as a traditional sprinkler or water-spray system, based on criteria in the manufacturer's design installation, operation, and maintenance manual. The designer applies these guidelines and performs necessary calculations, such as hydraulic calculations, for the system.

High-Pressure System

This system operates at pressures above 500 psi (34.5 bar).

Intermediate-Pressure System

This system operates at pressures between 175 psi (12.1 bar) and 500 psi (34.5 bar).

Low-Pressure System

This system operates at pressures below 175 psi (12.1 bar).

NanoMist System

This system has an ultrafine mist with very uniform drop size distribution with a volumetric mean droplet diameter in the 10 μm range.

Pre-engineered Water Mist System

This system has been developed for a hazard of a limited size and consistent features defining the compartment. It is installed per the manufacturer specifications and does not require engineering calculations.

Single-Fluid Nozzles

These nozzles discharge water only.

Twin-Fluid Nozzles

These nozzles combine two independent streams of fluid, one of water and one of compressed gas, at a nozzle to generate finely atomized spray.

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4.9.1.1 Spray Heat Absorption Ratio (SHAR)

$$\mathrm{SHAR} = \frac{Q_\mathrm{w}}{Q_\mathrm{f}}$$

where

Q_w = evaporation of a given mass of water (kW)

Q_f = heat given off by the fire (kW)

4.9.1.2 Required Extinguishing Medium Portion (REMP)

$$\mathrm{REMP} = \frac{m'_\mathrm{e}}{m'_\mathrm{g}}$$

where

m'_e = mass application rate of extinguishing agent required (kg/s)

m'_g = mass rate of fuel consumed (kg/s)

4.9.1.3 Spray Characteristics

To fully characterize a spray requires information about the following elements:

- Drop size distribution (DSD)
- Cone angle
- Velocity of the discharge jet(s)
- Mass flow rate
- Spray momentum (product of velocity and mass)

4.10 Pipe Diameters

4.10.1 Ductile Iron

Ductile Iron Pipe Inner Diameters (I.D.)

Size	Class	Nominal Thickness (in.)	Unlined Pipe I.D. (in.)	Cement-Lined I.D. (in.)
6"	350	0.25	6.40	6.28
8"	350	0.25	8.55	8.43
10"	350	0.26	10.58	10.46
12"	350	0.28	12.64	12.52
14"	250	0.28	14.74	14.55
	300	0.30	14.70	14.51
	350	0.31	14.68	14.49
16"	250	0.30	16.80	16.61
	300	0.32	16.76	16.57
	350	0.34	16.72	16.53
18"	250	0.31	18.88	18.69
	300	0.34	18.82	18.63
	350	0.36	18.78	18.59

4.10.2 Steel Pipe—Common Schedules

	Nominal Pipe Size	1"	1 1/4"	1 1/2"	2"	2 1/2"	3"	4"	6"	8"
Schedule 10	I.D. (in.)	1.097	1.442	1.682	2.157	2.635	3.260	4.260	6.357	8.249
	Water-Filled Weight (lbf/ft)	1.800	2.518	3.053	4.223	5.893	7.957	11.796	23.038	40.086
Schedule 40	I.D. (in.)	1.049	1.380	1.610	2.067	2.469	3.068	4.026		
	Water-Filled Weight (lbf/ft)	2.055	2.918	3.602	5.114	7.875	10.783	16.316		

5 SPECIAL HAZARD EXTINGUISHING SYSTEMS

5.1 Foam Agents

Test Average Effective Absorptivity for AFFF at Different Expansion Ratios

Expansion Ratio (ER)	Effective Absorptivity, α Foam
3	0.34 ± 0.09
6	0.42 ± 0.06
10	0.41 ± 0.04

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE

Surface Tension of Hydrocarbon Liquids and Fuels

Hydrocarbon Liquid	Grade	Surface Tension at 25°C (dyn/cm)
Cyclohexane	Certified A.C.S.	24.2
n-Heptane	Certified spectroanalyzed	19.8
n-Heptane	Commercial	20.9
Isooctane	Certified A.C.S.	18.3
Avgas	115/145	19.4[a] 19.5[b]
JP-4	Navy specification	22.4[a] 22.8[b]
JP-5	Navy specification	25.6[a] 25.8[b]
Motor fuel	Regular	20.5[a] 21.5[b]
Naphtha	Stove and lighting	20.6

[a] Sample 1 [b] Sample 2

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Interfacial Tensions, Spreading Coefficients, and Film Formation Observations for Various Surfactant Solution-Hydrocarbon Liquid Combinations

Surfactant Solution	Hydrocarbon Liquid	Interfacial Tension (dyn/cm)	Spreading Coefficient (dyn/cm)	Film Formed
FC-194 (lot 107) (solution surface tension of 15.5 dyn/cm at 25°C)	Cyclohexane	4.3	4.4	Yes
	n-Heptane, certified	5.5	–1.2	No
	n-Heptane, commercial	4.3	1.1	Yes (very slow spread)
	Avgas[a]	4.6	–0.7	No
	JP-4[a]	3.6	3.3	Yes
	JP-5[a]	4.9	5.2	Yes
	Motor fuel[a]	3.7	1.3	Yes
FC-195 (lot 9) (solution surface tension of 15.6 dyn/cm at 25°C)	Cyclohexane	3.2	5.4	Yes
	n-Heptane, certified	4.2	0.0	Yes (slow spread)
	Isooctane	2.5	0.2	Yes (slow spread)
	Avgas[a]	0.5	3.3	Yes
	JP-4[b]	3.6	3.6	Yes
	JP-5[b]	4.9	5.3	Yes
	Motor fuel[a]	2.6	2.3	Yes
	Naphtha	2.8	2.2	Yes
FC-195 (lot 10) (solution surface tension of 16.4 dyn/cm at 25°C)	Cyclohexane	1.5	6.3	Yes
	n-Heptane, certified	3.2	0.6	Yes
	Isooctane	2.8	–1.3	No
	Avgas[a]	2.1	1.0	Yes
	JP-4[a]	2.7	3.3	Yes
	JP-5[a]	4.2	5.0	Yes
	Motor fuel[a]	1.2	2.9	Yes
	Naphtha	0.8	3.4	Yes (slow spread)

[a] Sample 1 [b] Sample 2

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Comparison of Design Criteria for Low-Expansion and High-Expansion Foam Systems

Design/Hydraulic Step Function	Low-Expansion Foam System—Top Chamber	High-Expansion Foam System—Top Generator
Starting point	Foam chamber(s)	Foam generator(s)
Second determination	Foam solution requirement per chamber (gpm)	Expanded foam requirement per chamber (cfm)
Third determination	Foam solution delivery rate between foam maker and foam house	Same determination
Fourth determination	Size pipe from foam maker(s) to foam house	Size pipe from foam generator(s) to foam house
Fifth determination	Determine type and size of foam proportioner	Same determination
Sixth determination	Determine hydraulic requirements in foam house	Same determination
Seventh determination	Evaluate water supply/demand requirement at foam house	Same determination
Eighth determination	Assess requirement for pump in foam house; recalculate hydraulic requirements in foam house	Same requirement

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

5.2 Low-Expansion Foam Systems

$$Q = D \times T \times \% + HoseStream$$

where

Q = primary foam concentrate (gal) (system + hose)

D = foam discharge rate (gpm)

T = discharge time (min)

$\%$ = concentrate percent of foam (decimal)

5.2.1 Foam Discharge Rate

$$D = A \times R$$

where

D = foam discharge rate (gpm)

A = surface area (ft^2)

For tanks = $0.785d^2$

d = diameter (ft)

R = rate of application (gpm/ft^2)

5.3 High-Expansion Foam Systems

$$R = \left(\frac{V}{T} + R_S\right) C_N \times C_L$$

where

R = rate of discharge (cfm)

V = submergence volume (ft^3)

(volume of combustible + 10% or 2 ft, whichever is greater)

C_N = 1.15 (dimensionless)

C_L = foam leakage coefficient (between 1.0 and 1.2) (dimensionless)

$R_S = S \times Q$

where

S = sprinkler breakdown rate (10 cfm/gpm)

Q = estimated sprinkler discharge (gpm)

5.4 Carbon Dioxide (CO_2) Systems

Reference Properties of Carbon Dioxide

Chemical name	**Carbon dioxide**
Synonyms	**Carbon anhydride, carbonic acid gas, carbonic anhydride, dry ice**
CAS Registry No.[a]	124-38-9
Chemical formula	CO_2
Property	S.I. units
Molecular weight	44.01 g/mol
Vapor pressure at 2°F (–16.7 °C)	2,181.4 kPa
Specific gravity of gas at 70°F (21.1°C) and 1 atm	1.522
Solid to gas expansion ratio at 70°F (21.1°C) and 1 atm	0.5457 m^3/kg
Gas density at 70°F (21.1°C) and 1 atm	1.833 kg/m^3
Density of solid (dry ice) at –109.3°F (–78.5°C)	1,563 kg/m^3
Sublimation temperature at 1 atm	–78.5°C
Critical temperature	31.1°C
Critical pressure	7,381.8 kPa
Critical density	468 kg/m^3
Triple point	–56.6°C at 518 kPa
Latent heat of vaporization at –16.7°C, 2.18 MPa	276.8 kJ/kg
Latent heat of fusion at 518 kPa, at –93.8°C	547 kJ/kg
Latent heat of sublimation at –78.5°C, 101.3 kPa	571.0 kJ/kg
Specific heat at constant pressure, C_p, gas at 25°C	0.850 kJ/kg•°C
Specific heat at constant volume, C_V, gas at 25°C	0.657 kJ/kg•°C
Ratio of gas specific heats, C_p/C_V, at 15°C	1.304
Solubility in water at 20°C	0.90 vol/vol
Viscosity of saturated liquid at –16.7°C	0.000119 kg/m•s

[a] CAS numbers are unique numerical identifiers assigned by the Chemical Abstracts Service to every chemical described in the open scientific literature.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Carbon Dioxide Specific Heat, Thermal Conductivity, Viscosity

Temp (K)	C_p, liquid (J/kg•K)	Thermal cond., liquid (W/m•K)	Viscosity, liquid (µPa•s)	C_V, vapor (J/kg•K)	Thermal cond., vapor (W/m•K)	Viscosity, vapor (µPa•s)
220	1,962	0.1762	242.0	639	0.01130	11.14
225	1,977	0.1697	222.2	654	0.01175	11.41
230	1,997	0.1633	204.2	670	0.01222	11.69
235	2,021	0.1570	187.9	687	0.01274	11.98
240	2,051	0.1508	173.0	705	0.01330	12.27
245	2,087	0.1446	159.3	725	0.01392	12.58
250	2,132	0.1385	146.7	746	0.01461	12.90
255	2,187	0.1324	135.1	769	0.01540	13.25
260	2,255	0.1264	124.4	794	0.01631	13.61
265	2,342	0.1203	114.4	822	0.01738	14.02
270	2,454	0.1143	105.0	852	0.01869	14.47
275	2,603	0.1082	96.2	885	0.02033	14.99
280	2,814	0.1020	87.7	923	0.02247	15.60
285	3,133	0.0958	79.5	969	0.02542	16.36
290	3,676	0.0895	71.4	1,026	0.02982	17.36
295	4,794	0.0836	62.9	1,106	0.03722	18.79
300	8,698	0.0806	53.1	1,248	0.05369	21.31

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Material Compatibility of Carbon Dioxide

Material	Compatibility
Metals	
Aluminium	Satisfactory
Brass	Satisfactory
Copper	Satisfactory
Ferritic steels (e.g., carbon steels)	Satisfactory but risk of corrosion in presence of CO and/or moisture; cold brittleness
Stainless steel	Satisfactory
Plastics	
Polytetrafluoroethylene (PTFE)	Satisfactory
Polychlorotrifluoroethylene (PCTFE)	Satisfactory
Vinylidene polyfluoride (PVDF) (KYNAR™)	Satisfactory
Polyamide (PA) (NYLON™)	Satisfactory
Polypropylene (PP)	Satisfactory
Elastomers	
Buthyl (isobutene - isoprene) rubber (IIR)	Not recommended, significant swelling
Nitrile rubber (NBR)	Not recommended, significant swelling and significant loss of mass by extraction or chemical reaction
Chloroprene (CR)	Not recommended, significant swelling and significant loss of mass by extraction or chemical reaction
Chlorofluorocarbons (FKM) (VITON™)	Not recommended, significant swelling and significant loss of mass by extraction or chemical reaction
Silicon (Q)	Acceptable but strong rate of permeation
Ethylene-propylene (EPDM)	Acceptable but important swelling and significant loss of mass by extraction or chemical reaction
Lubricants	
Hydrocarbon-based lubricant	Satisfactory
Fluorocarbon-based lubricant	Satisfactory

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Acute Health Effects of High Concentrations of Carbon Dioxide

CO_2 Conc. Vol. %	Source	U.S. EPA Examining the Risks (2004)	Air Products (2004)	Rice (2004)
	Exposure Time	**Effects**	**Effects**	**Effects**
1			Slight increase in breathing rate.	Respiratory rate increased by about 37%.
2	Several hours	Headache, dyspnea upon mild exertion	Breathing rate increases to 50% above normal level. Prolonged exposure can cause headache, tiredness.	Ventilation rate raised by about 100%. Respiratory rate raised by about 50%; increased brain blood flow.
3	1 hr	Mild headache, sweating, and dyspnea at rest	Breathing increases to twice normal rate and becomes laboured. Weak narcotic effect. Impaired hearing, headache, increase in blood pressure and pulse rate.	Exercise tolerance reduced in workers when breathing against inspiratory and expiratory resistance.
4–5	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnea	Breathing increases to approximately four times normal rate; symptoms of intoxication become evident and slight choking may be felt.	Increase in ventilation rate by ~200%. Respiratory rate doubled, dizziness, headache, confusion, dyspnea.
5–10	Within minutes		Characteristic sharp odor noticeable. Very labored breathing, headache, visual impairment, and ringing in the ears. Judgment may be impaired, followed within minutes by loss of consciousness.	
6	1–2 min	Hearing and visual disturbances		
	< 16 min	Headache, dyspnea		
	Several hr	Tremors		
7–10	Few minutes	Unconsciousness, near unconsciousness		At 8–10%, severe headache, dizziness, confusion, dyspnea, sweating, dim vision. At 10%, unbearable dyspnea, followed by vomiting, disorientation, hypertension, and loss of consciousness.
	1.5 min to 1 hr	Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing		
10–15	1 to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness		
17–30	< 1 min	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death		
50–100	< 1 min			Unconsciousness occurs more rapidly above 10% level. Prolonged exposure to high concentrations may eventually result in death from asphyxiation.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Permissible Exposure Limits—U.S. Standards

Standard	Time-Weighted Average (8 hr day/40 hr week)	Short-Term Exposure Limit (15 min)	Immediately Dangerous to Life and Health
OSHA permissible exposure limit[a]	5,000 ppm (0.5%)		
NIOSH permissible exposure limit[b]	5,000 ppm (0.5%)	30,000 ppm (3%)	40,000 ppm (4%)
ACGIH permissible exposure limit[c]	5,000 ppm (0.5%)		

[a] OSHA: US Occupation Safety and Health Administration (1986)
[b] NIOSH: US National Institute of Occupational Safety and Health (1997)
[c] ACGIH: American Conference of Governmental Industrial Hygienists

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

5.4.1 CO_2 Total Flooding

In a total flooding system, a specific design concentration of carbon dioxide is needed to promptly extinguish surface fires under anticipated conditions. As such, the quantity of carbon dioxide required to achieve concentration *C* in an enclosure can be calculated as follows:

$$m = \frac{V}{s} \ln\left(\frac{100}{100 - C}\right)$$

where

m = quantity of CO_2 (kg)

V = enclosure volume (m^3)

s = specific volume of CO_2 vapor at the enclosure temperature (m^3/kg)

C = CO_2 concentration (vol %)

Minimum Extinguishing and Design Concentrations for Selected Flammable Liquids

Material	MEC (Vol. %)	DC (Vol. %)
Acetone	27*	34
Acetylene	55	66
Carbon disulfide	60	72
Ethyl alcohol	36	43
Hexane	29	35
Methyl alcohol	33	40
Propane	30	36

MEC: minimum extinguishing concentration
DC: design concentration
* Calculated from accepted residual oxygen values

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Flooding Factors vs. Hazard Volume

Protected Volume (V_p) (m^3)	Flooding Factor (kg/m^3)	Minimum Quantity (kg)
≤3.96	1.15	--
3.97–14.15	1.07	4.5
14.16–45.28	1.01	15.1
45.29–127.35	0.9	45.4
127.35–1,415	0.8	113.5
>1,415	0.74	1,135

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Material Conversion Factor

The material conversion factor, MCF, is used to increase the base design quantity (m_{BD}) for design concentrations exceeding 34% carbon dioxide. The MCF is used to find the corrected design quantity (m_{cf}) of carbon dioxide.

$$m_{BD} = V_p \times FF$$

$$m_{cf} = m_{BD} \times MCF$$

$$MCF = 2.41 \ln\left(\frac{100}{1 - C}\right)$$

where

m_{cf} = m_{BD} × MCF

V_p = protected volume (m^3)

FF = flooding factor (kg/m^3)

C = CO_2 concentration (vol%)

Unclosable Openings

In some cases, the enclosure surrounding the protected volume has openings that cannot be closed. The total quantity of carbon dioxide lost due to leakage from unclosable openings in a time period, *t*, can be found using the following equations, using SI and US units respectively:

$$m_{lo} = 116A\sqrt{\rho_1\left(\rho_1 - \rho_A\right)h}\ t$$

where

m_{lo} = quantity of CO_2 leaked through openings (kg)

A = area of opening (m^2)

h = height, center of opening to top of protected space (m)

ρ_1 = density of carbon dioxide-air atmosphere (kg/m^3)

ρ_A = density of air external to enclosure (kg/m^3)

t = time duration of leakage (min)

At 1 atm pressure and 21°C:

ρ_A = 1.202 kg/m^3

ρ_1 = 0.006220C + 1.202 kg/m^3

$$m_{lo} = 0.6\,C\rho_{CO_2}\,A\sqrt{\frac{2g\left(\rho_1 - \rho_A\right)h}{\rho_1}}\;t$$

where

m_{lo} = quantity of CO$_2$ leaked through openings (lb)

C = CO$_2$ concentration (vol. %)

A = area of opening (ft^2)

g = acceleration of gravity (32.2 ft/sec^2)

h = height, center of opening to top of protected space (ft)

ρ_{CO2} = density of carbon dioxide vapor (lb/ft^3)

ρ_1 = density of carbon dioxide-air atmosphere (lb/ft^3)

ρ_A = density of air external to enclosure (lb/ft^3)

t = time duration of leakage (min)

At 1 atm pressure and 70°F:

ρ_{CO_2} = 0.114 lb/ft^3

ρ_A = 0.0751 lb/ft^3

ρ_1 = 0.000388C + 0.0750 lb/ft^3

Ventilation Systems

Generally, mechanical ventilation of a protected volume should be arranged to shut down prior to discharge of a carbon dioxide extinguishment system. Where this is not possible, the quantity of carbon dioxide lost due to ventilation must be found. The amount lost is equal to the volume of fresh air introduced into the protected volume by the mechanical ventilation system over a time period (*t*) times the flooding factor.

$$m_{lv} = Q_v \times t \times FF$$

where

m_{lv} = CO$_2$ added to compensate for forced ventilation (kg)

Q_v = ventilation rate (kg/m^3)

t = duration of discharge (s)

FF = flooding factor (kg/m^3)

Temperature Extremes

The quantity of agent must also be adjusted to account for extreme temperatures in the protected volume whenever present. Extremes temperatures are defined as those above 93°C (200°F) and those below –18°C (0°F). For protected volumes that experience both high and low extreme temperatures, the high and low extreme temperature factors must be calculated and the one with the highest value is chosen.

$$\tau_H = 0.0036\,(T_H - 93)$$

$$\tau_L = -0.018\,(T_L + 18)$$

where

τ_H = extreme high temperature factor, in SI units

T_H = high temperature value (°C)

τ_L = extreme low temperature factor, in SI units

T_L = low temperature value (°C)

$$\tau_H = 0.002\,(T_H - 200)$$

$$\tau_L = 0.01\,(0 - T_L)$$

where

τ_H = extreme high temperature factor, in US units

T_H = high temperature value (°F)

τ_L = extreme low temperature factor, in US units

T_L = low temperature value (°F)

$$m_T = \tau(m_{cf} + m_{lo} + m_{lv})$$

where

m_T = additional carbon dioxide quantity for extreme temperature

τ = extreme high or low temperature factor, whichever is greater

m_{cf} = base quantity of carbon dioxide after applying MCF

m_{lo} = additional carbon dioxide quantity for leakage through openings

m_{lv} = additional carbon dioxide quantity for mechanical ventilation

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Design Parameters for Specific Deep-Seated Fire Hazards

Hazard Type	Min. Design Conc. (Vol. %)	Flooding Factor (kg/m^3)	Remarks
Dry electrical hazards in general, V < 56.6 m^3	50	1.6	
Dry electrical hazards in general, V > 56.6 m^3	50	1.33	Minimum quantity, 91 kg
Record (bulk paper) storage, ducts, covered trenches	65	2.0	
Fur storage vaults, dust collectors	75	2.66	

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

5.4.2 CO_2 Pressure Relief Venting

In some cases, the pressure rise in an enclosure due to carbon dioxide discharge is capable of damaging the enclosure construction. The risk of enclosure damage can be greatly reduced by designing and installing a means of pressure relief. The size of the minimum pressure relief area required is based on the maximum flow rate of carbon dioxide and is calculated using

$$A_v = \frac{239w}{\sqrt{P}}$$

where

A_v = vent area (mm^2)

w = carbon dioxide flow rate (kg/min)

P = allowable enclosure pressure limit (kPa)

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

$$X = \frac{Q}{1.3\sqrt{P}}$$

where

X = free venting area (in^2)

Q = calculated CO_2 flow rate (lb/min)

P = allowable strength of enclosure (lb/ft^2)

Allowable Pressure for Average Enclosures

Construction Type	P, kPa	Note
Light building	1.2	Venting sash remains open
Normal building	2.4	Venting sash designed to open freely
Vault building	4.8	

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

5.5 Clean Agents

Commercialized Halon Replacement Nomenclature

Chemical Name	Trade Name	ASHRAE Designation	Chemical Formula
Heptafluoropropane	FM-200	HFC-227ea	CF_3CHFCF_3
Trifluoromethane	FE-13	HFC-23	CHF_3
Chlorotetrafluoroethane	FE-24	HCFC-124	$CHClFCF_3$
Pentafluoroethane	FE-25	HFC-125	CHF_2CF_3
Dodecafluoro-2-methylpentan-3-one	Novec 1230	FK-5-1-12mmy2	$CF_3CF_2C(O)(CF(CF_3))_2$
Hexafluoropropane	FE-36	HFC-236fa	$CF_3CH_2CF_3$
Trifluoroiodide	Triodide	FIC-1311	CF_3I
$N_2/Ar/CO_2$	Inergen	IG-541	N_2 (52%)
			Ar (40%)
			CO_2 (8%)
N_2/Ar	Argonite	IG-55	N_2 (50%)
			Ar (50%)
Argon	Argon	IG-01	Ar (100%)
Nitrogen	Nitrogen	IG-100	N_2

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Comparisons of Systems in 500–5,000 m³ Range of Volumes

	Percentage Additional Weight When Compared to a Halon 1301 System						
	Halon 1301	CO_2	FE-13	FM-200	Novec 1230	Inergen	Water Mist
Weight Comparison							
500 m³	0	150	200	50	50	400	625
1,000 m³	0	163	188	38	50	450	613
3,000 m³	0	200	219	48	71	529	671
5,000 m³	0	186	211	36	58	497	522
Footprint Comparison							
500 m³	0	84	105	20	20	327	1,119
1,000 m³	0	82	94	20	20	365	889
3,000 m³	0	118	122	19	43	459	1,030
5,000 m³	0	99	107	6	19	404	636
Percentage Cost Comparison							
500 m³	0	108	315	202	259	277	1,032
1,000 m³	0	140	406	267	368	330	723
3,000 m³	0	200	553	351	513	449	478
5,000 m³	0	204	585	361	515	460	376

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Summary of Class A and Class B Extinguishing Concentrations for Various Agents and Equipment Manufacturers

Agent	Trade Name	Equipment Manufacturer	UL (NFPA 2001)				ISO 14520				
			Class B		Class A		Class B		Class A		
			Test	Design	Test	Design	Test	Design	Min (95% of Class B)	Test	Design
HFC-227ea	FM-200, FE-227	A	6.7	8.7							
		B	6.7	8.7							
		C	6.7	8.7							
		D	6.7	8.7	5.2	6.2					
		E	6.7	8.7	5.4	6.5					
		F	6.6	8.6			6.9	9.0	8.5	6.1 (4.9 WdCrib)	7.9
HFC-125	FE-25	A			6.7	8.0					
		B								8.6 (6.7 WdCrib)	11.2
		--	8.7	11.3			9.3	12.1	11.5		
	NAF-S-125	C	8.7	11.3	6.7	8.0				6.7	8.7
HFC-23	FE-13	A		18		18					
		B	12.9	16.8			12.6	16.4	15.6	12.5 (10.5 WdCrib)	16.3
FK-5-1-12	Novec 1230										
		A	4.5	5.9	3.5	4.2					
		B	4.5	5.9			4.5	5.9	5.6	4.1 (3.4 WdCrib)	5.3
IG-541	Inergen		28.9	37.6	28.5	34.2	31.7	41.2	39.1	30.7 (28.2 WdCrib)	36.5
IG-55	Argonite						36.5	47.5	45.1	31 (28.7 WdCrib)	40.3
IG-01	Argon						39.2	51.0	48.4	32.2 (30.7 WdCrib)	41.9
IG-100	Nitrogen						33.6	43.7	41.5	31.0 (30 WdCrib)	40.3

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Comparison of Design Concentrations for Class A Fires

Agent	Heptane MEC (NFPA 2001, 2008) (%)	Class A Design Conc. NFPA 2001/UL (%)	Ratio Class A Design to MEC (NFPA)	Class A Design Conc. (ISO 14520) (%)	Ratio Class A Design Conc. to MEC (ISO 14520)	Ratio Class A Design NFPA 2001 to ISO 14520
Halon 1301	3.4[a]	5[b]	1.47	--	--	--
CO_2	23[a]	>34[c]	1.48	--	--	--
HFC-227ea	6.7	6.25–7.0	0.93–1.04	7.9	1.2	0.79–0.88
HFC-125	8.7	8.0	0.92	11.2	1.3	0.71
HFC-23	12.9	16.8–18	1.3–1.4	16.3	1.26	1.03–1.1
FK-5-1-12	4.5	4.2	0.93	5.3	1.17	0.79
IG-541	31	34.2	1.1	36.5	1.17	0.94
IG-55	35	37.9	1.08	40.3	1.15	0.94
IG-01	42	--	--	41.9	1.0	--
IG-100	31	--	--	40.3	1.3	--

[a] From NFPA handbook (mid-range value) [b] From NFPA 12A [c] From NFPA 12

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

5.5.1 Clean Agent Hold Time and Leakage

In order to measure leakage in quiescent environments, the clean agent-air mixture density must be estimated using the following formula:

$$\rho_m = V_d \frac{C}{100} + \left[\frac{\rho_a (100 - C)}{100} \right]$$

where

ρ_m = clean agent-air mixture density (kg/m^3)

ρ_a = air density, 1.202 kg/m^3

C = clean agent concentration (%)

V_d = agent vapor density (kg/m^3), shown below

Agent	**Vapor Density (V_d) kg/m^3 (lb/ft^3)**
FC-3-10	9.85 (0.615)
HBFC-22B1	5.54 (0.346)
HCFC-Blend A	3.84 (0.240)
HFC-124	5.83 (0.364)
HFC-125	5.06 (0.316)
HFC-227ea	7.26 (0.453)
HFC-23	2.915 (0.182)
IG-541	1.43 (0.089)
Halon 1301	6.283 (0.392)

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

5.5.2 Atmospheric Lifetimes

Greenhouse gases break down in the atmosphere according to the following equation, which describes *e*-folding lifetimes instead of the more common half-lifetimes used in the nuclear field. This means that after a lifetime *L* there will be 1/*e* of the specimen left (0.368) instead of 1/2 of the specimen (0.5).

$$C = C_0 e^{-\mathrm{kt}}$$

where

C = concentration at time t

C_0 = initial concentration at time t

k = an experimentally determined rate constant, in units = 1/time

$$C = C_0 e^{-\mathrm{t/L}}$$

where L = the time it takes for the ratio of C:C_0 to be equal to $\frac{1}{e}$

Environmental Factors for Halocarbon Clean Agents

Designation	ODP	GWP (100 Years)	Atmospheric Lifetime (Years)
Halon 1301	12.000	7,030	65
HFC-227ea	0.000	2,900	34.2
HFC-23	0.000	14,310	270
HFC-125	0.000	3,450	29
NAFK-5-1-12	0.000	1	0.038
Inert gas	0.000	0	NA

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

5.5.3 Halocarbon Total Flooding

Toxicity Data for Halocarbon Clean Agent Fire Suppressants

Agent	Trade Name	LC_{50} and ALC (%)	NOAEL (%)	LOAEL (%)
FIC-1311	Triodide	>12.8	0.2	0.4
FK-5-1-12	Novec 1230	>10	10	>10
HCFC Blend A	NAFS-III	64	10	>10
HCFC-124	FE-24	23–29	1	2.5
HFC-125	FE-25	>70	7.5	10.0
HFC-227ea	FM-200	>80	9	10.5
HFC-23	FE-13	>65	30	>30
HFC-236fa	FE-36	>45.7	10	15
HFC Blend B	Halotron II	56.7[a]	5.0[a]	7.5[a]

1. LC_{50} is the concentration lethal to 50% of a rat population during a 4-hr exposure. ALC is the approx. lethal concentration.
2. Cardiac sensitization levels are based on the observance or nonobservance of serious heart arrhythmias in a dog. The usual protocol is a 5-min exposure followed by a challenge with epinephrine.
3. High concentration values are determined with the addition of oxygen to prevent asphyxiation.

[a] These values are for the largest component of the blend, HFC Blend B (HFC-134A).

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE

Physical Properties of Clean Halocarbon Agents (Metric Units)

Physical Property	Units	FIC-1311	FK-5-1-12	Blend A	HDFC Blend B	HFC HCFC-124	HFC-125	HFC-227ea	HFC-23	HFC-236fa
Molecular weight	NA	195.91	316.04	92.90	99.4	136.5	120	170	70.01	152
Boiling point at 760 mmHg	°C	–22.5	49	–38.3	–26.1	–12.0	–48.1	–16.4	–82.1	–1.4
Freezing point	°C	–110	–108	<107.2	–103	–198.9	–102.8	–131	–155.2	–103
Critical temperature	°C	122	168.66	124.4	101.1	122.6	66	101.7	26.1	124.9
Critical pressure	kPa	4,041	1,865	6,647	4,060	3,620	3,618	2,912	4,828	3,200
Critical volume	cc/mole	225	494.5	162	198	243	210	274	133	276
Critical density	kg/m^3	871	639.1	577	515.3	560	574	621	527	551.3
Specific heat, liquid at 25°C	kJ/kg °C	0.592	1.103	1.256	1.44	1.153	1.407	1.184	4.130 at 20°C	1.264
Specific heat, vapor at constant pressure (1 atm) and 25°C	kJ/k	0.3618	0.891	0.67	0.848	0.742	0.797	0.808	0.730 at 20°C	0.840
Heat of vaporization at boiling point	kJ/kg	112.4	88	225.6	217.2	165.9	164.1	132.6	239.3	160.4
Thermal conductivity of liquid at 25°C	W/m °C	0.07	0.059	0.09	0.082	0.0684	0.0592	0.069	0.0634	0.0729
Viscosity, liquid at 25°C	cP	0.196	0.524	0.21	0.202	0.257	0.14	0.184	0.044	0.286
Relative dielectric strength at 1 atm at 734 mm Hg, 25°C (N 2 = 1.0)	NA	1.41	2.3	1.32	1.014	1.55	0.955 at 21°C	2	1.04	1.0166
Solubility of water in agent	ppm	1.0062% by weight	<0.001	0.12% by weight	0.11% by weight	700 at 25°C	700 at 25°C	0.06% by weight	500 at 10°C	740 at 20°C

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Specific Volume Constants

Generic Name	Trade Name	k_1	k_2	k_1	k_2
		USCS	USCS	Metric	Metric
Halocarbons					
Halon 1301	Halon 1301	2.2062	0.005046	0.1478	0.00057
HFC-23	FE-13	4.7302	0.010699	0.3168	0.0011942
HFC-125	FM-25	2.722	0.006376	0.1828	0.0007085
HFC-227ea	FM-200	1.879775	0.0046625	0.1268	0.0005133
HFC-236fa	FE-36	2.0978	0.00514	0.1413	0.00058
FK-5-1-12	Novec 1230	0.9856	0.002441	0.0664	0.0002743
Inert Gases					
IG-01	Argon	8.40299	0.018281	0.5612	0.002054
IG-55	Argonite	9.8809	0.0214956	0.65979	0.0024134
IG-100	NN-100	11.976	0.02606	0.7997	0.002927
IG-541	Inergen	9.858	0.02143	0.659	0.00241

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Quantity of Halocarbon Agent

The quantity of halocarbon agent necessary to achieve an established design concentration is

$$w = \frac{V}{S}\left(\frac{C}{100 - C}\right)$$

where

V = net volume of protected space (ft^3 or m^3)

C = design concentration (%)

w = weight of agent required (lb or kg)

A_h, altitude correction factor, must be applied to the weight (w) of the agent required.

For –3,000 ft to 5,500 ft of equivalent altitude: $A_h = (-0.000036 \times X) + 1$

For 5,501 ft to 10,000 ft of equivalent altitude: $A_h = (-0.00003 \times X) + 0.96$

where

A_h = correction factor

X = altitude (ft)

Potential Human Health Effects of Hydrogen Fluoride in Healthy Individuals

Exposure Time	Hydrogen Fluoride (ppm)	Reaction
2 min	<50	Slight eye and nasal irritation
	50–100	Mild eye and upper respiratory tract irritation
	100–200	Moderate eye and upper respiratory tract irritation, slight skin irritation
	>200	Moderate irritation of all body surfaces, increasing concentration may impair escape
5 min	<50	Mild eye and nasal irritation
	50–100	Increasing eye and nasal irritation, slight skin irritation
	100–200	Moderate irritation of skin, eyes, and respiratory tract
	>200	Definite irritation of tissue surfaces, will impair escape at increased concentrations
10 min	<50	Definite eye, skin, and upper respiratory tract irritation
	50–100	Moderate irritation of all body surfaces
	100–200	Moderate irritation of all body surfaces, escape-impairing effects likely
	>200	Escape-impairing effects will occur, increasing concentrations can be lethal without medical intervention

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

5.5.4 Inert Gas Total Flooding

Physical Properties of Clean Inert Gas Agents (Metric Units)

Physical Property	Units	IG-01	IG-100	IG-541	IG-55
Molecular weight	NA	39.9	28.0	34.0	33.95
Boiling point at 760 mmHg	°C	–189.85	–195.8	–196	–190.1
Freezing point	°C	–189.35	–210.0	–78.5	–199.7
Critical temperature	°C	–122.3	–146.9	NA	–134.7
Critical pressure	kPa	4,903	3,399	NA	4,150
Specific heat, vapor at constant pressure (1 atm) and 25°C	kJ/kg °C	0.519	1.04	0.574	0.782
Heat of vaporization at boiling point	kJ/kg	163	199	220	181
Relative dielectric strength at 1 atm at 734 mm Hg, 25°C (N 2 = 1.0)	NA	1.01	1.0	1.03	1.01
Solubility of water in agent at 25°C	NA	0.006%	0.0013%	0.015%	0.006%

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

For inert gases, the following formula is used:

$$X = 2.303 \frac{V}{S} \log\left(\frac{100}{100 - C}\right) V_s$$

where

X = volume of inert gas required at 70°F or 21°C (ft^3 or m^3)

V_s = specific volume at 70°F or 21°C (ft^3 or m^3)

V = net protected hazard volume (ft^3)

S = specific volume (ft^3 or m^3)

$S = k_1 + k_2(T)$

where

T = minimum ambient temperature of the protected space (°F or °C)

k_1 and k_2 = constants in *Specific Volume Constants* table above

Altitude correction factor, Y, shall be applied.

For –3,000 ft to 5,500 ft of equivalent altitude: $Y = (-0.000036 \times X) + 1$

For 5,501 ft to 10,000 ft of equivalent altitude: $Y = (-0.00003 \times X) + 0.96$

where

Y = correction factor

X = altitude (ft)

Cup Burner Minimum Extinguishing Concentrations

Fuel	Cup Burner Extinguishment Concentration (vol%)				
	HFC-227eab	FC-3-1-10	HFC-23	HCFC Blend A	N2
Acetone	6.8	5.5[e]			
Acetonitrile	3.7				
AV gas	6.7				
n-Butanol	7.1				
n-Butyl acetate	6.6				
Cyclopentanone	6.7				
Diesel no. 2	6.7				
Ethanol	8.1	6.8[e]			
Ethyl acetate	5.6				
Ethylene glycol	7.8				
Gasoline (unleaded)	6.5				
Hydraulic fluid	5.8	4.3–4.5[a]			22–26[a]
JP-4	6.6				
JP-5	6.0[a]	4.8[a]			27[a]
	6.6[c]				
Methane	6.2				
Methanol	10.0	9.4[e]			
Methyl ethyl ketone	6.7				
Methyl isobutyl ketone	6.6				
Morpholine	7.3				
Propane	6.3	6.0[a]			32.5[a]
i-Propanol	7.3				
Pyrrolidine	7.0				
Tetrahydrofuran	7.2				
Toluene	5.8				
Turbo hydraulic oil 2380	5.1				
Xylene	5.3				

Note: For n-Heptane refer to NFPA 2001.

[a] from Hamins et al.
[b] from Robin
[c] from Sheinson et al.
[d] from Moore et al.
[e] from Ferreira et al.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

6 FIRE ALARM AND DETECTION

6.1 General Information

Fire alarm and detection systems rely heavily on the information contained in installation standards such as NFPA 72, National Fire Alarm and Signaling Code.

6.2 Heat Detector RTI

The use of RTI as a heat-transfer function is a simplification and incorporates both conductive and convective heat-transfer mechanisms.

$$\text{RTI} = \tau_0 \sqrt{u_0}$$

where

RTI = response time index ($\text{m}^{1/2}\text{s}^{1/2}$ or $\text{ft}^{1/2}\text{sec}^{1/2}$)

τ_0 = detector time constant (sec)

u_0 = gas velocity (1.5 m/s or 5.0 ft/sec, typ.)

The sensitivity of a detector can be expressed in terms of RTI as related to the flow of hot gases as

$$\text{RTI} = \frac{t_\text{r} u_0^{1/2}}{\ln\left(\dfrac{T_\text{g} - T_\text{a}}{T_\text{g} - T_\text{r}}\right)}$$

where

RTI = response time index ($\text{m}^{1/2}\text{s}^{1/2}$ or $\text{ft}^{1/2}\text{sec}^{1/2}$)

T_a = ambient temperature (°C or °F)

T_g = temperature of fire gases (°C or °F)

t_r = response time (sec)

u_0 = velocity at which τ_0 was measured (m/s or ft/sec)

T_r = T_s = rated operating temperature of a detector or sprinkler (°C or °F)

6.3 Rate of Heat Release

See Sections 3.2.6 to 3.2.10.

6.4 Heat Detector Spacing

6.4.1 Radial Distance from Fire Axis to Detector

$$s = r\sqrt{2}$$

where

S = spacing of detectors (ft or m)

r = radial distance from fire plume axis (ft or m)

$$r = \frac{S}{\sqrt{2}}$$

6.5 Smoke Detector Response

6.5.1 Obscuration

Percent obscuration:

$$O = 100\left(I - \frac{I}{I_0}\right)$$

Percent obscuration per unit distance, O_{u}:

$$O_{\mathrm{u}} = 100\left[1 - \left(\frac{I}{I_0}\right)^{1/I}\right]$$

where

I = intensity of light beam in presence of smoke (cd)

I_0 = initial intensity of light beam (cd)

Optical density:

$$D = \log_{10}\left(\frac{I_0}{I}\right) = -\log_{10}\left(\frac{I}{I_0}\right)$$

Optical density per unit distance, D_{u} (ft^{-1} or m^{-1}):

$$D_{\mathrm{u}} = \frac{D}{l} = \frac{1}{l}\log_{10}\left(\frac{I_0}{I}\right) = -\log_{10}\left(\frac{I}{I_0}\right)$$

where l = distance between source and photocell (ft or m)

6.5.2 Radiant Energy Detection

During the combustion process, electromagnetic radiation is emitted over a broad range of the spectrum. Currently, however, fire detection devices operate only in one of three bands: ultraviolet (UV), visible, or infrared (IR), where the wavelengths are defined within the following ranges:

Ultraviolet	0.1–0.35 μm
Visible	0.35–0.75 μm
Infrared	0.75–220 μm

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Radiant power to detector:

$$S = \frac{kPe^{\zeta d}}{d^2}$$

where

S = radiant power reaching detector (W)

k = proportionality constant for detector (m^{-2})

P = radiant power emitted by fire (W)

ζ = extinction coefficient of air (m^{-1})

d = distance between fire and detector (m)

6.5.3 Sensitivity Level

$$D_u = \frac{D_m(m)}{V_c} \qquad t_a = \frac{m}{m_{br}}$$

where

D_u = upper sensitivity level (m^{-1})

D_m = mass optical density (m^2/g)

m = mass (g)

V_c = volume of enclosure (m^3)

t_a = activation time (s)

m_{br} = mass burning rate (g/s)

6.6 Audibility Design

6.6.1 Sound Pressure Level

$$L_P = L_W + C_1 + C_2$$

where

L_P = sound pressure level (dBA)

L_W = sound power level (dB)

C_1 = adjustment for mounting position of sounder (dimensionless)

C_2 = adjustment for distance from sounder (dimensionless)

Adjustment for Mounting Position of Sounder (C_1)

Sounder Position	C_1
Wall/ceiling mounted (more than 1 m from any other major surface)	+5
Wall/ceiling mounted (closer than 1 m to one other major surface)	+7

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Adjustment for Distance (C_2) with Distance from Source (m)

Distance from Source (m)	C_2
1	–11
2	–17
3	–21
6	–27
12	–33
15	–35
20	–37
25	–39
30	–41
40	–43
50	–45
60	–47
80	–49
100	–51

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

6.6.2 Sound Power Level

$$L_W = L + 20\log_{10} r + 11$$

where

L_W = sound power level of sounder (dBA)

L = manufacturer's stated output (dBA)

r = distance (m)

6.7 Illumination Design

6.7.1 Illumination

$$E = \frac{I}{d^2}$$

where

E = illumination (lumens per unit area or footcandle)

I = intensity of light source (cd)

d = distance from light source to object (ft)

6.7.2 Effective Intensity

$$I_e = \frac{\left(\int_{t_1}^{t_2} I dt\right)}{\left(a + t_2 - t_1\right)}$$

where

I_e = effective intensity

I = instantaneous intensity

t_1 = time (s) of beginning of that part of the flash where I exceeds I_e

t_2 = time (s) of end of that part of the flash where I exceeds I_e

6.8 Voltage Drop Calculation

$$V_{\text{load}} = V_{\text{terminals}} - \left(I_{\text{load}} R_{\text{conductors}}\right)$$

where

V_{load} = 16 volts minimum operating voltage of appliance (unless otherwise specified)

$V_{\text{terminals}}$ = 20.4 volts (unless otherwise specified)

I_{load} = total current draw of appliance (A)

$R_{\text{conductors}}$ = conductor resistance (Ω)

7 SMOKE CONTROL

7.1 Fundamentals

7.1.1 Door Opening Forces

$$F = F_{DC} + \frac{k_d W A \Delta P}{2(W - d)}$$

where

F = total door opening force (lb or N)

F_{DC} = force to overcome door closer (lb or N)

W = door width (ft or m)

A = door area (ft^2 or m^2)

ΔP = pressure difference across door (in. H_2O or Pa)

d = distance from doorknob to edge of knob side of door (ft or m)

k_d = coefficient, 5.20 or 1.00

7.1.2 Wind Pressure

$$P_W = C_W K_W V^2$$

where

P_W = wind pressure (in. H_2O)

C_W = dimensionless pressure coefficient ranging from –0.8 to 0.8, with positive values for windward walls and negative values for leeward walls

K_W = coefficient, 4.82×10^{-4}

V = wind velocity (mph)

Local Design Wind

$$U_H = U_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{a_{met}}\left(\frac{H}{\delta}\right)^{a}$$

where

U_H = wind velocity at wall height H (mph or m/s)

U_{met} = measured velocity (mph or m/s)

H_{met} = height of wind measurement(ft or m)

δ_{met} = boundary layer height in vicinity of wind anemometer (ft or m)

a_{met} = wind exponent in vicinity of wind anemometer (dimensionless)

H = height of wall (ft or m)

δ = boundary layer height at wall (ft or m)

a = wind exponent at wall (dimensionless)

Wind Pressure on a Wall

$$p_w = 0.00645\, C_w \rho_o U_H^2$$

$$p_w = \frac{1}{2}\, C_w \rho_o U_H^2 \text{ for SI units}$$

where

p_w = wind pressure (in. H_2O or Pa)

C_w = pressure coefficient (dimensionless)

ρ_o = outside air density (lb/ft^3 or kg/m^3)

U_H = wind velocity at wall height H (mph or m/s)

7.1.3 Height of Flame Tip (z_l)

$$z_l = 0.533\dot{Q}_c^{2/5}$$

where

z_l = limiting elevation (ft)

$\dot{Q}_c$ = convection portion of heat release rate (Btu/sec)

= 70% of $\dot{Q}$ total = $0.7\dot{Q}$

7.1.4 Fuel Mass Consumed

Steady Fires

$$\dot{m}_f = \frac{\dot{Q}_t}{H_c}$$

where

$\dot{m}_f$ = mass burning rate (kg/s)

$\dot{Q}_t$ = total heat release rate for steady fires (kW)

H_c = heat of combustion (kJ/kg)

Unsteady t^2 fires

$$\dot{m}_f = 333 \frac{t^3}{H_c t_g^2}$$

where

$\dot{m}_f$ = mass burning rate (kg/s)

t = time (s)

H_c = heat of combustion (kJ/kg)

t_g = growth time (s)

7.1.5 Flow Paths

Effective Area for Flow Paths in Parallel

$$A_e = \sum_{i=1}^{n} A_i$$

where

A_e = effective flow area (ft^2 or m^2)

A_i = flow area of path i (ft^2 or m^2)

Effective Area for Flow Paths in Series

$$A_e = \left(\sum_{i=1}^{n} \frac{1}{A_i^2} \right)^{-1/2}$$

where

A_e = effective flow area (ft^2 or m^2)

A_i = flow area of path i (ft^2 or m^2)

7.1.6 Stack Effect/Buoyancy

$$\Delta P = K_S \left(\frac{1}{T_O} - \frac{1}{T_I} \right) h$$

where

ΔP = pressure difference (in. H_2O or Pa)

K_S = coefficient (7.64 or 3,460)

T_O = absolute temperature of outside air (°R or K)

T_I = absolute temperature of inside air (°R or K)

h = distance above neutral plane (ft or m)

Pressure difference for normal/reverse stack effect:

$$\Delta p_{\mathrm{SO}} = 7.63\left(\frac{1}{T_{\mathrm{O}}+460}-\frac{1}{T_{\mathrm{S}}+460}\right)z$$

$$\Delta p_{\mathrm{SO}} = 3{,}460\left(\frac{1}{T_{\mathrm{O}}+273}-\frac{1}{T_{\mathrm{S}}+273}\right)z \text{ for SI units}$$

where

Δp_{SO} = pressure difference from a shaft to the outside (in. H_2O or Pa)

T_{O} = temperature of outside air (°F or °C)

T_{S} = temperature of the shaft (°F or °C)

z = distance above neutral plane (ft or m)

7.1.7 Pressure Difference

$$\Delta p_{\mathrm{FS}} = 7.63\left(\frac{1}{T_{\mathrm{O}}+460}-\frac{1}{T_{\mathrm{F}}+460}\right)z$$

$$\Delta p_{\mathrm{FS}} = 3{,}460\left(\frac{1}{T_{\mathrm{O}}+273}-\frac{1}{T_{\mathrm{F}}+273}\right)z \text{ for SI units}$$

where

Δp_{FS} = pressure difference from fire space to surroundings (in. H_2O or Pa)

T_{O} = temperature of surroundings (°F or °C)

T_{F} = temperature of fire space (°F or °C)

z = distance above neutral plane (ft or m)

7.1.8 Untreated Pressurization Air

Stairwell Temperature

$$T_{\mathrm{S}} = T_{\mathrm{O}} + \eta(T_{\mathrm{B}} - T_{\mathrm{O}})$$

where

T_{S} = temperature in stairwell (°F or °C)

T_{O} = temperature of outside air (°F or °C)

T_{B} = temperature in building (°F or °C)

η = heat-transfer factor (dimensionless)

7.1.9 Scaling Relationships

Quintiere's review of scaling relationships based on preserving the Froude number, Fr (defined as v/gl):

For the relationships in this section the following apply:

- Subscript m identifies value for small-scale model
- Subscript F identifies value for full-scale building
- l = characteristic length

Temperature

$$T_{\mathrm{m}} = T_{\mathrm{F}}$$

Geometric Position

$$x_{\mathrm{m}} = x_{\mathrm{F}}\left(\frac{l_{\mathrm{m}}}{l_{\mathrm{F}}}\right)$$

where x = geometric position

Pressure

$$\Delta p_{\mathrm{m}} = \Delta p_{\mathrm{F}}\left(\frac{l_{\mathrm{m}}}{l_{\mathrm{F}}}\right)$$

where Δp = pressure difference

Velocity

$$v_{\mathrm{m}} = v_{\mathrm{F}}\left(\frac{l_{\mathrm{m}}}{l_{\mathrm{F}}}\right)^{1/2}$$

where v = velocity

Time

$$t_{\mathrm{m}} = t_{\mathrm{F}}\left(\frac{l_{m}}{l_{\mathrm{F}}}\right)^{1/2}$$

where t = time

Convective Heat Release

$$\dot{Q}_{\mathrm{c,m}} = \dot{Q}_{\mathrm{c,F}}\left(\frac{l_{\mathrm{m}}}{l_{\mathrm{F}}}\right)^{5/2}$$

where $\dot{Q}_{\mathrm{c}}$ = convective portion of heat-release rate of fire

$\dot{Q}_{\mathrm{c}}$= convection portion of heat release rate (Btu/sec)

$= 70\%$ of $\dot{Q}$ total $= 0.7\dot{Q}$

Volumetric Flow Rate

$$V_{\mathrm{fan,\,m}} = V_{\mathrm{fan,\,F}}\left(\frac{l_{\mathrm{m}}}{l_{\mathrm{F}}}\right)^{5/2}$$

where

V_{fan}, m = volumetric flow rate for small-scale model ($\mathrm{m^3/s}$)

V_{fan}, F = volumetric flow rate for full-scale building ($\mathrm{m^3/s}$)

l_{m} = length for small-scale model (m)

l_{f} = length for full-scale building (m)

7.1.10 Equivalent Width

Balcony spill plume:

$$L = w + b$$

where

L = width of balcony spill plume (m)

w = width of balcony opening from area of origin (m)

b = distance from store opening to balcony edge (m)

7.1.11 Gas Species Concentration

$$\text{ppm}_i = \frac{\text{MW}_{\text{air}}}{\text{MW}_i} Y_i \times 10^6$$

where

ppm_i = concentration (parts per million)

MW_{air} = molecular weight of air (kg)

MW_i = molecular weight of species i (kg)

Y_i = mass fraction of gas species

7.1.12 Exposure to Toxic Gases

Approximate effects of exposure to toxic gases:

$$\text{FED} = \frac{\sum_{i=1}^{n} C_i \Delta t_i}{LCt_{50}}$$

where

FED = fractional effective dose (dimensionless)

C_i = mass concentration of material burned at end of time interval i (lb/ft^3 or g/m^3)

Δt_i = time interval i (min)

LCt_{50} = lethal exposure dose from test data (lb-min/ft^3 of g-min/m^3)

n = number of discrete concentration time pairs

7.1.13 Heat Exposure for Hyperthermia

$$F_{\text{Ith}} = \sum_{i=1}^{n} \frac{\Delta t}{exp(5.67 - 0.0152T_i)}$$

$$F_{\text{Ith}} = \sum_{i=1}^{n} \frac{\Delta t}{exp(5.185 - 0.0273T_i)} \text{ for SI units}$$

where

F_{Ith} = total cumulative dose (dimensionless)

Δt = time interval (min)

T_i = temperature of air in interval i (°F or °C)

7.2 Smoke

Where makeup air could come into contact with the plume, the maximum air velocity is 200 ft/min (1.02 m/s). A higher makeup air velocity is permitted when supported by an engineering analysis.

7.2.1 Expansion Ratio

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{T_{\text{out}} + 460}{T_{\text{in}} + 460}$$

where

V_{out} = volumetric flow of smoke out of fire compartment (cfm or m^3/s)

V_{in} = volumetric flow of air into fire compartment (cfm or m^3/s)

T_{out} = temperature of smoke leaving fire compartment (°F or °C)

T_{in} = temperature of air entering fire compartment (°F or °C)

7.2.2 Optical Densities

Smoke-Filling

$$D = \frac{D_{\text{m}}\dot{Q}}{\chi_{\text{a}} H_{\text{c}} A(H - z)}$$

where

D = optical density per unit path length (m^{-1})

D_{m} = mass optical density (m^2/kg)

$\dot{Q}$ = heat release rate of fire (kW)

χ_{a} = combustion efficiency (dimensionless)

H_{c} = heat of combustion (kJ/kg)

A = cross-sectional area of atrium (m^2)

H = height of ceiling above top of fuel surface (m)

z = clear height, position of smoke layer interface above top of fuel surface (m)

Vented

$$D = \frac{D_{\text{m}}\dot{Q}}{\chi_{\text{c}} \Delta H_{\text{c}} \left(\frac{\dot{m}}{\rho}\right)}$$

where

D = optical density per unit path length (m^{-1})

D_{m} = mass optical density (m^2/kg)

$\dot{Q}$ = heat-release rate of fire (kW)

χ_{c} = combustion efficiency (dimensionless)

H_{c} = heat of combustion (kJ/kg)

$\dot{m}$ = mass entrainment rate in plume (kg/s)

ρ = density (kg/m^3)

7.2.3 Height of First Indication of Smoke for Steady Fires

$$\frac{z}{H} = 0.67 - 0.28\ln\left(\frac{\left(\frac{t\dot{Q}^{1/3}}{H^{4/3}}\right)}{\left(\frac{A}{H^2}\right)}\right)$$

Note: For SI Units, use 1.11 instead of 0.67

where

z = height of first indication of smoke above base of fire (m)

H = ceiling height above fire surface (m)

t = time (sec)

$\dot{Q}$ = heat release rate from steady fire (kw)

A = cross-sectional area (length × width) of space being filled with smoke (m^2)

$\frac{A}{H^2}$ = aspect ratio

Steady Fire Smoke Layer Position

$$\frac{z}{H} = \left[1 + \frac{2k_v t\dot{Q}^{1/3}}{3\left(\frac{A}{H^2}\right)H^{4/3}}\right]^{-3/2}$$

where

z = clear height, position of smoke layer interface above top of fuel surface (m)

H = height of ceiling above top of fuel surface (m)

k_v = volumetric entrainment constant (0.065 $m^{4/3}kW^{-1/3}s^{-1}$)

t = time (s)

$\dot{Q}$ = heat-release rate of fire (kW)

A = cross-sectional area of atrium (m^2)

t^2 Fire Smoke Layer Position

$$\frac{z}{H} = \left[1 + \frac{4k_v t\left(\frac{t}{t_g}\right)^{2/3}}{\left(\frac{A}{H^2}\right)H^{4/3}}\right]^{-3/2}$$

where

z = clear height, position of smoke layer interface above the top of fuel surface (m)

H = height of ceiling above top of fuel surface (m)

k_v = volumetric entrainment constant (0.065 $m^{4/3}kW^{-1/3}s^{-1}$)

t = time (s)

t_g = growth time (s)

A = cross-sectional area of the atrium (m^2)

Functional Relationship of the Mass Entrainment Rate

$$\dot{m} = f\left(\dot{Q}_c^{1/3} z^{5/3}\right)$$

where

$\dot{m}$ = mass entrainment rate in plume (kg/s)

$\dot{Q}_c$ = convective portion of heat release rate of fire (kW)

$\dot{Q}_c$ = convection portion of heat release rate (Btu/sec)

= 70% of $\dot{Q}$ total = $0.7\dot{Q}$

z = clear height, position of smoke layer interface above top of fuel surface (m)

The limiting height (z_f) may be estimated as

$$z_f = 0.166\dot{Q}_c^{2/5}$$

For clear heights less than the limiting height ($z < z_f$), the entrainment rate is

$$\dot{m} = 0.032\dot{Q}_c^{3/5} z$$

For clear heights greater than or equal to the limiting height ($z \geq z_f$), the entrainment rate is

$$\dot{m} = 0.071\dot{Q}_c^{1/3} z^{5/3} + 0.0018\dot{Q}_c$$

The validity of neglecting z_0 in the above equation is based on the observation that z_0 is typically small compared to z.

See Chapter 3, Section 3.1.11 for calculation of virtual origin.

7.2.4 Height of First Indication of Smoke for Unsteady (or Growing) Fires

$$\frac{z}{H} = 0.23\left[\frac{t}{t_g^{2/5} H^{4/5}\left(\frac{A}{H^2}\right)^{3/5}}\right]^{-1.45} \quad \text{or} \quad t = t_g^{2/5} H^{4/5}\left(\frac{A}{H^2}\right)^{3/5} \sqrt[1.45]{\frac{0.23H}{z}}$$

Note: For SI Units, use 0.91 instead of 0.23

where

z = height of first indication of smoke above fire surface (ft or m)

H = ceiling height above the surface (ft or m)

t = time (sec)

t_g = growth time (sec) (time for fire to reach 1,000 Btu/sec or 1,055 kW)

A = cross-sectional area of smoke filled space (ft^2 or m^2)

7.2.5 Transport Lag

Steady Fire Plume Transport Lag

$$t_{pl} = 0.67 H^{4/3} / \dot{Q}^{1/3}$$

t^2 Fire Plume Transport Lag

$$t_{\text{pl}} = 0.1H^{4/5}t_{\text{g}}^{2/5}$$

Steady Fire Ceiling Jet Transport Lag

$$t_{\text{cj}} = \frac{r^{11/6}}{1.2\dot{Q}^{1/3}H^{1/2}}$$

t^2 Fire Ceiling Jet Transport Lag

$$t_{\text{cj}} = \frac{0.72rt_{\text{g}}^{2/5}}{H^{1/5}}$$

For all:

t_{pl} = plume transport lag (s)

H = height of ceiling above top of fuel (m)

$\dot{Q}$ = heat release rate of fire (kW)

t_{g} = growth time (s)

r = horizontal distance from plume centerline (m)

t_{cj} = ceiling jet transport lag (s)

7.2.6 Mass Flow Rate if $H > z_l$ (Axisymmetric Plume)

Use where ambient temperature rise is more than 4°F.

$$m = \left[0.022\dot{Q}_c^{1/3}z^{5/3}\right] + 0.0042\dot{Q}_{\text{c}}$$

where

m = mass flow rate of plume at height z (lb/sec)

$\dot{Q}_{\text{c}}$ = convection portion of heat release rate (Btu/sec)

$\dot{Q}_{\text{c}}$ = convection portion of heat release rate (Btu/sec)

= 70% of $\dot{Q}$ total = $0.7\dot{Q}$

z = height above the fuel (ft)

$$z_l = 0.166\dot{Q}_{\text{c}}^{2/5}$$

when $z > z_l$, $m = 0.071\dot{Q}_{\text{c}}^{1/3}z^{5/3} + 0.0018\dot{Q}_{\text{c}}$

when $z \le z_l$, $m = 0.032\dot{Q}_{\text{c}}^{3/5}z$

where

z_l = limiting elevation (m)

$\dot{Q}_c$ = convective portion of heat-release rate (kW)

$\dot{Q}_{\text{c}}$ = convection portion of heat release rate (Btu/sec)

= 70% of $\dot{Q}$ total = $0.7\dot{Q}$

z = distance from base of fire to smoke layer interface (m)

m = mass flow rate in plume at height z (kg/s)

$$z_l = 0.533\dot{Q}_c^{2/5}$$

$$\text{when } z > z_l,\ m = \left(0.022\dot{Q}_c^{1/3} z^{5/3}\right) + 0.0042\dot{Q}_c$$

$$\text{when } z \le z_l,\ m = 0.0208\dot{Q}_c^{3/5} z$$

where

z_l = limiting elevation (ft)

$\dot{Q}_c$ = convective portion or heat release rate (Btu/sec)

$\dot{Q}_c$ = convection portion of heat release rate (Btu/sec)

= 70% of $\dot{Q}$ total = $0.7\dot{Q}$

z = distance above the base of the fire to the smoke layer interface (ft)

m = mass flow rate in plume at height z (lb/sec)

7.2.7 Average Mass Vent Flow Rate of Fire Plume

$$m_p = \left(\frac{\rho_o^2 g}{2}\right)^{1/2} A_v d^{1/2}$$

where

m_p = mass flow rate of the plume (lb/sec)

ρ_o = density of air (0.075 lb/ft^3)

g = acceleration of gravity (32.2 ft/sec^2)

A_v = aerodynamic vent area (ft^2)

d = depth of the smoke layer (ft)

7.2.8 Volumetric Flow Rate

$$V = \frac{60m}{\rho}$$

where

V = volumetric flow rate (ft^3/min)

m = mass flow rate of plume at height z (lb/sec)

ρ = density of air (0.075 lb/ft^3)

Ratio of Volumetric Flows

$$\frac{V_{out}}{V_{in}} = \frac{T_{out} + 460}{T_{in} + 460}$$

$$\frac{V_{out}}{V_{in}} = \frac{T_{out} + 273}{T_{in} + 273} \text{ for SI units}$$

where

V_{out} = volumetric flow of smoke out of fire compartment (cfm or m^3/s)

V_{in} = volumetric flow of air into fire compartment (cfm or m^3/s)

T_{ou} = temperature of smoke leaving fire compartment (°F or °C)

T_{in} = temperature of air entering fire compartment (°F or °C)

Relationship for Volumetric Rate and Mass Rate

$$\dot{V} = \frac{\dot{m}}{\rho}$$

7.2.9 Density of Smoke

$$\rho_s = \frac{528\rho_o}{460 + T}$$

where

ρ_0 = density of ambient air at sea level ($0.0765\ \text{lb/ft}^3$)

ρ_s = density of smoke at temperature T (lb/ft^3)

T = temperature of smoke (°F)

$$\rho_s = \frac{144P_{\text{atm}}}{R(460 + T)}$$

where

P_{atm} = atmospheric pressure (14.696 psi)

R = gas constant (53.34)

ρ_s = density of smoke at temperature T (lb/ft^3)

T = temperature of smoke (°F)

Density of Air and Smoke

$$\rho = \frac{144p}{R(T + 460)}$$

$$\rho = \frac{p}{R(T + 273)} \text{ for SI units}$$

where

ρ = density (lb/ft^3 or kg/m^3)

p = pressure (lb/in^2 or Pa)

R = gas constant [$53.34\ \text{ft-lb}_f/\text{lb}_m\text{-°R}$ or 287 J/kg-K]

T = temperature (°F or °C)

7.2.10 Maximum Flow Rate to Avoid Plugholing

$$m_{\max} = 0.354\beta d^{\frac{5}{2}}\left(\frac{T_s - T_o}{T_s}\right)^{\frac{1}{2}}\left(\frac{T_o}{T_s}\right)^{\frac{1}{2}}$$

where

$m_{\max}$ = maximum mass rate of exhaust without plugholing (lb/sec)

β = exhaust location (dimensionless)

d = depth of smoke layer below exhaust inlet (ft)

T_s = absolute temperature of smoke layer (°R)

T_o = absolute temperature of ambient layer (°R)

Volumetric Flow Rate

$$V_{\max} = 452\gamma d^{5/2}\left(\frac{T_s - T_o}{T_o}\right)^{1/2}$$

where

$V_{\max}$ = maximum volumetric flow rate without plugholing at T_s (ft^3/min)

γ = exhaust location factor

= 1 for exhaust inlets centered no closer than twice the diameter from nearest wall
0.5 for exhaust inlets centered less than twice the diameter from nearest wall
0.5 for exhaust inlets on a wall

d = depth of smoke layer below lowest point of exhaust inlet (ft)

T_s = absolute temperature of smoke layer (°R)

T_o = absolute temperature of ambient layer (°R)

To avoid plugholing, the maximum exhaust capacity at an extract point is:

$$\dot{V}_{\max} = 4.16\gamma d^{5/2}\left(\frac{\Delta T}{T_o}\right)^{1/2}$$

where γ = factor relating to the location of the vent; if the vent is in the middle of the space, $\gamma = 1$

7.2.11 Plume Rise

$$z_m = 3.79F^{1/4}G^{-3/8}$$

where

z_m = maximum rise of plume (m)

$$F = \frac{g\dot{Q}_c}{T_o\rho_o c_p} \quad \text{and} \quad G = -\left(\frac{g}{\rho_o}\right)\frac{d\rho_o}{dz}$$

where

g = gravity = 9.81 m/s^2

$\dot{Q}_c$ = convective portion of heat release rate (kW)

$\dot{Q}_c$ = convection portion of heat release rate (Btu/sec)

= 70% of $\dot{Q}$ total = $0.7\dot{Q}$

ρ_0 = density of ambient air at sea level (kg/m^3)

z = clear height, position of smoke layer interface above top of fuel surface (m)

T_o = ambient temperature (K)

c_p = specific heat (kJ/kg-K)

For standard conditions and ideal gas behaviors:

$$F = 0.0277\,\dot{Q}_c \quad \text{and} \quad G = 0.0335\,\frac{dT_o}{dz}$$

Using simplified *F* and *G* above:

$$z_m = 5.54\dot{Q}_c^{1/4}\left(\frac{\Delta T_o}{H}\right)^{-3/8}$$

where *H* = height of ceiling above top of fuel surface (m)

Minimum fire size for smoke to reach atrium ceiling without stratifying:

$$\dot{Q}_c = 0.00118H^{5/2}\Delta T_o^{3/2}$$

7.2.12 Plume Width

$$d = 2.4\alpha z$$

where

d = plume diameter (m)

z = clear height, position of smoke layer interface above top of fuel surface (m)

where

$$\alpha \cong 0.15$$
$$d = 0.36z$$

Handa and Sugawa Empirical Correlation

$$d = d_o z^{1/2}$$

where d_o = diameter of fire (m)

7.2.13 Plume Diameter

$$d = 0.48\left(\frac{T_c}{T_o}\right)^{1/2} z$$

where

T_c = temperature of plume centerline (K)

T_o = ambient temperature (K)

z = clear height, position of smoke layer interface above top of fuel surface (m)

7.2.14 Balcony Spill Plume—Air Entrainment

Where the height of the smoke layer is less than 15 m

$$\dot{m} = 0.36\left(\dot{Q}W^2\right)^{1/3}\left(z_\mathrm{b} + 0.25H\right)$$

where

W = width of balcony opening from area of origin (m)

z_b = position of smoke layer interface above top of balcony (m)

H = height of ceiling above top of fuel surface (m)

$\dot{Q}$ = heat release rate of fire (kW)

$\dot{m}$ = mass flow rate in plume (kg/s)

Where the height of the smoke layer is less than 15 m and the width of the plume is less than 10 m

$$\dot{m} = 0.59\dot{Q}^{1/3}W^{1/5}\left(z_\mathrm{b} + 0.17\dot{W}^{7/15}H + 10.35W^{7/15} - 15\right)$$

7.2.15 Average Temperature of Fire Plume

$$T_\mathrm{p} = T_\mathrm{o} + \frac{\dot{Q}_\mathrm{c}}{mc_\mathrm{p}}$$

where

T_p = average plume temperature at elevation z (°F)

T_o = ambient temperature (°F)

$\dot{Q}_\mathrm{c}$ = convection portion of heat release rate (Btu/sec)

m = mass flow rate of plume at height z (lb/sec)

c_p = specific heat of plume gases (0.24 Btu/lb-°F)

7.2.16 Plume Centerline Temperature

$$T_\mathrm{c} = 0.08T_\mathrm{o}\dot{Q}_\mathrm{c}^{2/3}z^{-5/3} + T_\mathrm{o}$$

where

T_c = temperature of plume centerline (K)

T_o = ambient temperature (K)

$\dot{Q}_\mathrm{c}$ = convection portion of heat release rate (kW)

z = clear height, position of smoke layer interface above top of fuel surface (m)

Volumetric venting rate for other heat release rates/temperature rises:

$$\frac{Q_\mathrm{c1}}{Q_\mathrm{c2}} = \frac{V_1}{V_2}\,\frac{\Delta T_\mathrm{ad1}}{T_\mathrm{ad2}}\,\frac{T_2}{T_1}$$

7.2.17 Temperature During Filling Period

$$T = T_o \exp\left[\frac{(1-\chi_l)Q}{Q_o}\right]$$

where

χ_l = heat-loss fraction from smoke to enclosure (dimensionless)

T_o = ambient temperature (K)

Q = total heat release (kJ)

Q_o = $\rho_o\, c_p\, T_o\, A\, (H - z)$ (kJ)

where A = cross-sectional area of atrium (m^2)

ρ_0 = density of ambient air (kg/m^3)

c_p = specific heat (kJ/kg-K)

T_o = ambient temperature (K)

A = cross sectional area of atrium (m)

H = height of atrium (m)

Z = clear height, position of smoke layer interface above top of fuel surface (m)

7.2.18 Temperature Rise of Smoke Layer

$$\Delta T = \frac{(1-\chi_l)\dot{Q}_c}{c_p \dot{m}}$$

where

χ_l = heat-loss fraction from smoke to enclosure (dimensionless)

$\dot{Q}_c$ = convection portion of heat-release rate (kW)

$\dot{m}$ = mass entrainment rate in plume (kg/s)

7.2.19 Species of Smoke

Smoke-Filling

$$\Upsilon_i = \frac{f_i Q}{\rho_o \chi_a H_c A(H-z)}$$

where

Q = total heat release (kJ)

ρ_0 = density of ambient air (kg/m^3)

Υ_i = mass fraction of gas species i, in kg of species i per kg of smoke

f_i = yield fraction of species i, in kg of species i per kg of fuel consumed

χ_a = combustion efficiency (dimensionless)

H_c = heat of combustion (kJ/kg)

A = cross-sectional area of atrium (m^2)

H = height of ceiling above top of fuel surface (m)

z = clear height, position of smoke layer interface above top of fuel surface (m)

Vented

$$\Upsilon_i = \frac{f_i Q}{\dot{m}\chi_a H_c}$$

Q = total heat release (kJ)

$\dot{m}$ = mass entrainment rate in plume (kg/s) [all others per above]

7.2.20 Smoke Layer Temperature

$$T_s = T_o + \frac{k_s \dot{Q}_c}{mc_p}$$

where

T_s = smoke layer temperature (°C)

T_o = ambient temperature (°C)

k_s = fraction of convective heat release contained in smoke layer; assume that $k_s = 1.0$ unless another value is given

$\dot{Q}_c$ = convective portion of heat release rate (kW)

$\dot{Q}_c$ = convection portion of heat release rate (Btu/sec)

= 70% of $\dot{Q}$ total = $0.7\dot{Q}$

m = mass flow rate of the plume at elevation z, distance above the base of the fire (kg/s)

c_p = specific heat of plume gases (1.0 kJ/kg•°C)

7.2.21 Vented Fire Smoke Layer Temperature Change

$$\Delta T = \frac{\left[60\left(1 - x_1\right)\dot{Q}_c\right]}{\rho_o c_p V}$$

where

ΔT = temperature rise in smoke layer (°F)

x_1 = total heat-loss factor from smoke layer to atrium boundaries (assume maximum temperature rise will occur, $\therefore x_1 = 0$)

$\dot{Q}_c$ = convective heat release rate (Btu/sec)

$\dot{Q}_c$ = convection portion of heat release rate (Btu/sec)

= 70% of $\dot{Q}$ total = $0.7\dot{Q}$

ρ_o = density of ambient air (0.075 lb/ft^3)

c_p = specific heat of plume gases (0.241 Btu/lb-°F)

V = volumetric vent rate (ft^3/min)

7.2.22 Smoke Flow Across an Opening/Pressurization

$$V = 776\,CA\sqrt{\frac{2\Delta P}{\rho}} \quad (\text{English})$$

where

V = volumetric airflow rate (ft^3/min)

C = flow coefficient (0.65)

A = flow area (also leakage area) (ft^2)

ΔP = pressure difference across flow path (in. H_2O)

ρ = density of air entering the flow path (lb/ft^3)

$$V = CA\sqrt{\frac{2\Delta P}{\rho}} \quad (\text{SI})$$

where

V = volumetric airflow rate (m^3/s)

C = flow coefficient (0.65)

A = flow area (also leakage area) (m^2)

ΔP = pressure difference across flow path (Pa)

ρ = density of air entering the flow path (kg/m^3)

7.2.23 Flow Rate of Smoke Through a Vent

$$\frac{1}{2}\rho_o \mu^2 = \Delta\rho g d$$

where

ρ = density of smoke (kg/m^3)

ρ_o = density of ambient air (kg/m^3)

$\Delta\rho$ (kg/m^3) = $\rho_o - \rho$

$$\dot{m} = \rho A_v u$$

where

$\dot{m}$ = mass flow rate through vent (kg/s)

A_v = flow area of vent (m^2)

g = gravitational acceleration (9.8 m/s^2)

$$\dot{m} = \left(2\rho_o^2 g\right)^{1/2}\left(\frac{T_o \Delta T}{T^2}\right)^{1/2} A_v d^{1/2}$$

Flow rate increases with smoke temperature and depth:

$$\dot{m} = \left(2\rho_o^2 g\right)^{1/2} \left(\frac{T_o \Delta T}{T^2}\right)^{1/2} \frac{A_v d^{1/2}}{\sqrt{1 + \frac{C_d^2 A_v^2 T_o}{C_{d,i}^2 A_i^2 T_o}}}$$

where

T_o = ambient air temperature (K)

T = gas temperature (K)

d = depth of smoke layer (m)

7.2.24 Vent Area

Effect of inlet pressure can replace A_v with effective vent area A_v^*:

$$\frac{1}{A_v^{*2}} = \frac{1}{A_v^2} + \frac{1}{A_i^2}\left(\frac{T_o}{T}\right)$$

Ratio of actual vent area to effective vent area, K:

$$K = \frac{A_v}{A_v^*} = \left[1 + \left(\frac{A_v}{A_i}\right)^2 \frac{T}{T_o}\right]^{1/2}$$

7.3 Airflow

7.3.1 Airflow Rate for Pressure Differences – Barriers

$$V = K_f A \sqrt{\Delta P}$$

where

V = airflow velocity (ft/min)

K_f = coefficient (2,610)

A = flow area (ft^2)

ΔP = pressure difference across flow path (in. H_2O)

7.3.2 Critical Airflow Velocity for Smoke Control

$$V_K = K_V \left(\frac{Q}{W}\right)^{1/3}$$

where

V_K = critical air velocity to prevent smoke backflow (ft/min or m/s)

Q = heat release rate into corridor (Btu/sec or kW)

W = corridor width (ft or m)

K_V = coefficient (86.9 or 0.292)

7.3.3 Velocity Required for Opposed Airflow Above Smoke Layer Interface

$$v_e = 38\left[gH\left(\frac{T_f - T_o}{T_f}\right)\right]^{1/2}$$

where

v_e = limiting air velocity (ft/min)

g = acceleration of gravity (32.2 ft/sec^2)

H = height of opening as measured from top of fuel surface (ft)

T_f = temperature of heated smoke (°R)

T_o = temperature of ambient air (°R)

$$v_e = 0.64\left[gH\left(\frac{T_f - T_o}{T_f}\right)\right]^{1/2}$$

where

v_e = limiting air velocity (m/sec)

g = acceleration of gravity (9.81 m/s^2)

H = height of opening as measured from top of fuel surface (m)

T_f = temperature of heated smoke (K)

T_o = temperature of ambient air (K)

7.3.4 Velocity Required for Opposed Airflow Below Smoke Layer Interface

$$v_e = 17\left(\frac{Q}{z}\right)^{1/3}$$

where

v_e = limiting average air velocity (ft/min)

Q = heat-release rate of the fire (Btu/sec)

z = distance above the base of the fire to the bottom of the opening (ft)

$$v_e = 0.057\left(\frac{Q}{z}\right)^{1/3}$$

where

v_e = limiting average air velocity (m/s)

Q = heat release rate of fire (kW)

z = distance above base of fire to bottom of opening (m)

7.3.5 Capacity Required for Opposed Airflow

Volumetric capacity of mechanical equipment required to deliver necessary velocity for opposed airflow

$$v_{oa} = A_o v_e$$

where

v_{oa} = volumetric flow rate (m^3/s)

A_o = cross-sectional area of opening (m^2)

v_e = limiting average air velocity (m/s)

7.3.6 Leakage Area

$$A_e = \left(\frac{1}{A_{sr}^2} + \frac{1}{A_{ir}^2} + \frac{1}{A_{io}^2}\right)^{-1/2}$$

where

A_{sr} = leakage area between shaft and lobby (ft^2 or m^2)

A_{ir} = leakage area between building and lobby (ft^2 or m^2)

A_{io} = leakage area between building and outside (ft^2 or m^2)

Flow Areas of Walls and Floors of Commercial Buildings

Construction Element	Leakage	Area Ratio		
		Leakage Area per Unit Wall Area		
		in²/ft²	ft²/ft²	m²/m²
Exterior Building Walls (includes construction cracks, cracks around windows and doors)	Tight	7.2×10^{-3}	5.0×10^{-5}	5.0×10^{-5}
	Average	2.5×10^{-2}	1.7×10^{-4}	1.7×10^{-4}
	Loose	5.0×10^{-2}	3.5×10^{-4}	3.5×10^{-4}
	Very loose	1.7×10^{-1}	1.2×10^{-3}	1.2×10^{-3}
Stairwell Walls (includes construction cracks but not cracks around windows or doors)	Tight	2.0×10^{-3}	1.4×10^{-5}	1.4×10^{-5}
	Average	1.6×10^{-2}	1.1×10^{-4}	1.1×10^{-4}
	Loose	5.0×10^{-2}	3.5×10^{-4}	3.5×10^{-4}
Elevator Shaft Walls (includes construction cracks but not cracks around doors)	Tight	2.6×10^{-2}	1.8×10^{-4}	1.8×10^{-4}
	Average	1.2×10^{-1}	8.4×10^{-4}	8.4×10^{-4}
	Loose	2.6×10^{-1}	1.8×10^{-3}	1.8×10^{-3}
		Leakage Area per Unit Floor Area		
		in²/ft²	ft²/ft²	m²/m²
Floors (includes construction cracks and gaps around penetrations)	Tight	9.5×10^{-4}	6.6×10^{-6}	6.6×10^{-6}
	Average	7.5×10^{-3}	5.2×10^{-5}	5.2×10^{-5}
	Loose	2.4×10^{-2}	1.7×10^{-4}	1.7×10^{-4}

Note: The data in this table are for use with the orifice equation with a flow coefficient of $C = 0.65$.
Floor leakage does not account for gaps that sometimes exist between the floor and curtain walls.

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7.3.7 Limiting Average Velocity Through Communicating Space

$$v_e = 17\left(\frac{Q}{z}\right)^{1/3}$$

where

v_e = limiting air velocity (ft/min)

Q = heat release rate of fire (Btu/sec)

z = distance above the base of the fire to the bottom of the opening (ft)

7.3.8 Elevator Pressurization

Pressure Differences Criteria for Elevator Pressurization Simulations

System	Minimum		Maximum	
	in. H_2O	Pa	in. H_2O	Pa
Pressurized elevators	0.10	25	0.25	62
Pressurized stairwells	0.10	25	0.35	87

The above criteria are for the elevator simulations discussed in Chapter 11 of the *Handbook of Smoke Control Engineering*, and some projects may have different criteria depending on code requirements and requirements of specific applications.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Flow Areas and Flow Coefficients of Doors Used for Elevator Pressurization Simulations

Flow Path	Path Name	Flow Coefficient	Flow Area	
			ft^2	m^2
Single door (closed)	DOOR-SC	0.65	0.25	0.023
Single door (opened)	DOOR-SO	0.35	21	2.0
Double door (closed)	DOOR-DC	0.65	0.48	0.045
Double door (opened)	DOOR-DO	0.35	42	3.9
Elevator door (closed)	DOOR-EC	0.65	0.65	0.06
Elevator door (opened)	DOOR-EO	0.65	6	0.56

The values in this table were chosen for the elevator simulations discussed in Chapter 11 of the Handbook of Smoke Control Engineering. The flow areas and flow coefficients appropriate for a design analysis of a specific building may be different.
The path name is an identifier used in the CONTAM simulations.

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7.3.8.1 Leakage Factors

Flow Areas and Flow Coefficients of Leakages Used for Elevator Pressurization Simulations

Flow Path	Leakage	Path Name	Flow Coefficient	Flow Area	
				ft^2 per ft^2 of Wall	m^2 per m^2 of Wall
Exterior walls	Tight	WALL-EXT	0.65	0.5×10^{-4}	0.5×10^{-4}
	Average			0.17×10^{-3}	0.17×10^{-3}
	Loose			0.35×10^{-3}	0.35×10^{-3}
	Very loose			0.12×10^{-2}	0.12×10^{-2}
Interior walls	Loose	WALL	0.65	0.35×10^{-3}	0.35×10^{-3}
Floor (or roof)	Tight	FLOOR	0.65	0.66×10^{-5}	0.66×10^{-5}
	Average			0.52×10^{-4}	0.52×10^{-4}
	Loose			0.17×10^{-3}	0.17×10^{-3}
				ft^2 per ft of wall	m^2 per m of wall
Curtain wall gap	Tight	FLOORW	0.65	0.002	0.00061
	Loose			0.02	0.0061

The values in this table were chosen for the elevator simulations discussed in Chapter 11 of the *Handbook of Smoke Control Engineering*. The flow areas and flow coefficients appropriate for a design analysis of a specific building may be different. The path name is an identifier used in the CONTAM simulations.

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7.3.9 Elevator Piston Effect for Elevators

$$\Delta p_{u,ir} = \frac{1.66 \times 10^{-6} \rho}{2} \left(\frac{A_s A_e U}{A_a A_{ir} C_c} \right)^2$$

$$\Delta p_{u,ir} = \frac{\rho}{2} \left(\frac{A_s A_e U}{A_a A_{ir} C_c} \right)^2 \text{ for SI units}$$

where

$\Delta p_{u,ir}$ = upper limit pressure difference from shaft to building (in. H_2O or Pa)

ρ = air density in hoistway (lb/ft^3 or kg/m^3)

A_S = cross-sectional area of shaft (ft^2 or m^2)

A_{ir} = leakage area between building and lobby (ft^2 or m^2)

A_a = free area around elevator car (ft^2 or m^2)

A_e = effective area (ft^2 or m^2)

U = elevator car velocity (ft/min or m/s)

C_c = flow coefficient for flow around car (dimensionless)

C_c was determined experimentally to be 0.94 for multiple car hoistways and 0.83 for a single car hoistway. The free area around the elevator car is the cross-sectional area of the shaft minus the cross-sectional area of the car.

7.3.10 Stairwell Pressurization

$$\Delta P_{\mathrm{SB}} = \Delta P_{\mathrm{SBb}} + \frac{by}{1 + \left(\frac{A_{\mathrm{SB}}}{A_{\mathrm{BO}}}\right)^2}$$

where

ΔP_{SB} = P = pressure difference between stairwell and building (in. H_2O) (92A T5.2.1.1)

ΔP_{SBb} = S = pressure difference between stairwell and building at bottom of stairwell (in. H_2O)

A_{SB} = A = flow area between stairwell and building (ft^2)

A_{BO} = O = flow area between building and outside (ft^2)

y = Y = distance above stairwell bottom (ft)

$$b = K_{\mathrm{s}}\left(\frac{1}{T_{\mathrm{O}}} - \frac{1}{T_{\mathrm{S}}}\right)$$

where

b = B = temperature factor (in. H_2O/ft)

K_{s} = K = 7.64

T_{O} = T = absolute temperature of outside air (°R)

T_{S} = S = absolute temperature of stairwell air (°R)

$$Q = K_{\mathrm{q}} \frac{NA_{\mathrm{SB}}}{\sqrt{\rho}} \left(\frac{\Delta P_{\mathrm{SBt}}^{3/2} - \Delta P_{\mathrm{SBb}}^{3/2}}{\Delta P_{\mathrm{SBt}} - \Delta P_{\mathrm{SBb}}}\right)$$

where

Q = flow rate of pressurization air (ft^3/min)

N = number of floors

A_{SB} = A = flow area between stairwell and building (ft^2)

ρ = P = density of air (0.075 lb/ft^3)

ΔP_{SBb} = B = pressure difference at bottom of stairwell (in. H_2O)

ΔP_{SBt} = T = pressure difference at top of stairwell (in. H_2O)

K_{q} = 475

Orifice equation for analysis of pressurization smoke control systems:

$$m = 12.9CA\sqrt{2\rho\Delta p}$$

$$m = CA\sqrt{2\rho\Delta p} \text{ for SI units}$$

Orifice equation for standard atmospheric pressure and mass flow at 70°F (21°C):

$$m_{\mathrm{sv}} = 2{,}610\, CA\sqrt{\Delta p}$$

$$m_{\mathrm{sv}} = 0.839\, CA\sqrt{\Delta p} \text{ for SI units}$$

where

m = mass flow through the path (lb/sec or kg/s)

m_{sv} = mass flow through the path (scfm or standard m^3/s)

C = flow coefficient (dimensionless)

A = flow area (or leakage area) (ft^2 or m^2)

Δp = pressure difference across path (in. H_2O or Pa)

ρ = gas density in flow path (lb/ft^3 or kg/m^3)

Orifice equation in terms of volumetric flow:

$$V = 776\, CA \sqrt{\frac{2\Delta p}{\rho}}$$

$$V = CA \sqrt{\frac{2\Delta p}{\rho}} \text{ for SI units}$$

where V = volumetric flow through the path (cfm or m^3/s)

7.3.11 Stairwell Pressurization Height Limitation

$$H_m = K_m \frac{\Delta p_{max} - \Delta p_{min}}{\left(\frac{1}{T_O} - \frac{1}{T_B}\right)} \left[1 + \left(\frac{A_{SB}}{A_{SO}}\right)^2\right]$$

where

H_m = height limit (ft)

Δp_{max} = maximum allowable pressure difference between stairwell and building (in. H_2O)

Δp_{min} = minimum allowable pressure difference between stairwell and building (in. H_2O)

T_O = absolute temperature of outside air (°R)

T_B = absolute temperature of building air (°R)

A_{SB} = flow area between stairwell and building (ft^2)

A_{SO} = flow area between building and outside (ft^2)

K_m = 0.131

$$H_m = 0.131 \frac{F_R\left(\Delta p_{max} - \Delta p_{min}\right)}{\left|\frac{1}{T_o + 460} - \frac{1}{T_s + 460}\right|}$$

$$H_m = 2.89 \times 10^{-4} \frac{F_R\left(\Delta p_{max} - \Delta p_{min}\right)}{\left|\frac{1}{T_o + 273} - \frac{1}{T_s + 273}\right|} \text{ for SI units}$$

where

H_m = height limit (ft or m)

F_R = flow area factor (dimensionless)

Δp_{max} = maximum design pressure difference (in. H_2O or Pa)

Δp_{min} = minimum design pressure difference (in. H_2O or Pa)

Flow Area Factor

$$F_R = 1 + \frac{A_{SB}^2 \left(T_B + 460\right)}{A_{BO}^2 \left(T_S + 460\right)}$$

$$F_R = 1 + \frac{A_{SB}^2 \left(T_B + 273\right)}{A_{BO}^2 \left(T_S + 273\right)} \text{ for SI units}$$

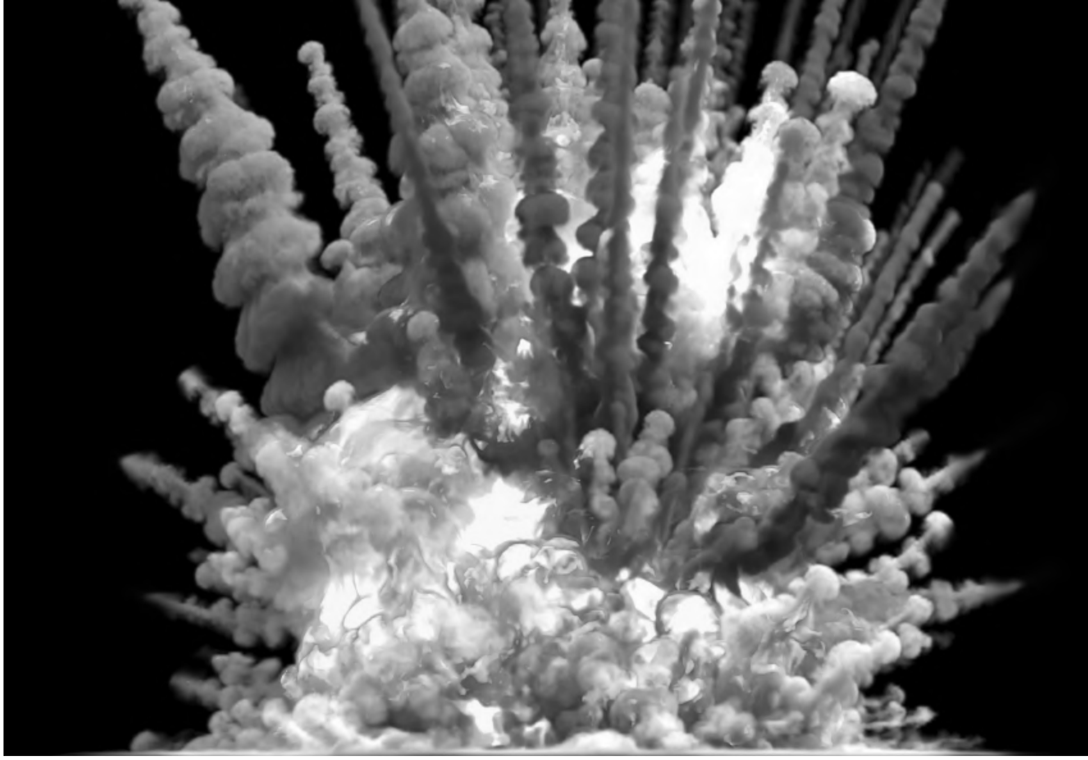
where

A_{SB} = flow area between stairwell and building (ft^2 or m^2)

A_{BO} = flow area per stairwell between building and outside (ft^2 or m^2)

T_S = temperature in stairwell (°F or °C)

T_B = temperature in building (°F or °C)



8 HAZARDOUS MATERIALS

8.1 Flammability

Flammable describes any solid, liquid, vapor, or gas that will ignite easily and burn rapidly. A flammable liquid is defined by NFPA and USDOT as a liquid with a flash point below 100°F (38°C). Flammability limits are given by volume % in air.

8.1.1 Lower Flammable Limit

$$\mathrm{LFL} = \frac{V_{\mathrm{LFL}}}{0.147}$$

where

LFL = lower flammable limit

V_{LFL} = vapor pressure of liquid at its LFL (psia)

$$\mathrm{LFL} = \frac{V_{\mathrm{LFL}}}{1.01}$$

where

LFL = lower flammable limit

V_{LFL} = vapor pressure of liquid at its LFL (kPa)

$$\mathrm{LFL} = \frac{100V}{P}$$

where

LFL = lower flammable limit

V = vapor pressure of liquid at its LFL at ambient pressure

P = ambient pressure

8.1.1.1 Lower Flammable Limit Concentration of a Fuel Mixture

$$\mathrm{LFL}_{\mathrm{m}} = \frac{100}{\sum_{i=1}^{n}\left(\frac{C_{\mathrm{f_i}}}{\mathrm{LFL_i}}\right)}$$

where

C_{f} = volume percent of fuel gas i in fuel gas mixture

$\mathrm{LFL_i}$ = lower flammable limit of fuel gas i

8.1.2 Flammable Vapor Concentrations (Le Chatelier's Rule)

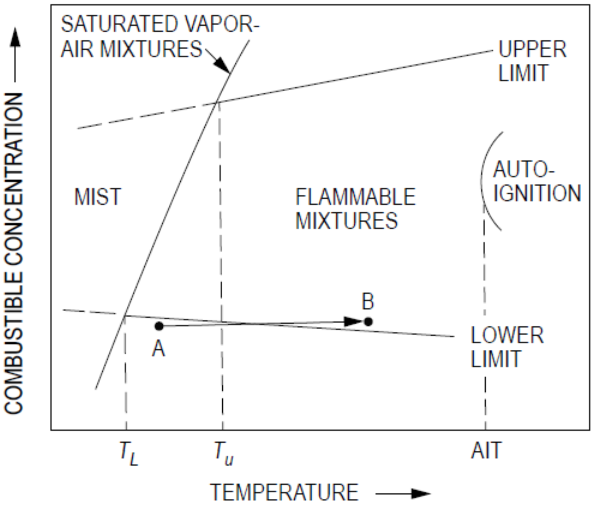
$$\mathrm{LFL}_{\mathrm{mix}} = \frac{1}{\sum_{j=1}\left(\frac{\chi_{\mathrm{j}}}{\mathrm{LFL_j}}\right)}$$

where

χ_{j} = molar concentration of fuel gas j in fuel mixture

$\mathrm{LFL_j}$ = lower flammable limit of gas or vapor j

8.1.3 Flammable Vapor Concentrations



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8.1.4 Volume of Vapor Production from Liquid

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To calculate the volume of vapor produced by solvent:

English units: $\textit{Vapor equivalent of 1 gal} = 111 \times \dfrac{\textit{specific gravity of liquid}}{\textit{vapor density of vapor}}$

Metric units: $\textit{Vapor equivalent of 1 liter} = 0.83 \times \dfrac{\textit{specific gravity of liquid}}{\textit{vapor density of vapor}}$

8.1.5 Volume of Air Required to Maintain Lower Flammable Limit

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English units: $Volume\ of\ air\ required = \dfrac{ft^3\ barely\ explosive\ mixture}{gal\ of\ solvent} = \left(\dfrac{ft^3\ mixture}{gal\ solvent}\right)\left(\dfrac{100 - LEL_T}{LEL_T}\right)$

Metric units: $Volume\ of\ air\ required = \dfrac{m^3\ barely\ explosive\ mixture}{L\ of\ solvent} = \left(\dfrac{m^3\ mixture}{L\ solvent}\right)\left(\dfrac{100 - LEL_T}{LEL_T}\right)$

where

LEL_T = lower explosive limit expressed in percent by volume in air, corrected for temperature other than STP

8.1.6 Aerosols

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Aerosol classification levels are based on the total chemical heat of combustion (ΔH_c) and are

Level 1 = total chemical heat of combustion equal to or less than 8,600 Btu/lb or 20 kJ/g

Level 2 = total chemical heat of combustion greater than 8,600 Btu/lb or 20 kJ/g, and less than or equal to 13,000 Btu/lb or 30 kJ/g

Level 3 = total chemical heat of combustion greater than 13,000 Btu/lb or 30 kJ/g

Total heat of combustion is determined by summing the products of the component percentage and the component heat of combustion:

$$Total\ \Delta H_c = \sum\left(\Delta H_c \times \%\ volume\right)$$

8.2 Vapor Clouds

8.2.1 Spill Rate—Dispenser

A valve remaining unintentionally open would spill liquid on the ground at a rate determined by a pump or by the pipe system upstream of the valve.

8.2.2 Spill Rate—Pressurized Liquid

Use the orifice-flow equation:

$$\dot{m} = CA\sqrt{2\rho\left(P_1 - P_a + \rho g h\right)}$$

where

$\dot{m}$ = vapor source mass flow rate (kg/s)

ρ = liquid density (kg/m^3)

P_1 = pressure of liquid (Pa)

P_a = ambient pressure (Pa)

A = area of orifice opening (m^2)

h = elevation of liquid above orifice (m)

C = discharge coefficient (assumed to be ~0.60)

g = acceleration due to gravity (9.81 m/s^2)

8.2.3 Spill Area and Thickness

Assume the liquid spreads instantaneously either to cover the entire containment area or to reach the minimum pool thickness (when the spill is uncontained). In most applications, the surface roughness of the concrete or soil where the liquid has spilled dominates the surface tension effects. Examples of minimum pool heights are

Substrate	Minimum Pool Height (h_{min})
Dry soil	2 cm (0.8 in)
Wet soil	1 cm (0.4 in)
Concrete	0.5 cm (0.2 in)

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8.3 Explosions

Protection from explosions that produce shock waves (detonations, waves traveling at or above the speed of sound) must be handled differently than explosions producing slower-pressure waves (deflagrations).

8.3.1 Pressure Damage Thresholds

Pressure Damage Thresholds for Buildings

Pressure (kPa)	Damage Description
3.5–7	Small and large windows usually shattered
7–15	Wood and aluminum panel fasteners failed; panels buckled or blown out
15–20	Unreinforced concrete and cinderblock walls shattered
20	Steel frame buildings distorted and pulled away from foundations
20–28	Self-framing steel panel building demolished
35–50	Nearly complete destruction of houses

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Blast Damage—Overpressure Correlation

Pressure (kPa)	Type of Damage
0.1–0.3	Minimum damage to glass panels
1–1.5	Typical window glass breakage
3.5–7.5	Windows shattered, plaster cracked, minor damage to buildings
5	Brick walls – minor damage
7–10	Person knocked down
7–15	Wood and aluminum panels fasteners failed; panels buckled or blown out
7.5–12.5	Panels of sheet metal buckled
7.5–15	Failure of wooden siding in conventional homes
12.5–20	Failure of walls constructed of concrete blocks or cinder blocks
14	Brick walls – major damage
15–20	Unreinforced concrete and cinderblock walls shattered
20	Steel frame buildings distorted and pulled away from foundation
20–28	Self-framing steel panel building demolished
20–30	Oil storage tanks ruptured
20–31	Wood frame buildings collapsed
27	Cladding of light industrial buildings ruptured
30–50	Utility poles broken off
30–50	Serious damage to buildings with structural steel framework
35–50	Nearly complete destruction of houses
40–60	Reinforced concrete structures severely damaged
40–60	Railroad cars overturned
200–500	Probable total destruction of most buildings
205	Steel towers blown down
606	Crater damage

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8.3.2 Blast Wave Energy

$$E = \alpha \Delta H_c m_F$$

where

E = blast wave energy (kJ)

α = yield fraction of available combustion energy participating in blast wave generation (conservative value is 0.5)

ΔH_c = theoretical net heat of combustion (kJ/kg)

m_F = mass of flammable vapor released (kg)

8.3.3 TNT Mass Equivalent

$$W_{\text{TNT}} = \frac{E}{4,200}$$

where

W_{TNT} = equivalent weight of TNT (kg)

E = blast wave energy (kJ)

1 kg TNT has an explosive energy of 4,200 (kJ/kg)

8.3.4 Blast Wave Energy of a BLEVE

A boiling-liquid expanding-vapor explosion (BLEVE) is defined as

$$E = m\left(u_{\text{r}} - u_{\text{a}}\right)$$

where

E = blast wave energy (kJ)

m = mass of liquid in vessel (kg)

u_{r} = internal energy (per unit mass) of liquid at rupture (kJ/kg)

u_{a} = internal energy (per unit mass) of vapor after expansion (kJ/kg)

8.3.5 Fireball Size and Dynamics—Originating from a BLEVE

The maximum size of a fireball is governed primarily by the mass of the fuel released and vaporized. Although the fireballs are rarely spherical, an equivalent spherical volume is widely used to characterize the size of a fireball. The maximum diameter of the equivalent spherical fireball is given by

$$D = 5.8\, m^{1/3}$$

where

D = maximum diameter (m)

m = mass of fuel (kg)

The maximum fireball diameter is independent of the initial pressure of the fuel, as long as the pressure and temperature are sufficient to vaporize the fuel.

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8.3.6 Burning Duration of a Fireball—Originating from a BLEVE

8.3.6.1 For Momentum-Dominated Fireballs

$$t_{\text{d}} = 0.45\, m^{1/3}$$

where

t_{d} = duration of burning (s)

m = mass of fuel (kg) (< 30,000 kg)

8.3.6.2 For Buoyancy-Dominated Fireballs

As would be expected, for atmospheric pressure releases:

$$t_d = 2.6\, m^{1/6}$$

where

t_d = duration of burning (s)

m = mass of fuel (kg) (> 30,000 kg)

8.3.7 Time to Fireball Liftoff

The time to fireball liftoff is given by

$$t_e = 1.1\, m^{1/6}$$

where

t_e = time to liftoff (s)

m = mass of fuel (kg)

8.3.8 Fireball Exposure to Target (Point Source Method)

$$Z_p = 12.73 V_{va}^{1/3}$$

$$q_{max} = \frac{828 m^{0.771}}{R^2}$$

where

Z_p = rise of **center** of fireball above tank (m)

V_{va} = fuel vapor volume (m^3)

q_{max} = peak thermal radiation from fireball (kW/m^2)

m = mass of fuel (kg)

R = distance from center of fireball to target (m)

8.3.9 Minimum Required Explosion Vent Area

$$A_v = 1 \times 10^{-4}\left(1 + 1.54 P_{stat}^{4/3}\right) K_{ST} V^{3/4} \sqrt{\frac{P_{max}}{P_{red}} - 1}$$

where

K_{ST} = deflagration index (bar m/s)

P_{max} = maximum explosion pressure (bar g)

P_{stat} = vent deployment pressure, in bar g, in response to slowly increasing (static) pressure

V = enclosure volume (m^3)

P_{red} = reduced pressure (less than P_{max}) in enclosure because of venting (bar g)

NFPA 68, Standard on Explosion Protection by Deflagration Venting, specifies that the value of P_{red} shall be no greater than 2/3 the enclosure strength based either on incipient permanent deformation or actual enclosure (structural member) rupture, at the discretion of the facility owner.

This equation is applicable to compact enclosure with $\frac{L}{D} \le 2$, and lightweight vent disks/panels.

8.4 Explosion Venting

8.4.1 Minimum P_{red} for Nonrelieving Wall Construction

$$\textit{Minimum } P_{\text{red}} = P_{\text{stat}} + 0.024 \text{ bar (or 50 psf or 0.35 psig)}$$

P_{stat} = vent deployment pressure, in bar g, in response to slowly increasing (static) pressure

P_{red} = reduced pressure (less than $P_{\max}$) in enclosure because of venting (bar g)

8.4.2 Vent Area for Low-Strength Enclosures

Minimum recommended vent area for venting of low-strength enclosures from gases, gas mixtures, and mists:

$$A_{\text{v}} = \frac{C\left(A_{\text{s}}\right)}{\left(P_{\text{red}}\right)^{1/2}}$$

where

A_{v} = minimum vent area (ft^2)

C = fuel constant or venting parameter (psi$^{1/2}$) (found in NFPA 68, 7.2.2.1)

A_{s} = internal surface area of enclosure including floor, roof, and all walls (ft^2)

P_{red} = maximum pressure to be attained during vented deflagration (psi)

C = venting equation constant, given as a function of laminar burning velocity for different gases (bar$^{1/2}$ or psi$^{1/2}$)

For psi$^{1/2}$: $C = (6.1 \times 10^{-5})\left(S_{\text{u}}^2\right) + (6.1 \times 10^{-4})(S_{\text{u}}) + 0.0416$

For bar$^{1/2}$: $C = (1.57 \times 10^{-5})\left(S_{\text{u}}^2\right) + (1.57 \times 10^{-4})(S_{\text{u}}) + 0.0109$

where S_{u} = fuel fundamental burning velocity (cm/s) (must be less than 60 cm/s)

8.4.3 Vent Area for High-Strength Enclosures

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$$D = 2\left(\frac{A^*}{\pi}\right)^{1/2}$$

where

D = equivalent diameter (ft)

A^* = cross-sectional area normal to the longest dimension (ft^2)

$\frac{L}{D}$ ratio

D = equivalent diameter (m)

L = maximum distance between adjacent vent edges (m)

For $\frac{L}{D} \leq 2$ and volume $\leq$ 1,000 m^3:

$$A_\text{v} = \left[\left(0.127\log_{10}K_\text{G} - 0.0567\right)P_\text{red}^{-0.582} + 0.175\,P_\text{red}^{-0.572}\left(P_\text{stat} - 0.1\right)\right]V^{2/3}$$

where

A_v = A = vent area (m^2)

K_G = K = deflagration index of gas (bar•m/s) $\leq$ 550

P_red = R = 2 bar and at least 0.05 bar greater than P_sta

P_stat = $S \leq$ 0.5 bar

V = enclosure volume (m^3)

For $2 > \frac{L}{D} < 5$, and $P_\text{red} \leq$ 2.0 bar, additional vent area must be added to A_v:

$$\Delta A = \frac{A_\text{v}K_\text{G}\left[\left(\frac{L}{D}\right) - 2\right]^2}{750}$$

Final $A_\text{v} = \Delta A + A_\text{v}$

8.4.4 Vent Area Threshold Mass

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$$M_\text{T} = \left[6.67\left(P_\text{red}^{0.2}\right)\left(n^{0.3}\right)\left(\frac{V}{K_\text{st}^{0.5}}\right)\right]^{1.67}$$

where

M_T = threshold mass (kg/m^2)

P_red = reduced pressure after deflagration (bar)

n = number of panels

V = enclosure volume (m^3)

K_st = deflagration index (bar•m/s)

8.4.5 Venting One End of Elongated Enclosure

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$$L_3 \leq 12\frac{A}{p}$$

where

L_3 = longest dimension of the enclosure (ft)

A = cross-sectional area through which burning mixture must vent (ft^2)

p = perimeter of that cross section (ft)

For highly turbulent gas mixtures, the length-to-diameter ratio should not exceed 2:

$$L_3 \le 8\frac{A}{p}$$

8.4.6 Effects of Vent Ducts (Cubical Vessels)

$$\frac{P''_{\text{red}}}{P_{\text{red}}} = 1 + \left[17.3\left(\frac{A_{\text{v}}}{V^{0.753}}\right)^{1.6}\frac{L}{D}\right]$$

where

P''_{red} = P = pressure during a vented deflagration with vent duct in place (bar)

P_{red} = R = pressure during a vented deflagration without vent duct (bar)

A_{v} = A = vent area (m^2)

V = enclosure volume (m^3)

L = duct length (m)

D = equivalent diameter of vent duct (m)

8.4.7 Venting of Deflagrations of Dusts and Hybrid Mixtures

(Source: NFPA 68, Standard on Explosion Protection by Deflagration Venting, Section 8.2.2.
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$$A_{\text{v0}} = 0.0001\left(1 + 1.54\,P_{\text{stat}}^{4/3}\right)K_{\text{st}}V^{3/4}\sqrt{\frac{P_{\max}}{P_{\text{red}}} - 1}$$

where

A_{v0} = vent area (m^2)

P_{stat} = nominal static burst pressure of vent (bar)

K_{st} = deflagration index (bar•m/s)

V = enclosure volume (m^3)

$P_{\max}$ = maximum pressure of deflagration (bar)

P_{red} = reduced pressure after deflagration (bar)

Equation is valid for:

1. $5 \text{ bar} \le P_{\max} \le 12 \text{ bar}$
2. $10 \text{ bar•m/s} \le K_{\text{st}} \le 800 \text{ bar•m/s}$
3. $0.1 \text{ m}^3 \le V \le 10{,}000 \text{ m}^3$
4. $P_{\text{stat}} \le 0.75 \text{ bar}$

See Section 8.4.3 for $\frac{L}{D}$ ratio

When $\frac{L}{D} \le 2$, A_{v1} shall be set equal to A_{v0}.

For $2 \le \frac{L}{D} \le 6$, A_{v1} shall be calculated as:

$$A_{v1} = A_{v0}\left[1 + 0.6\left(\frac{L}{D} - 2\right)^{0.75} \exp\left(-0.95\, P_{red}^{2}\right)\right]$$

8.4.8 Partial Volume Deflagrations (PVDs)

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$$A_{vpv} = A_{v0} X_r^{-1/3} \left(\frac{\left(X_r - \frac{P_{red}}{P_{max}}\right)}{\left(1 - \frac{P_{red}}{P_{max}}\right)}\right)^{1/2}$$

where

A_{vpv} = required vent area for PVD (m^2)

A_{v0} = required vent area for entire enclosure if filled with ignitable mixture (m^2)

X_r = fill fraction at the time of PVD

P_{max} = maximum pressure of deflagration (bar)

P_{red} = reduced pressure after deflagration (bar)

$\Pi = \frac{P_{red}}{P_{max}}$

8.4.9 Deflagration Index

The deflagration index, *K*, is computed from the maximum rate of pressure rise attained by combustion in a closed vessel with volume, *V*, and is defined by

$$K = \left(\frac{dP}{dT}\right)_{max} \times V^{1/3}$$

8.5 Dusts

8.5.1 Flammability of Dusts

(Source: NFPA *Fire Protection Handbook* 20th ed., p. 6-147.
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The flammability of dust can be defined with six classes:

Class 1: No self-sustained combustion

Class 2: Local combustion of a short duration

Class 3: Local sustained combustion but no propagation

Class 4: Propagating, smoldering combustion

Class 5: Propagating open flame

Class 6: Explosive combustion

The class is determined through testing. A sample of the dust (a ridge 2 cm wide × 4 cm long) is ignited at one end with a 1,000°C gas flame or platinum wire (glowing). The class number relates to a modified test procedure. With the modified test, material may show flame propagation instead of melting due to the mixing of dust with diatomaceous earth (20% by weight).

8.5.2 Ignition Sensitivity

(Source: NFPA *Fire Protection Handbook*, 20th ed.
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The ignition sensitivity and explosion severity of a dust are defined as

$$\mathrm{IS} = \frac{(T_\mathrm{i} \times E_\mathrm{m} \times C_\mathrm{m})_{\text{Pittsburgh coal dust}}}{(T_\mathrm{i} \times E_\mathrm{m} \times C_\mathrm{m})_{\text{sample dust}}}$$

$$\mathrm{ES} = \frac{(P_\mathrm{max} \times R_\mathrm{max})_{\text{sample dust}}}{(P_\mathrm{max} \times R_\mathrm{max})_{\text{Pittsburgh coal dust}}}$$

where

T_i = ignition temperature of dust cloud

E_m = minimum ignition energy of dust cloud

C_m = minimum concentration for combustible dust cloud

P_max = maximum explosion pressure

R_max = maximum rate of pressure rise in test apparatus

8.5.3 Explosibility of Data Powders and Dusts

Material	Median particle size (µm)	Min. explosive concentration (g/m^3)	Min. cloud ignition temperature (°C)	Min. layer ignition temperature (°C)	Minimum ignition energy (mJ)	P_{max} (bar•m)	K_{st} (bar•m/s)
Activated carbon	18	60	790	>450	-	8.8	44
Aluminum powder	<10	60	560	430	-	11.2	515
Aluminum shavings	240	No ignition					
Ascorbic acid	39	60	460	melts	-	9.0	111
Calcium stearate	<10	30	580	>450	16	9.2	99
Coal, bituminous	4	60	510	260	-	9.1	59
Corn starch	<10	-	520	>450	300	10.2	128
Epoxy resin	26	30	510	melts	-	7.9	129
Fructose	200	60	440	440	180	7.0	28
Iron from filter	12	500	580	>450	-	5.2	50
Magnesium	28	30	-	-	-	17.5	508
Methyl cellulose	37	30	410	450	29	10.1	209
Milk powder	165	60	460	330	75	8.1	90
Napthalene	95	15	660	>450	<1	8.5	178
Paper tissue dust	54	30	540	300	-	8.6	52
Phenolic resin	<10	15	610	>450	-	9.3	129
Polyethylene, 1.d.	<10	30	420	melts	-	8.0	156
Polyethylene, 1.d.	150	125	480	melts	-	7.4	54
Polyvinylchloride	25	125	750	>450	-	9.3	129
Rubber	80	30	500	230	13	8.5	138
Silicon	<10	125	>850	>450	54	10.2	126
Sugar	10	60	440	melts	14	8.3	75
Sulfur	20	30	280	-	6.8	151	
Toner	23	60	530	melts	8	8.8	145
Wood from chip board	43	60	490	320	-	9.2	102
Zinc	<10	250	570	440	-	6.7	125

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8.5.4 Fireball Hazard

$$D = K\left(\frac{V}{n}\right)^{1/3}$$

where

D = axial distance (front) from vent (ft or m) and diameter of fireball at that distance

K = flame length factor: 10 for metal dusts, 8 for agricultural dusts

V = volume of vented enclosure (m^3 or ft^3)

n = number of vents

9 PASSIVE BUILDING SYSTEMS

9.1 General

During the course of a fire, structures must maintain their integrity for a sufficient period of time to allow for evacuation and firefighting operations. In performance-based codes, these goals are defined by estimated time for evacuation and firefighting operations based on one or more selected design fires for the occupancy.

9.1.1 Fire Load

Fire load is a measure of the maximum heat release if all the combustibles in a defined area burn to completion. This load is determined by multiplying the mass of each combustible with the heat of combustion. Fire load includes combustible contents, interior finish, floor finish, and structural elements and is generally expressed in lb/ft^2 or kg/m^2.

9.1.2 Analytical Method for Fire Resistance

A broad-based analytical method for fire resistance will consider three aspects:

1. Fire exposure
2. Heat transfer
3. Structural response

The two most important fire effects that alter a structure's resistance from that at ambient are the high-temperature degradation of its mechanical properties (strength and stiffness) and thermally induced strains. These cause softening, weakening, and damage to even noncombustible construction materials and directly lead to a progressive reduction of load-carrying resistance at higher temperatures. Meanwhile, fire-induced thermal elongations can

1. Lead to displacements so large that they influence the effects of action (a term used to designate bending moments, axial forces, or shear forces) in the structure, or
2. When restrained, generate additional effects of action, typically in the form of compressive forces

These dual responses demonstrate that fire is clearly time-dependent with effects on both the load and the resistance sides of the equation for strength limit. Similar to the real-time history response of a structure subjected to an earthquake, load-resistance interactions exist that usually give rise to nonlinear structural behavior and permanent distortions/damage.

Factors to be considered and evaluated in a structural analysis:

- Local member or frame instability
- Floor slab effects
- Thermal strains
- Tensile membrane action of composite floors
- Connection moment-rotation behavior
- Nonuniform heating
- Material strength limit states

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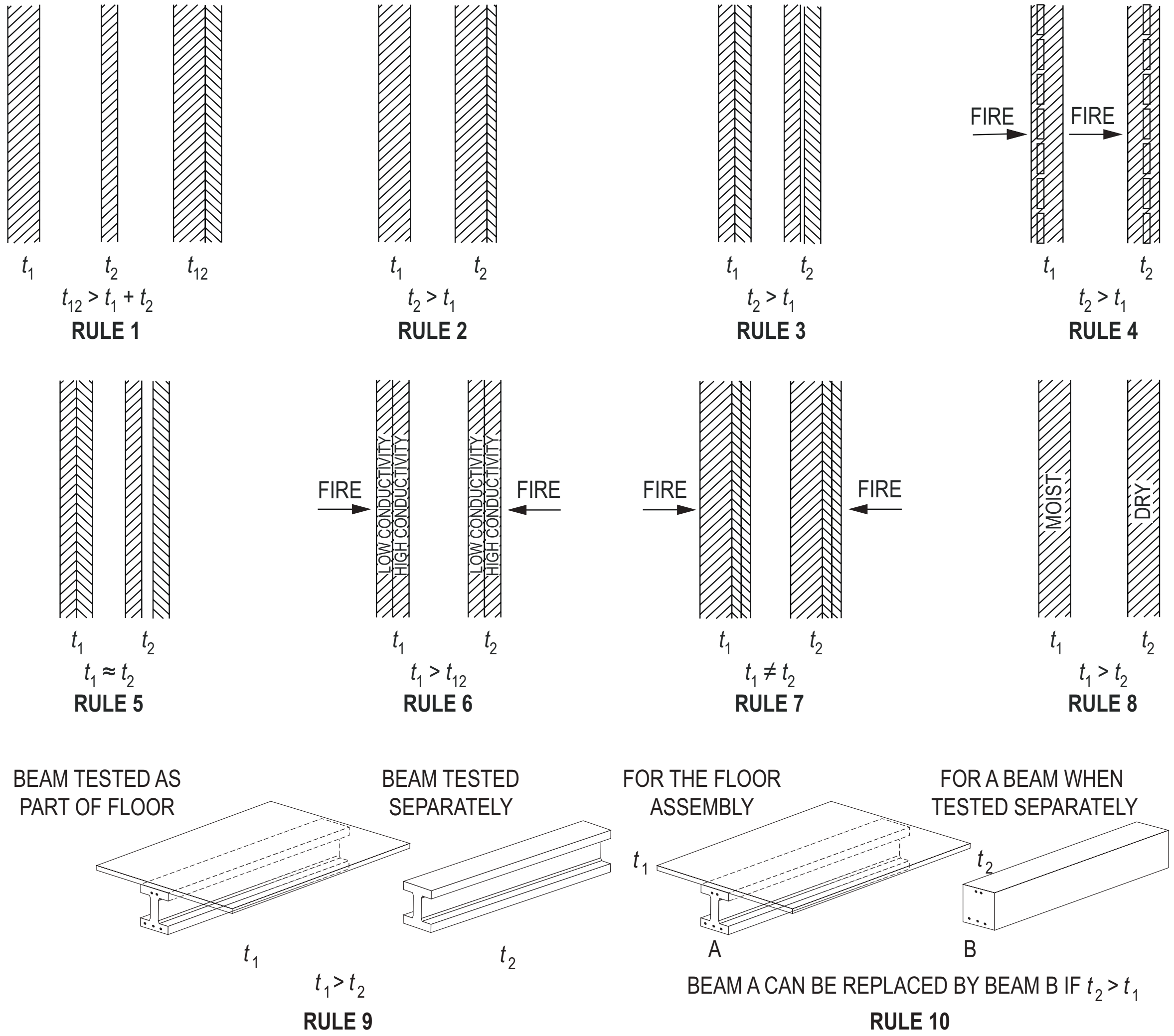
9.1.3 Fire Endurance Rules—Harmathy's Ten Rules of Fire Endurance

In all figures *t* represents time in no particular units.



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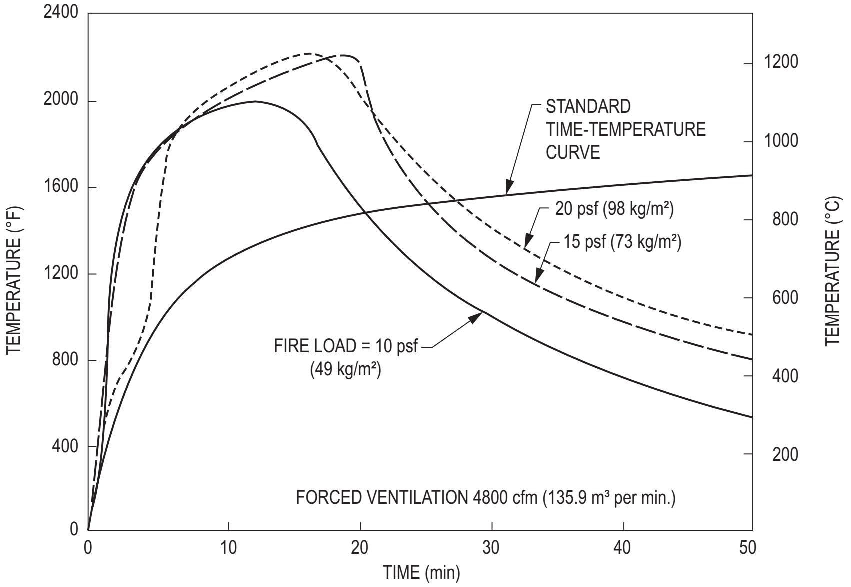
9.1.4 Time-Temperature Curve—General



ASTM E119 Standard Fire and Real Fire Time-Temperature Curves

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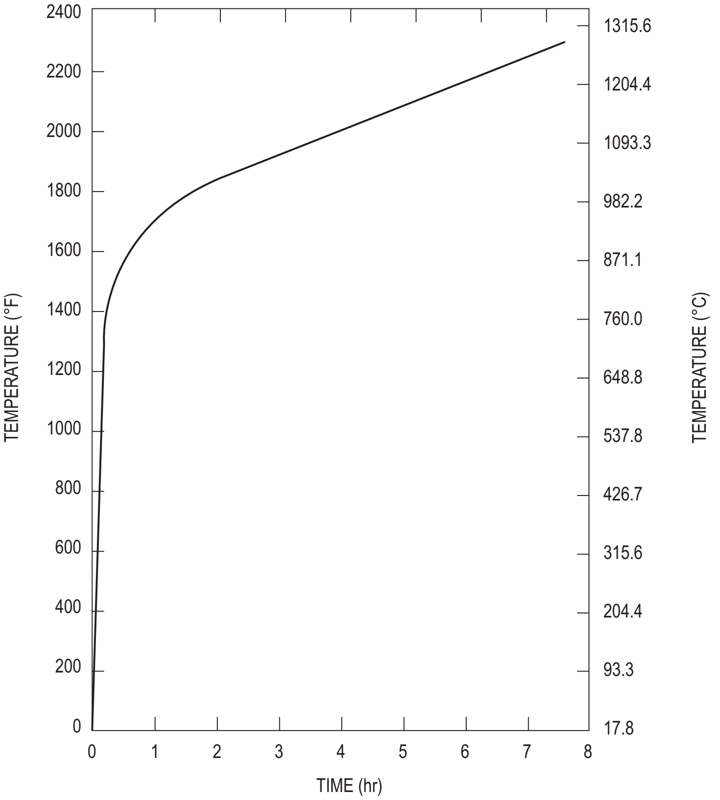
9.1.5 ASTM E119

9.1.5.1 ASTM E119 Time-Temperature Curve



ASTM E119 Standard Time-Temperature Curve

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9.1.5.2 Key Points on the Standard Time-Temperature Curve

From the ASTM E119 standard time-temperature curve:

Time	Temperature (°F)
5 minutes	1,000
10 minutes	1,300
30 minutes	1,550
1 hour	1,700
2 hours	1,850
4 hours	2,000
8 hours & over	2,300

9.1.5.3 ASTM E119 Test Endpoint Criteria

Structural Member	Location	Maximum Temperature °F (°C)
Walls/partitions (bearing and nonbearing)	Unexposed side	
	Average	250 (139) [a]
	Single point	325 (181) [a]
Steel columns	Average	1,000 (538)
	Single point	1,200 (649)
Floor/roof assemblies and loaded beams	Unexposed side	
	Average	250 (139) [a]
	Single point	325 (181) [a]
	Steel beam	
	Average	1,100 (593)
	Single point	1,300 (704)
	Prestressing steel	800 (426)
	Reinforcing steel	1,100 (593)
	Open-web steel joists	1,100 (593)
Steel beams/girders (not loaded)	Average	1,000 (538)
	Single point	1,200 (649)

[a] Maximum temperature cited refers to maximum temperature rise about initial conditions.

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9.1.6 Flame Spread Index Per ASTM E-84

	Class A	Class B	Class C
Flame spread index	0–25	26–75	76–200
Smoke development index	0–450	0–450	0–450

9.2 Steel

The following types of calculation methods are available to assess the fire resistance of steel structural members:

1. Empirical correlations
2. Heat-transfer analyses
3. Structural analyses

The principal material properties of interest are yield strength, ultimate strength, modulus of elasticity, coefficient of thermal expansion, density, specific heat, and thermal conductivity.

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9.2.1 Yield Strength

For $0 < T \leq 600°\text{C}$:

$$\sigma_{yT} = 1 + \frac{T}{900 \ln\left(\frac{T}{1{,}750}\right)} \sigma_{y0}$$

$$E_T = 1 + \frac{T}{2{,}000 \ln\left(\frac{T}{1{,}100}\right)} E_0$$

For $T > 600°\text{C}$:

$$\sigma_{yT} = \frac{340 - 0.34T}{T - 240} \sigma_{y0}$$

$$E_T = \frac{690 - 0.69T}{T - 53.5} E_0$$

For any temperature:

$$\alpha_T = (0.04T + 12) \times 10^{-6}$$

where

σ_{yT} = yield strength temperature T (psi or MPa)

σ_{y0} = yield strength at 68°F or 20°C (psi or MPa)

E_T = modulus of elasticity at temperature T (psi or MPa)

E_0 = modulus of elasticity at 68°F or 20°C (psi or MPa)

α_T = coefficient of thermal expansion at temperature T (ft/ft °F or m/m °C)

T = steel temperature (°F or °C)

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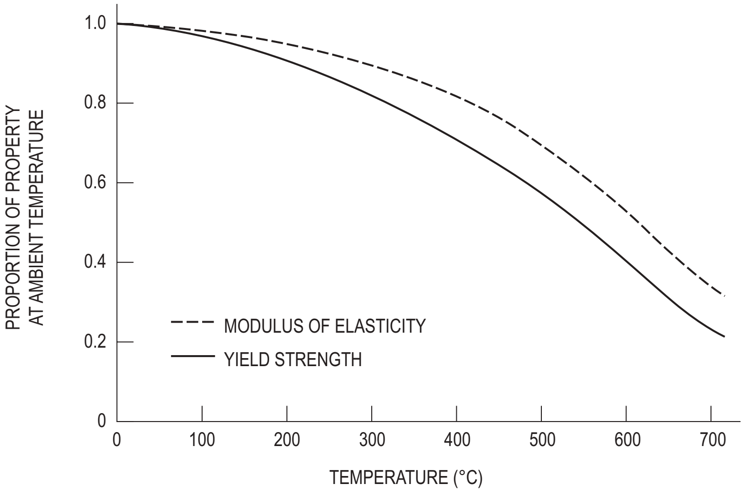
9.2.2 Temperature Effects on Properties of ASTM A36 Steel



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9.2.3 Insulation of Steel Members

Insulation of steel is achieved by surrounding the steel with materials that preferably have the following characteristics:

1. Noncombustibility and the added attribute of not producing smoke or toxic gases when subjected to elevated temperatures
2. Thermal protective capability when subjected to elevated temperatures
3. Product reliability giving positive assurance of consistent, uniform protection characteristics
4. Availability in a form that permits efficient and uniform application
5. Sufficient bond strength and durability to prevent either dislodgement or surface damage during normal construction operations
6. Resistance to weathering or erosion resulting from atmospheric conditions

In addition to the insulating qualities of the protection materials, chemical reactions may occur in the insulation, further reducing the rate of heat transfer. The chemical reactions include calcination, ablation, intumescence, thermal hydrogeneration, and sublimation. Insulating methods include the use of board products, spray-applied materials, and concrete encasement.

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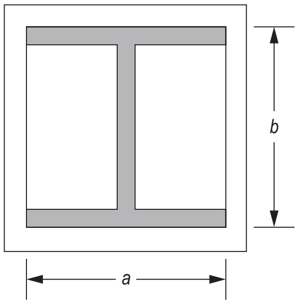
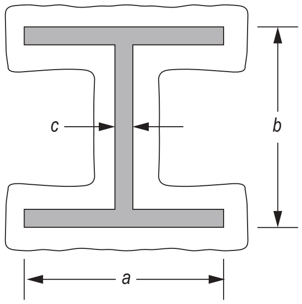
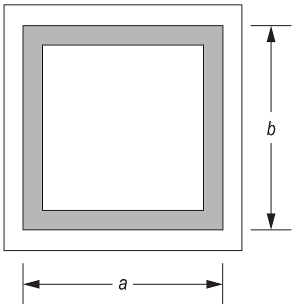
9.2.4 Heated Perimeter (D) for Steel Columns



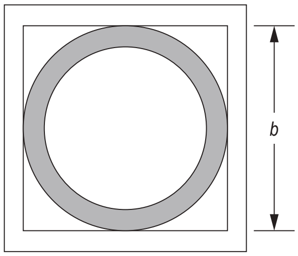
$D = 2(a + b)$



$D = 4a + 2b - 2c$



$D = 2(a + b)$



$D = 4b$

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9.2.5 Fire Endurance Equations for Steel Columns

Empirical Equations for Steel Columns

Member/Protection	Solution	Symbols
Column/unprotected	$R = 10.3\ (W/D)^{0.7}$, for $W/D < 10$	R = fire endurance time (min)
	$R = 8.3\ (W/D)^{0.8}$, for $W/D \geq 10$ (for critical temperature of 1,000°F)	W = weight of steel section per linear foot (lb/ft)
		D = heated perimeter (in.)
Column/ gypsum wallboard	$R = 130\left(\frac{hW'/D}{2}\right)^{0.75}$ where $W' = W + \frac{50hD}{144}$	R = fire endurance time (min)
		h = thickness of protection (in.)
		W' = weight of steel section and gypsum wallboard (lb/ft)
Column/spray-applied materials and some board products—wide flange shapes	$R = \left[C_1\left(W/D\right) + C_2\right]h$	R = fire endurance time (min)
		C_1 and C_2 = constants for specific protection material
Column/spray-applied materials and some board products—hollow sections	$R = C_1\left(\frac{A}{P}\right)h + C_2$	R = fire endurance time (min)
		C_1 and C_2 = constants for specific protection material
		The A/P ratio of a circular pipe is determined by $\frac{A}{P}_{\text{pipe}} = \frac{t\left(d - t\right)}{d}$ where d = outer diameter of pipe (in.) t = wall thickness of pipe (in.)
		The A/P ratio of a rectangular or square tube is determined by $\frac{A}{P}_{\text{tube}} = \frac{t\left(a + b - 2t\right)}{a + b}$ where a = outer width of tube (in.) b = outer length of tube (in.) t = wall thickness of tube (in.)
Column/concrete cover or encased	$R = R_0(1 + 0.03m)$ where $R_0 = 0.17\left(\frac{W}{D}\right)^{0.7} + 0.28\left(\frac{h^{1.6}}{k_c^{0.2}}\right) \times \left\{1 + 26\left[\frac{H}{\rho_r c_c h\left(L + h\right)}\right]^{0.8}\right\}$	R_0 = fire endurance at zero moisture content of concrete (min)
		m = equilibrium moisture content of concrete (% by volume)
		b_f = width of flange (in.)
		d = depth of section (in.)
		k_c = thermal conductivity of concrete at ambient temperature in (Btu/hr-ft-°F)
		H = thermal capacity of steel section at ambient temperature (if covered, = 0.11 W Btu/ft-°F; if encased, = $0.11\ W + [(\rho_r c_c)/144]\ (b_f d - A_s)$)
		c_c = specific heat of concrete at ambient temperature (Btu/lb-°F)
		L = inside dimension of one side of *square* concrete box protection (in.); if encased, $L = (b_f + d)/2$
		A_s = cross-sectional area of steel column (in^2)

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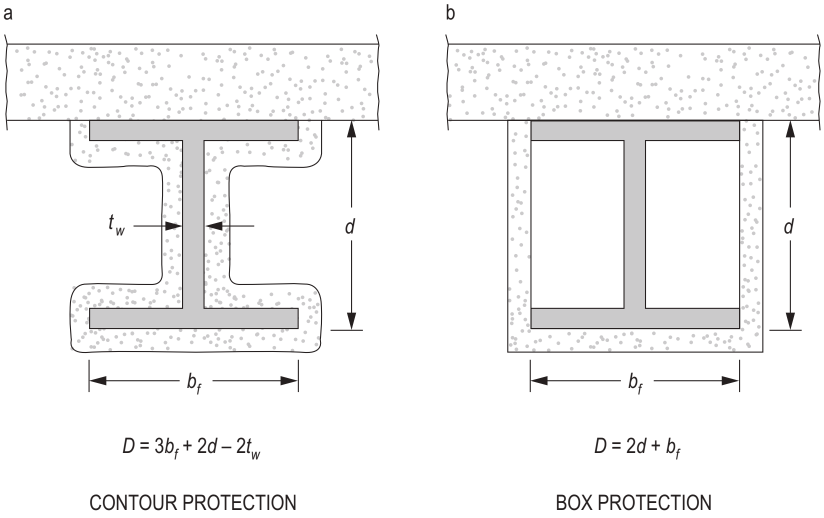
9.2.6 Heated Perimeter (*D*) for Beams



Heated Perimeter for Steel Beams

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9.2.7 Beam or Column Substitution

$$h_1 = \left(\frac{\frac{W_2}{D_2} + 0.6}{\frac{W_1}{D_1} + 0.6} \right) h_2$$

where

h = thickness of spray-applied fire protection (in.)

W = weight of steel beam (lb/ft)

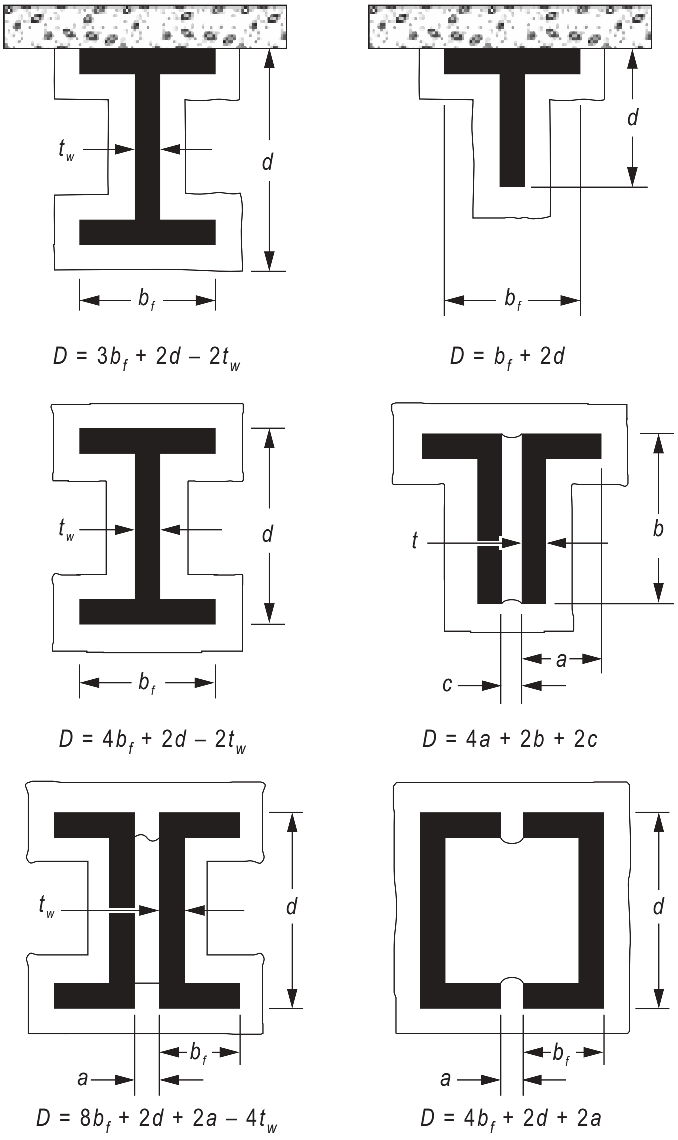
D = heated perimeter of steel beam (in.)

Subscripts:

1 = substitute beam and required protection thickness

2 = beam and protection thickness specified in referenced tested design or tested assembly

9.2.8 Heated Perimeter (*D*) of Steel Trusses



$D = 3b_f + 2d - 2t_w$

$D = b_f + 2d$

$D = 4b_f + 2d - 2t_w$

$D = 4a + 2b + 2c$

$D = 8b_f + 2d + 2a - 4t_w$

$D = 4b_f + 2d + 2a$

Heated Perimeter for Steel Truss Shapes

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9.2.9 Steel Truss Protection

Typical Fire Protection Methods for Steel Trusses

Truss Type	Fire Protection Method		
	Membrane	Envelope	Individual Element
Transfer	—	X	X
Staggered	—	X	X
Interstitial	X	X	X

Practical Guidelines for Thickness of Gypsum Wallboard for Steel Truss Envelope Protection

Fire Endurance (hr)	Gypsum X	Wallboard Type
1	5/8" (16 mm)	5/8" (16 mm)
2	1-1/4" (32 mm)	—
3	—	1-1/2" (38 mm)

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9.2.10 Unprotected Steel Member Temperature Rise

The equation for temperature rise during a short period, ΔT, is:

$$\Delta T_s = \frac{\alpha}{c_s\left(\frac{W}{D}\right)}\left(T_f - T_s\right)\Delta t$$

where

ΔT_s = temperature rise in steel (°F or °C)

α = heat-transfer coefficient from exposure to steel member (Btu/ft^2-s-°R or W/m^2•K)

D = heater perimeter (ft or m)

c_s = steel specific heat (Btu/lb-°F or J/kg•°C)

W = steel weight per linear foot (lb/ft or kg/m)

T_f = fire temperature (°R or K)

T_s = steel temperature (°R or K)

Δt = time step (sec)

9.2.10.1 Heat-Transfer Coefficient

$\alpha = \alpha_r + \alpha_c$

where

α_c = convective heat-transfer coefficient = (9.8×10^{-4}) to (1.2×10^{-3}) Btu/sec-ft^2-°R^4, or 20 to 25 W/m^2•K^4

α_r = radiative heat-transfer coefficient

$$\alpha_r = \frac{C_1 \varepsilon_f}{T_f - T_s}\left(T_f^4 - T_s^4\right)$$

where

C_1 = 4.76×10^{-13} Btu/sec-ft^2-°R^4, or 5.67×10^{-8} W/m^2•K^4

ε_f = effective emissivity (see table below)

Effective Emissivity

Type of Construction	Effective Emissivity
1. Column exposed to fire on all sides	0.7
2. Column outside facade	0.3
3. Floor girder with floor slab of concrete, only the underside of the bottom flange being directly exposed to fire	0.5
4. Floor girder with floor slab on the top flange:	
Girder of 1 section for which the width-depth ratio is not less than 0.5	0.5
Girder of 1 section for which the width-depth ratio is less than 0.5	0.7
Box girder and lattice girder	0.7

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9.2.11 Protected Steel Member Temperature Rise

$$\Delta T_s = \frac{k_c}{c_s h\left(\frac{W}{D}\right)}\left(T_f - T_s\right)\Delta t$$

where

ΔT_s = temperature rise in steel (°F or °C)

D = heater perimeter (ft or m)

c_s = steel specific heat (Btu/lb-°F or J/kg•°C)

k_i = thermal conductivity of insulation material (Btu/ft-hr-°F or W/m•°C)

h = protection thickness (ft or m)

W = steel weight per linear foot (lb/ft or kg/m)

T_f = fire temperature (°R or K)

T_s = steel temperature (°R or K)

Δt = time step (sec)

9.3 Concrete/Masonry

9.3.1 Thermal Properties of Concrete at 70°F

	Normal-Weight Concrete	**Structural Lightweight Concrete**
Thermal Conductivity (*k*)	0.95 Btu/ft-hr-°F (1.64 W/m•K)	0.35 Btu/ft-hr-°F (0.61 W/m•K)
Specific Heat (*c*)	0.20 Btu/lb-°F (835 J/kg•K)	0.20 Btu/lb-°F (835 J/kg•K)

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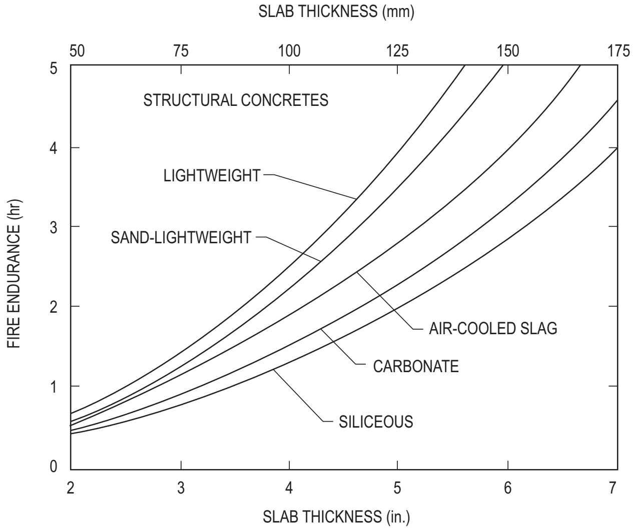
9.3.2 Fire Endurance of a Concrete Slab



Effect of Thickness and Type of Aggregate, Based on Heat Transmission

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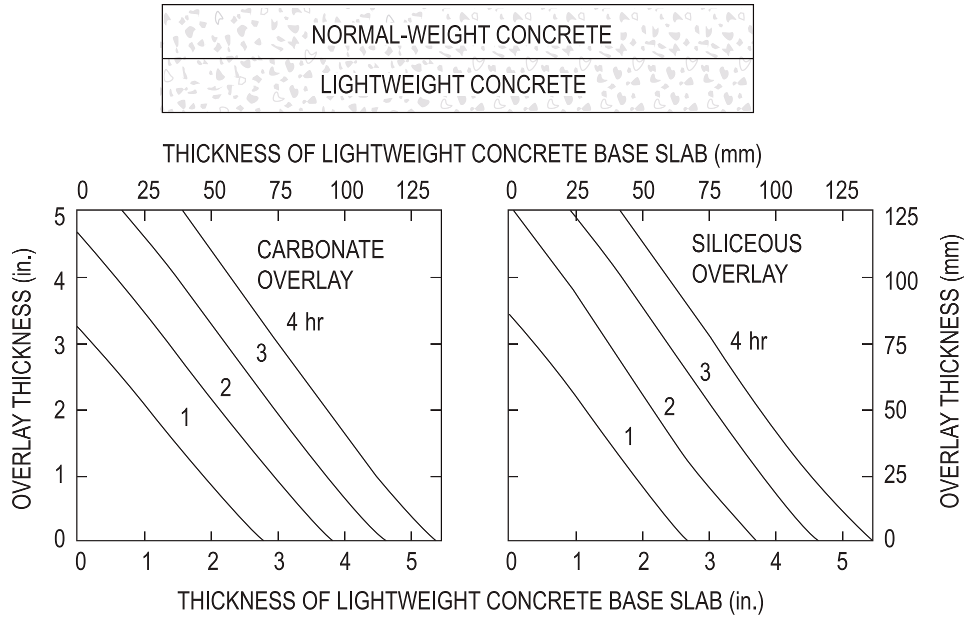
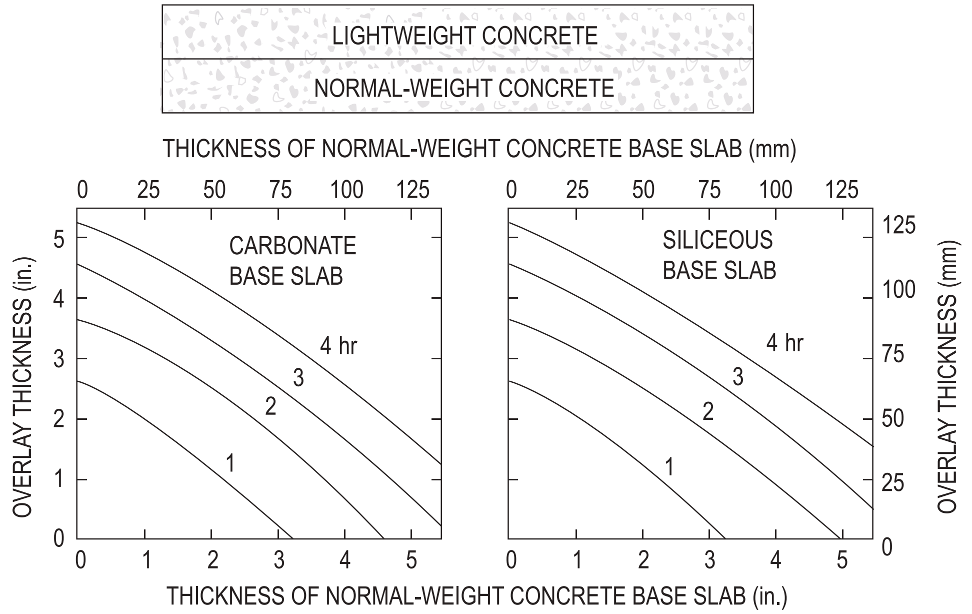


NORMAL-WEIGHT CONCRETE OVERLAY ON LIGHTWEIGHT CONCRETE SLAB



LIGHTWEIGHT CONCRETE OVERLAY ON NORMAL WEIGHT CONCRETE SLAB

Fire Endurance of Base Slabs and Overlays of Normal-Weight or Lightweight Concretes, Based on Heat Transmission

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

9.3.3 Concrete Column Fire Resistance

	Minimum Column Dimension for Fire Resistance Rating, in inches (mm)				
	1 hr	1.5 hr	2 hr	3 hr	4 hr
Semi-lightweight	8 (200)	8.5 (216)	9 (225)	10.5 (270)	12 (305)
Siliceous	8 (200)	9 (225)	10 (255)	12 (305)	14 (356)
Carbonate	8 (200)	9 (225)	10 (255)	11 (280)	12 (305)

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

9.4 Timber/Wood

9.4.1 Fire Resistance of Wood Frame and Protective Coverings

The addition of insulation to a wall assembly can increase its fire resistance. Adding rock wool or slag mineral wool insulation batts for additional protection to the wood-stud wall generally has an assigned time of 15 minutes.

Time Assigned to Protective Membranes

Description of Finish	Time (min)
3/8 in. (9.5 mm) Douglas fir plywood	5
1/2 in. (13 mm) Douglas fir plywood	10
5/8 in. (16 mm) Douglas fir plywood, phenolic bonded	15
3/8 in. (9.5 mm) gypsum board	10
1/2 in. (13 mm) gypsum board	15
5/8 in. (16 mm) gypsum board	20
1/2 in. (13 mm) Type X gypsum board	25
5/8 in. (16 mm) Type X gypsum board	40
2 layers of 3/8-in. (9.5-mm) gypsum board	25
1 layer of 3/8-in. (9.5-mm) and 1 layer of 1/2-in. (13-mm) gypsum board	35
2 layers of 1/2-in. (13-mm) gypsum board	40

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Time Assigned for Contribution of Wood Frame

Description of Frame	Time (min)
Wood wall studs, 16 in. (406 mm) on center	20
Wood floor and roof joists, 16 in. (406 mm) on center	10
Wood floor and roof truss assemblies, 24 in. (610 mm) on center	5

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

Minimum size for studs is nominal 2 in. × 4 in. (51 mm × 102 mm). Wood joists are not to be less than nominal 2 in. (51 mm) in thickness. The spacing between studs on joists should not exceed 16 in. (406 mm) on center.

9.4.2 Char Depth

$$d_{\text{char}} = \beta t$$

where

d_{char} = char depth

β = charring rate, typically assumed to be 0.6 mm/min (1.5 in./hr) for all woods

t = time (min)

9.4.3 Char Rate – White and Nordheim

$$t = m\, x_c^{1.23}$$

where

t = time (min)

m = char-rate coefficient

x_c = char depth (mm)

The char-rate coefficients (m) range from 0.42 to 0.84 mm/min$^{1.23}$ for the eight species. Average values for the char-rate coefficients are 0.555 for southern pine, 0.554 for western red cedar, 0.598 for redwood, 0.734 for Engelmann spruce, 0.498 for basswood, 0.653 for hard maple, 0.747 for red oak, and 0.607 for yellow poplar. The char-rate coefficient is correlated to density, moisture content, and a char contraction factor, defined as the thickness of the char layer at the end of the fire exposure divided by the original thickness of the wood layer that was charred (char depth).

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

9.4.4 Thermal Conductivity of Wood

Many physical and mechanical properties of wood change with moisture content below the fiber saturation point. The equilibrium moisture content is about 9%. Moisture generally reduces the strength of wood. Moisture also reduces the charring rate.

For moisture content of 25% or less, densities greater than 300 kg/m^3, and temperature of 24°C, the average thermal conductivity of wood perpendicular to the grain is:

$$k = S\,(0.0001941 + 0.000004046M) + 0.01864$$

where

k = thermal conductivity (W/m•K)

S = density based on volume at current moisture content and over-dry mass (kg/m^3)

M = moisture content (%)

Conductivity increases about 2–3% per 10°C.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

9.4.5 Heat Capacity of Dry Wood

$$c_\rho = 0.1031 + 0.003867T$$

where

c_ρ = heat capacity (kJ/kg•K) of dry wood

T = temperature (K)

9.5 Tied Fire Walls

Tied fire walls are fastened to and usually encase members of the structural frame of the building, according to NFPA 221, Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls. To remain stable, the pull of the collapsing structural members on the fire side of the wall must be resisted by the strength of the structure on the other side.

If the wall is not located at the center of strength, the lateral resistance of the frame on either side of the wall should be sufficient to resist the maximum horizontal component of the force that could result from collapsing structural framework on the opposite side. The horizontal force at each tie should be computed using this formula:

$$H = \frac{wBL^2}{8S}$$

where

H = horizontal pull per tie (lb or kg)

w = dead load plus 25% of live load of the roof (lb/ft^2 or kg/m^2)

B = distance between ties (ft or m)

L = span of structural member running perpendicular to wall (ft or m)

S = sag (ft or m) that may be assumed as:

$0.07L$ for open-web steel trusses

$0.09L$ for solid-web steel beams

$0.06L$ for wood trusses

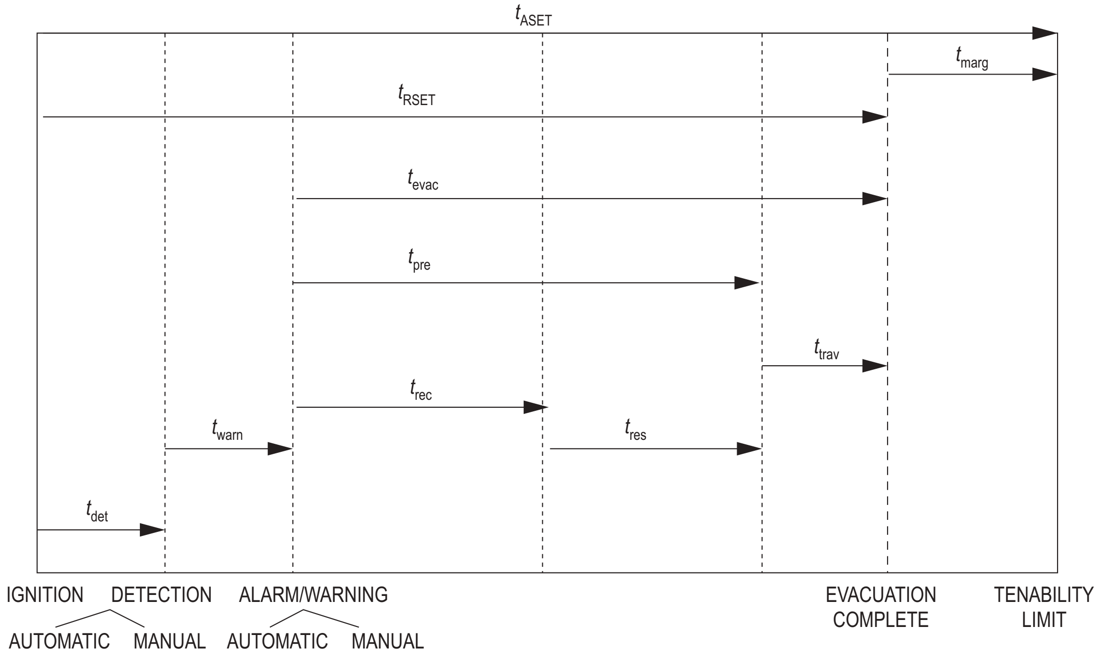
10 EGRESS AND OCCUPANT MOVEMENT

10.1 General

Factors that may influence people's responses and behaviors during evacuations in fire situations:

- Occupant characteristics—including mobility limitations and cognitive abilities
- Human response to cues (recognition time)
- Decision making (response time)
- Movement—including susceptibility to effects from products of combustion
- Fire environment impact

10.1.1 Egress Timeline



Engineering Timeline

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

where

t_{det} = detection time, the interval between fire ignition and the first detection of the fire by a device or individual

t_{warn} = warning time, the interval between detection of the fire and the time at which an alarm signal is activated or notification of occupants takes place

t_{pre} = pre-evacuation time, the interval between the time at which a general alarm signal or warning is given and the time at which the first deliberate evacuation movement is made (includes recognition time and response time)

t_{rec} = recognition time, the interval between the time at which the alarm signal is perceived and the time at which the occupant interprets this signal as indicating a fire/emergency event

t_{res} = response time, the interval between recognition time and the time that the first move is made to evacuate the building

t_{trav} = travel time, the time needed, once movement toward an exit has begun, for all occupants to reach a place of safety

t_{evac} = evacuation time, the time from the alarm signal to the time at which the occupants reach a place of safety

t_{RSET} = required safe egress time, calculated time necessary between ignition of a fire and the time at which all occupants can reach an area of safety

t_{ASET} = available safe egress time, calculated time available between ignition of a fire and the time at which tenability criteria are exceeded in the means of egress

10.1.2 Limitations in the Hydraulic Model of Occupant Movement

The following are limitations of the hydraulic model of occupant movement calculations:

- Behaviors that detract from movement are not explicitly considered.
- The numbers of people in a structural component are considered rather than their identity and their individual attributes.
- Movement between egress components is considered (e.g., from room to room), rather than within them.
- The results are deterministic and will therefore remain the same unless changes are made to the scenario or the assumptions employed.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.1.3 Required Safe Egress Time (RSET)

$$\text{RSET} = t_{\text{d}} + t_{\text{n}} + t_{\text{p-e}} + t_{\text{e}}$$

where

t_{d} = time from fire ignition to detection; that is, the detection phase

t_{n} = time from detection to notification of occupants of a fire emergency; that is, the notification phase

$t_{\text{p-e}}$ = time from notification (or cue reception) until evacuation commences; that is, the pre-evacuation phase

t_{e} = time from the start of purposive evacuation movement until safety is reached; that is, the evacuation phase

10.1.4 Component Effective Widths

Component effective width = component width – boundary layer width

Exit Route Element	Boundary Layer Width	
	in.	cm
Stairways—wall or side of tread	6	15
Railings, handrails [a]	3.5	9
Theater chairs, stadium benches	0	0
Corridors, ramp walls	8	20
Obstacles	4	10
Wide concourses, passageways	<18	46
Doors, archways	6	15

[a] Where handrails are present, use the value of the actual handrail if it results in a lesser effective width.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.2 Evacuation Movement

The following people-movement characteristics are needed to estimate the movement time:

- Speed
- Specific flow
- Calculated flow

10.2.1 Evacuation Speed

If the population density is less than approximately 0.05 persons/ft^2 (0.54 persons/m^2) of exit route, individuals will move at their own pace, independent of the speed of others. If the population density exceeds about 0.35 persons/ft^2 (3.8 persons/m^2), it is assumed that no movement will take place until enough of the crowd has passed from the crowded area to reduce the population density. Between the population density limits of 0.05 and 0.35 persons/ft^2 (0.54 and 3.8 persons/m^2), the relationship between speed and population density is assumed to be represented by a linear function. The equation of this function is

$$S = k - akD$$

where

S = speed along the line of travel

D = population density, in persons per unit area

k = constant, as listed in the table of "Constants for Equations for Evacuation Speed"

= k_1; and $a = 2.86$ for speed, in ft/min, and density is in persons/ft^2

= k_2; and $a = 0.266$ for speed, in m/s, and density is in persons/m^2

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.2.2 Evacuation Speed Constants

Constants for Equations for Evacuation Speed

Exit Route Element		k_1	k_2
Corridor, aisle, ramp, doorway:		275	1.40
Stairs:			
Riser (in.)	Tread (in.)		
7.5	10	196	1.00
7.0	11	212	1.08
6.5	12	229	1.16
6.5	13	242	1.23

1 in. = 25.4 mm

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.2.3 Conversion Factors for Travel Along a Stair

Conversion Factors for Relating Line of Travel Distance to Vertical Travel for Various Stair Configurations

Risers (in.)	Tread (in.)	Conversion Factor
7.5	10.0	1.66
7.0	11.0	1.85
6.5	12.0	2.08
6.5	13.0	2.22

1 in. = 25.4 mm

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.2.4 Unimpeded Travel Speed

Maximum (Unimpeded) Exit Flow Speeds

Exit Route Element		Speed Along Line of Travel	
		ft/min	m/s
Corridor, aisle, ramp, doorway:		235	1.19
Stairs:			
Riser (in.)	Tread (in.)		
7.5	10	167	0.85
7.0	11	187	0.95
6.5	12	196	1.00
6.5	13	207	1.05

1 in. = 25.4 mm

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.2.5 Specific Flow

Specific flow, F_s, is the flow of evacuating persons past a point in the exit route, per unit of time per unit of effective width, W_e, of the route involved. The equation for specific flow is

$$F_s = S \times D$$

where

F_s = specific flow (persons/ft/min or persons/m/s of effective width)

D = population density (persons/ft^2 or persons/m^2 of effective width)

S = speed of movement (ft/min or m/s)

10.2.6 Specific Flow Related to Population Density

$$F_s = (1 - a\,D)\,k\,D$$

where

F_s = specific flow (persons/ft/min or persons/m/s)

a = 2.86 for speed (ft/min) and density (persons/ft^2)

= 0.266 for speed (m/s) and density (persons/m^2)

D = population density (persons/ft^2 or persons/m^2)

k is as listed in the table of "Constants for Equations for Evacuation Speed"

10.2.7 Maximum Specific Flow

(This information is from the following source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, Chapter 59, pp. 2,126–2,127, Equation 59.8)

Occurs when the density is 0.175 persons/ft^2 (1.9 persons/m^2) of exit route space.

Maximum Specific Flow, F_{sm}

Exit Route Element		Maximum Specific Flow	
		Persons/min/ft of effective width	Persons/s/m of effective width
Corridor, aisle, ramp, doorway:		24.0	1.3
Stairs:			
Riser (in.)	Tread (in.)		
7.5	10	17.1	0.94
7.0	11	18.5	1.01
6.5	12	20.0	1.09
6.5	13	21.2	1.16

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.2.8 Calculated Flow

The calculated flow, F_c, is the predicted flow rate of persons passing a particular point in an exit route. The equation for calculated flow is based on the assumption that the achievable flow rate through a component is directly proportional to its width.

$$F_c = F_s \times W_e$$

where

F_c = calculated flow

F_s = specific flow

W_e = effective width of the component being traversed

$F_c = (1 - a\ D)k\ D\ W_e$

where

F_c is in persons/min when $k = k_1$ (see table in section 10.2.2), D is in persons/ft^2, and W_e is in ft.

F_c is in persons/s when $k = k_2$ (see table in section 10.2.2), D is persons/m^2, and W_e is in m.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.2.9 Time for Passage

The time for passage, t_p, is the time for a group of persons to pass a point in an exit route and is expressed as

$$t_p = \frac{P}{F_c}$$

$$t_p = \frac{P}{(1 - a\ D)kDW_e}$$

where

t_p = time for passage: in min when F_c is in persons/min; in sec when F_c is in persons/sec

P = population size, in persons

10.2.10 Travel Data

UNASSISTED Movement Speeds on Stairs (m/s) for People with Disabilities/Elderly

Source (Author, Year)	Observational Conditions (**L**: Location, **N**: Nature, **SC**: Spatial Configuration, **P**: Participants, **V**: Variable)	Configuration			Sample			Results	Additional Information
		Direction (Up, Down)	Slope	Distance	Collection Method	Description	Size	Mean (m/s) [Standard Deviation, Range]	
DESCENT									
Jiang et al., 2012	L:China N:ET SC:2 floors, in subway station P:[S1–3: mixed age/gender] V:different mobility capabilities (S1–3)	Down	17.7° #	1 storey	Video	S1: Disability, no aid	40	0.85 [0.19, 0.32-1.34]	# Derived from information in paper
						S2: Single crutch	20	0.43 [0.14, 0.21-0.69]	Measurements to 0.04-sec precision. Instructed to move "at the highest speed could maintain"
						S3: Double crutch	40	0.33 [0.13, 0.12-0.68]	Results also presented by gender and by varying passage widths
Kuligowski et al., 2012	L:USA N:AE SC:13 floors, assisted-living residential building P:[S1–2: mixed elderly] V:different mobility capabilities (S1–2)	Down	25.1° #	13 storey	Video	S1: Elderly, no aid	83	0.41 [0.17, 0.11-0.91]	# Derived from information in paper. Low densities implied; however, speeds presented may not always be unimpeded movement speeds.
						S2: Disability, using cane	14	0.23 [0.08, 0.11-0.33]	Paper also presents localized speeds between various floor groupings
Sørensen and Dederichs, 2012	L:Denmark N:[ET1–4] SC:ET1–2:2/ET3–4:3 P:mixed gender, 10–69 years V: –	Down	–	–	Video	Visually impaired	46	0.73 [0.09, 0.54-0.92]	Paper also explores and presents relationship between speed and density

Source (Author, Year)	Observational Conditions (**L**: Location, **N**: Nature, **SC**: Spatial Configuration, **P**: Participants, **V**: Variable)	Configuration			Sample			Results	Additional Information
		Direction (Up, Down)	Slope	Distance	Collection Method	Description	Size	Mean (m/s) [Standard Deviation, Range]	
Jiang et al., 2009 In Chinese; data provided by author in China.	L:China N:ET SC:[40 m, subway station] P:[S1–3: mixed age/ gender] V:different mobility capabilities (S1–3)	Down	17.7° #	1 storey	Video	S1: Disability, no aid	9	0.81 [0.11, 0.68-1.06]	# Derived from information in paper Measurements to 0.04-sec precision Instructed to move "at the highest speed could maintain"
						S2: Single crutch	6	0.28 [0.08, 0.18-0.40]	
						S3: Double crutch	10	0.31 [0.13, 0.12-0.48]	
Fujiyama and Tyler, 2004	L:UK N:[ET1–2]. ET1: normal movement; ET2: fast movement SC:[1, various geometries] P:[S1–8: age 60–81, mixed gender] V:Impact of component slope (CS1–4), with the procedure employed (ET1–2)	Down	CS1: 38.8°	3.5 m #	Observer		18	CS1,ET1: 0.60 [0.16, –] CS1,ET2:0.79 [0.22, –]	# Incline length derived from horizontal and vertical length given in paper Paper also explores correlation between physical characteristics and walking speeds and between speed on horizontal and stairs Asked to walk at both "normal" and "fast" speeds
			CS2: 35°	3.7 m #			18	CS2,ET1: 0.72 [0.20, –] CS2,ET2; 0.86 [0.22, –]	
			CS3: 30.5°	4.6 m #			18	CS3,ET1:0.73 [0.17, –] CS3,ET2:0.96 [0.21, –]	
			CS4: 24.6°	3.4 m #			18	CS4,ET1:0.91 [0.26, –] CS4,ET2:1.15 [0.30, –]	

Source (Author, Year)	Observational Conditions (**L**: Location, **N**: Nature, **SC**: Spatial Configuration, **P**: Participants, **V**: Variable)	Configuration			Sample			Results	Additional Information
		Direction (Up, Down)	Slope	Distance	Collection Method	Description	Size	Mean (m/s) [Standard Deviation, Range]	
Boyce et al., 1999a	L:UK N:[ET/Unimp] SC:[1] P:[S1–5: mixed age/gender] V:different mobility capabilities (S1–5)	Down	37°–38°	1 storey	Observer, stop-watch	S1: Locomotion disability (all)	30	0.33 [0.16, 0.11–0.70]	Measurements to 0.1-sec precision [a] Rollator user, not used during descent. Instructed to move in "prompt manner"
						S2: Locomotion disability, no aid	19	0.36 [0.14, 0.13–0.70]	
						S3: Crutches	1	0.22	
						S4: Walking stick	9	0.32 [0.12, 0.11–0.49]	
						S5: Rollator [a]	1	0.16	
Proulx et al., 1995	L:Canada N:[UE1–3] S:[UE1–3 mid-rise apartment] P:[mixed age/gender + disability]. S1 included those with movement disabilities; S2 were over 65 years old. V:different trials involving populations with different mobility levels (UE1–3) and age attributes (S1–2)	Down	–	6–7 storey	Video	UE1, S1	–	0.88 [a]	[a] Note – all speed calculations include times at rest/stop Speeds measured during low density but may not necessarily be unimpeded speeds
						UE2, S1	–	0.61	
						UE3, S1	–	0.57	
						UE2, S2	–	0.57	
						UE3, S2	–	0.58	

Source (Author, Year)	Observational Conditions (**L**: Location, **N**: Nature, **SC**: Spatial Configuration, **P**: Participants, **V**: Variable)	Configuration			Sample			Results	Additional Information
		Direction (Up, Down)	**Slope**	**Distance**	**Collection Method**	**Description**	**Size**	**Mean (m/s) [Standard Deviation, Range]**	
ASCENT									
Jiang et al., 2012	L:China N:[ET/Unimp] SC:[2 floors in subway station] P:[S1–3: mixed age/ gender] V:different mobility capabilities (S1–3)	Up	17.7° #	1 storey	Video	S1: Disability, no aid	40	0.76 [0.18, 0.52–1.19]	# Derived from information in paper
						S2: Single crutch	20	0.39 [0.14, 0.18–0.67]	Measurements to 0.04-sec precision. Instructed to move "at the highest speed could maintain"
						S3: Double crutch	40	0.27 [0.14, 0.08–0.50]	Results also presented by gender and by varying passage widths
Fujiyama and Tyler, 2004	L:UK N:[ET1–2]:ET1, normal movement; ET2, fast movement SC:[1, various geometries] P:[S1–8: age 60–81, mixed gender] V:impact of component slope (CS1–4) given the procedure employed (ET1–2)	Up	CS1:38.8°	3.5 #	Observer		18	CS1,ET1:0.56 [0.15, –] CS2,ET2:0.77 [0.23, –]	# Incline length derived from paper Paper also explores correlation between physical characteristics and walking speeds and between speed on horizontal and stairs Instructed to walk at both "normal" and "fast" speeds
			CS2: 35°	3.7 #			18	CS2,ET1:0.64 [0.15, –] CS2,ET2:0.85 [0.25, –]	
			CS3: 30.5°	4.6 #			18	CS3,ET1:0.68 [0.15, –] CS3,ET2:0.91 [0.23, –]	
			CS4: 24.6°	3.4 #			18	CS4,ET1:0.83 [0.19, –] CS4,ET2:1.14 [0.26, –]	

Source (Author, Year)	**Observational Conditions** (**L**: Location, **N**: Nature, **SC**: Spatial Configuration, **P**: Participants, **V**: Variable)	**Configuration**			**Sample**			**Results**	**Additional Information**
		Direction (Up, Down)	**Slope**	**Distance**	**Collection Method**	**Description**	**Size**	**Mean (m/s) [Standard Deviation, Range]**	
Jiang et al., 2009 In Chinese; data provided by author in China	L:China N:[ET/Unimp] SC:[40 m, subway station] P:[S1–3: mixed age/gender] V:different mobility capabilities (S1–3)	Up	17.7°	1 storey	Video	S1: Disability, no aid	9	0.77 [0.13, 0.62–1.06]	
						S2: Single crutch	6	0.32 [0.09, 0.19–0.43]	
						S3: Double crutch	10	0.25 [0.11, 0.10–0.37]	
Boyce et al., 1999a	L:UK N:[ET/Unimp] SC:[1] P:[S1–5: mixed age/gender] E:– V:different mobility capabilities (S1–5)	Up	37°–38°	1 storey	Observer, stop-watch	S1: Locomotion disability (all)	30	0.38 [0.14, 0.13–0.62]	[a] Rollator user, not used during descent Instructed to move in "prompt manner"
						S2: Locomotion disability, no aid	19	0.43 [0.13, 0.14–0.62]	
						S3: Crutches	1	0.22 [–, 0.13–0.31]	
						S4: Walking stick	9	0.35 [0.11, 0.18–0.49]	
						S5: Rollator [a]	1	0.14	

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3 Egress Behavior in Smoke

10.3.1 Smoke Density and Visibility – Jin

$$V = \frac{1}{C_s}\log_e\left[\frac{L_t}{\left(\frac{\delta_c aE}{\pi}\right)}\right]$$

where

V = visibility of signs at the obscuration threshold (m)

C_s = smoke density expressed by the extinction coefficient (1/m) (hereafter, smoke density will be expressed by the extinction coefficient in 1/m)

L_t = brightness of signs (cd/m^2)

δ_c = contrast threshold of signs in smoke at the obscuration threshold (0.01~0.05)

a = σ_s/C_s (0.4~1.0) and $C_s = \sigma_s + \sigma_{ab}$ (σ_s: scattering coefficient; σ_{ab}: absorption coefficient)

E = mean illuminance of illuminating light from all directions in smoke (1m/m^2) or (1x)

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3.1.1 Extinction Coefficient (C_s)

Note that the extinction coefficient C_s can be obtained by the following equation:

$$C_s = \frac{1}{D}\log_e\left(\frac{I}{I_o}\right)$$

where

I_o = intensity of the incident light (cd)

I = intensity of light through smoke (cd)

D = light path length (m)

10.3.1.2 Visibility at 5–15 m

The visibility, V, at the obscuration threshold of signs is found to be

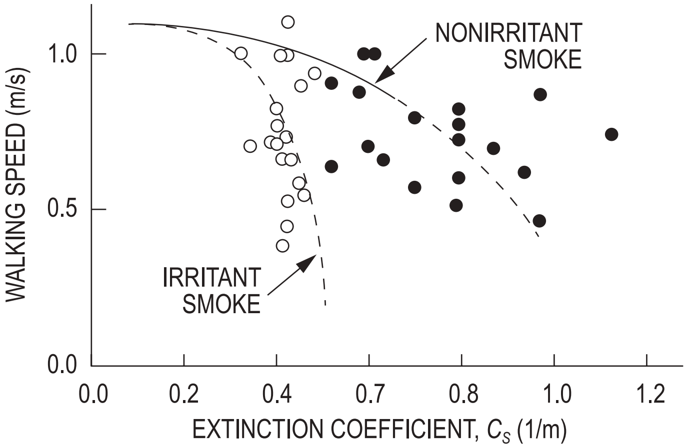
For a light-emitting sign: $V = \frac{5}{C_s} \sim V = \frac{10}{C_s}$

For a reflecting sign: $V = \frac{2}{C_s} \sim V = \frac{4}{C_s}$

The visibility of other objects—such as walls, floors, doors, and stairways in an underground shopping mall or a long corridor—varies depending on the interior and its contrast condition; however, the minimum value for reflecting signs may be applicable.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3.2 Walking Speeds in Smoke



Walking Speed in Fire Smoke

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3.3 Occupant Exposure to Heat

Tolerance limit of 0.25 W/cm^2 or 2.5 kW/m^2 for radiant heat exposure, below which exposure can be tolerated for several minutes.

5 kW/m^2 for a person to get burned in 13 sec on bare skin; 40 sec for a second-degree burn.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3.3.1 Skin Exposure to Radiant Heat

$$t_{\mathrm{I,rad}} = \frac{r}{\dot{q}''^{1.33}}$$

where

$t_{\mathrm{I,rad}}$ = exposure time, min

$\dot{q}''$ = radiant heat flux (kW/m^2)

r = radiant heat exposure dose [(kW•m^{-2})$^{4/3}$ min]

A relationship for time (min) to the second-degree burning of skin due to radiant flux, q kW/m^2, is

$$t_{I,\mathrm{rad}} = 6.9q^{-1.56}$$

10.3.3.2 Radiant Heat Endpoint for Exposed Skin

Endpoint	Radiant Heat Exposure Dose, r [(kW•m^{-2})$^{4/3}$ min]
Severe skin pain	1.33–1.67
2nd-degree burns	4.0–12.2
3rd-degree (full thickness) burns	16.7

10.3.4 Toxicity

In fires, three major toxic effects are important:

1. The concentrations of irritant gases likely to impair escape efficiency or cause incapacitation (sensory irritation)
2. The exposure doses (C_t product doses) of asphyxiant gases likely to cause a) incapacitation through confusion and loss of consciousness or b) death
3. The exposure doses of irritants likely to cause death through lung edema and inflammation after the fire

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3.4.1 Fractional Irritant Concentration (FIC)

When FIC = 1, a tenability endpoint (escape impairment) is predicted. Incapacitation is predicted at higher concentrations (FIC ~ 3–5).

$$\mathrm{FIC} = \mathrm{FIC}_{\mathrm{HCl}} + \mathrm{FIC}_{\mathrm{HBr}} + \mathrm{FIC}_{\mathrm{HF}} + \mathrm{FIC}_{\mathrm{SO_2}} + \mathrm{FIC}_{\mathrm{NO_2}} + \mathrm{FIC}_{\mathrm{CH_2CHO}} + \mathrm{FIC}_{\mathrm{CH_2O}} + \Sigma\,\mathrm{FIC}_{\mathrm{x}}$$

where

$\Sigma\,\mathrm{FIC}_{\mathrm{x}} = \mathrm{FIC}_{\mathrm{s}}$ for any other irritants present

10.3.4.2 Irritant Concentrations of Common Fire Gases

Gas	Concentration Predicted to Impair Escape in Half the Population (ppm)	Concentration Predicted to Cause Incapacitation in Half the Population (ppm)
HCl	200	900
HBr	200	900
HF	200	900
SO_2	24	120
NO_2	70	350
CH_2CHO (acrolein) [a]	4	20
HCHO (formaldehyde) [a]	6	30

[a] Where the concentrations of acrolein and formaldehyde (or other important irritants) are unknown, a term derived from smoke density, 0.5 OD/m, may be used as an indication of irritancy likely to impair escape efficiency.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3.4.3 Fractional Effective Dose (FED)

$$\mathrm{FED} = \int_{\mathrm{t1}}^{\mathrm{t2}} \sum_{i=1}^{n} \frac{C_{\mathrm{i}}}{(Ct)_{\mathrm{i}}}\,\Delta t$$

where

C_{i} = average concentration of a dose-related toxicant, such as an asphyxiant gas "I", over the chosen time increment

Δt = chosen time increment (min)

$(Ct)_{\mathrm{i}}$ = specific exposure dose (concentration × minutes) that would constitute an effective dose (i.e., an exposure dose producing a defined endpoint, such as preventing an occupant's safe escape)

10.3.4.4 Fraction of an Incapacitating Dose for Single Species

$$F_{\mathrm{Ico}} = \frac{conc.\ gas\ \ present \times time}{conc. \times time\ \ for\ incapacitation}$$

If the fractional doses per each minute are summed throughout the exposure, the dose and time to incapacitation can be predicted.

10.3.4.5 Carbon Monoxide/Carboxyhemoglobin

$$F_{\mathrm{Ico}} = 3.317 \times 10^{-5}\,(\mathrm{CO})^{1.036}\,\frac{V\,t}{D}$$

where

(CO) = carbon monoxide concentration (ppm v/v 20°C)

V = volume of air breathed each minute (L/min)

t = exposure time (min)

D = exposure dose percent (COHb) for incapacitation

The following values may be taken for V and D:

Activity Level of Subject	*V* (L/min)	*D* (percent COHb)
Resting or sleeping	8.5	40
Light work—i.e., walking to escape	25	30
Heavy work—i.e., slow running, walking up stairs	5	20

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3.4.6 Average Concentration of Asphyxiant Gases—Single Armchair Room Burn

For each minute during the first 6 minutes of a single armchair room burn:

Asphyxiant Gas	At 1 min	At 2 min	At 3 min	At 4 min	At 5 min	At 6 min
CO (ppm)	0	0	500	2,000	3,500	6,000
HCN (ppm)	0	0	0	75	125	174
CO_2 %	0	0	1.5	3.5	6	8
O_2 %	20.9	20.9	19	17.5	15	12

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.3.4.7 Time to Incapacitation from Oxygen Depletion

$$t_{\mathrm{I_o}} = \exp\left[8.13 - 0.54\left(20.9 - \%\,\mathrm{O_2}\right)\right]$$

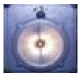
$$Dose\ to\ incapacitation = \left(20.9 - \%\,\mathrm{O_2}\right)\left(t_{\mathrm{I_o}}\right)$$

For a short exposure time, t, fraction of an incapacitating dose of hypoxia:

$$F_{\mathrm{I_o}} = \frac{\left(20.9 - \%\,\mathrm{O_2}\right)(t)}{\left(20.9 - \%\,\mathrm{O_2}\right)\left(t_{\mathrm{I_o}}\right)}$$

$$F'_{\mathrm{I_o}} = \frac{1}{t_{\mathrm{I_o}}}\ \text{for each minute of exposure}$$

10.4 Emergency Lights

No.	Type	Purpose of Utilization	Light Source Area		Max Luminance (cd/m^2)[a]	Illuminance (tx)[b]	Regression Linear Function	
			Appearance	Size (cm)			Slope (k_1)	Intercept (k_2)
1.	Ordinary emergency light	Emergency light and exit sign used for ship		9.5	10,000	7	4.5	3.4
2.	Hanging lamp	Emergency light		13.0	1,000	3	9.2	2.1
3.	Halogen lamp #1	General purpose (unidirectional)		5.5	10,000	690	47.6	–6.1
4.	Halogen lamp #2	General purpose (wide-directional)		5.5	60,000	34	32.9	–3.9
5.	MIL standard emergency lamp	Emergency light based on US military specification		10.0	16,230	103	8.9	2.0

[a] Max luminance is the highest luminance of light source surface.

[b] Illuminance is the vertical illuminance from 1 m against the light source center.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

10.5 Remoteness of Exits

(Source: NFPA 101, Life Safety Code.
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7.5.1.3.1. Where more than one exit, exit access, or exit discharge is required from a building or portion thereof, such exits, exit accesses, or exit discharges shall be remotely located from each other and be arranged to minimize the possibility that more than one has the potential to be blocked by any one fire or other emergency condition.

7.5.1.3.2. Where two exits, exit accesses, or exit discharges are required, they shall be located at a distance from one another not less than one-half the length of the maximum overall diagonal dimension of the building or area to be served, measured in a straight line between the nearest edge of the exits, exit accesses, or exit discharges, unless otherwise provided in 7.5.1.3.3 through 7.5.1.3.5.

7.5.1.3.3. In buildings protected throughout by an approved, supervised automatic sprinkler system in accordance with Section 9.7, the minimum separation distance between two exits, exit accesses, or exit discharges, measured in accordance with 7.5.1.3.2, shall be not less than one-third the length of the maximum overall diagonal dimension of the building or area to be served.

11 PHYSICAL PROPERTIES

11.1 General

11.1.1 Hearing

Threshold of hearing = 0 dB = 0.00002 Pa = 1×10^{-12} W/m^2

11.1.2 Properties of Air

Thermal Properties of Air at Ambient Temperatures

Air Properties at 10°C		
Density	ρ_a	1.293 kg/m^3
Thermal conductivity	k_a	0.02492 W/m•K
Dynamic viscosity	μ_a	1.71×10^{-5} kg/m•s
Prandtl number	Pr_a	0.71

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.1.3 Properties of Water

Property	USCS	Metric
Weight	8.34 lb/gal	
Density at 70ºF or 21ºC	62.4 lb/ft^3	1,000 kg/m^3
Specific heat of water	1 Btu to raise 1 lb of water 1ºF	4.186 kJ/kg•K
Latent heat of vaporization for 1 lb or 0.45 kg of water	970.3 Btu	2,254.8 kJ/kg
Heat of fusion of ice to convert 1 lb or 0.45 kg of ice into water (32ºF)	143.4 Btu	151.3 kJ
Vapor pressure (absolute) at 70ºF or 21ºC	0.361 psia	2.49 kPa
Vapor pressure (head) at 70ºF or 21ºC	0.84 ft	0.26 m
Vapor pressure (absolute) at 90ºF or 32ºC	0.70 psia	4.83 kPa
Vapor pressure (head) at 90ºF or 32ºC	1.6 ft	0.78 m

11.1.4 Properties of Metals

Metal	Symbol	Atomic Weight	Density ρ (kg/m^3) Water = 1,000	Melting Point (°C)	Melting Point (°F)	Specific Heat (J/kg•K)	Electrical Resistivity (10^{-8} Ω•m) at 0°C (273.2 K)	Heat Conductivity λ (W/m•K) at 0°C (273.2 K)
Aluminum	Al	26.98	2,698	660	1,220	895.9	2.5	236
Antimony	Sb	121.75	6,692	630	1,166	209.3	39	25.5
Arsenic	As	74.92	5,776	subl. 613	subl. 1,135	347.5	26	–
Barium	Ba	137.33	3,594	710	1,310	284.7	36	–
Beryllium	Be	9.012	1,846	1,285	2,345	2,051.5	2.8	218
Bismuth	Bi	208.98	9,803	271	519	125.6	107	8.2
Cadmium	Cd	112.41	8,647	321	609	234.5	6.8	97
Caesium	Cs	132.91	1,900	29	84	217.7	18.8	36
Calcium	Ca	40.08	1,530	840	1,544	636.4	3.2	–
Cerium	Ce	140.12	6,711	800	1,472	188.4	7.3	11
Chromium	Cr	52	7,194	1,860	3,380	406.5	12.7	96.5
Cobalt	Co	58.93	8,800	1,494	2,721	431.2	5.6	105
Copper	Cu	63.54	8,933	1,084	1,983	389.4	1.55	403
Gallium	Ga	69.72	5,905	30	86	330.7	13.6	41
Gold	Au	196.97	19,281	1,064	1,947	129.8	2.05	319
Indium	In	114.82	7,290	156	312	238.6	8	84
Iridium	Ir	192.22	22,550	2,447	4,436	138.2	4.7	147
Iron	Fe	55.85	7,873	1,540	2,804	456.4	8.9	83.5
Lead	Pb	207.2	11,343	327	620	129.8	19.2	36
Lithium	Li	6.94	533	180	356	4,576.2	8.55	86
Magnesium	Mg	24.31	1,738	650	1,202	1,046.7	3.94	157
Manganese	Mn	54.94	7,473	1,250	2,282	502.4	138	8
Mercury	Hg	200.59	13,547	–39	–38	142.3	94.1	7.8
Molybdenum	Mo	95.94	10,222	2,620	4,748	272.1	5	139
Nickel	Ni	58.69	8,907	1,455	2,651	439.6	6.2	94
Niobium	Nb	92.91	8,578	2,425	4,397	267.9	15.2	53
Osmium	Os	190.2	22,580	3,030	5,486	129.8	8.1	88
Palladium	Pd	106.4	11,995	1,554	2,829	230.3	10	72
Platinum	Pt	195.08	21,450	1,772	3,221	134	9.81	72
Potassium	K	39.09	862	63	145	753.6	6.1	104
Rhodium	Rh	102.91	12,420	1,963	3,565	242.8	4.3	151
Rubidium	Rb	85.47	1,533	38.8	102	330.7	11	58
Ruthenium	Ru	101.07	12,360	2,310	4,190	255.4	7.1	117
Silver	Ag	107.87	10,500	961	1,760	234.5	1.47	428
Sodium	Na	22.989	966	97.8	208	1,235.1	4.2	142
Strontium	Sr	87.62	2,583	770	1,418	–	20	–
Tantalum	Ta	180.95	16,670	3,000	5,432	150.7	12.3	57
Thallium	Tl	204.38	11,871	304	579	138.2	10	10
Thorium	Th	232.04	11,725	1,700	3,092	117.2	14.7	54

Metal	Symbol	Atomic Weight	Density ρ (kg/m³) Water = 1,000	Melting Point (°C)	Melting Point (°F)	Specific Heat (J/kg•K)	Electrical Resistivity (10^{-8} Ω•m) at 0°C (273.2 K)	Heat Conductivity λ (W/m•K) at 0°C (273.2 K)
Tin	Sn	118.69	7,285	232	449	230.3	11.5	68
Titanium	Ti	47.88	4,508	1,670	3,038	527.5	39	22
Tungsten	W	183.85	19,254	3,387	6,128	142.8	4.9	177
Uranium	U	238.03	19,050	1,135	2,075	117.2	28	27
Vanadium	V	50.94	6,090	1,920	3,488	481.5	18.2	31
Zinc	Zn	65.38	7,135	419	786	393.5	5.5	117
Zirconium	Zr	91.22	6,507	1,850	3,362	284.7	40	23

11.1.5 Typical Material Properties

Typical Material Properties

(Use these values if the specific alloy and temper are not listed in Table 2 below)

Material	Modulus of Elasticity, *E* [Mpsi (GPa)]	Modulus of Rigidity, *G* [Mpsi (GPa)]	Poisson's Ratio, *v*	Coefficient of Thermal Expansion, *α* [10^{-6} °F (10^{-6} °C)]	Density, ρ [lb/in³ (Mg/m³)]
Steel	29.0 (200.0)	11.5 (80.0)	0.30	6.5 (11.7)	0.282 (7.8)
Aluminum	10.0 (69.0)	3.8 (26.0)	0.33	13.1 (23.6)	0.098 (2.7)
Cast Iron	14.5 (100.0)	6.0 (41.4)	0.21	6.7 (12.1)	0.246–0.282 (6.8–7.8)
Wood (Fir)	1.6 (11.0)	0.6 (4.1)	0.33	1.7 (3.0)	–
Brass	14.8–18.1 (102–125)	5.8 (40)	0.33	10.4 (18.7)	0.303–0.313 (8.4–8.7)
Copper	17 (117)	6.5 (45)	0.36	9.3 (16.6)	0.322 (8.9)
Bronze	13.9–17.4 (96–120)	6.5 (45)	0.34	10.0 (18.0)	0.278–0.314 (7.7–8.7)
Magnesium	6.5 (45)	2.4 (16.5)	0.35	14 (25)	0.061 (1.7)
Glass	10.2 (70)	–	0.22	5.0 (9.0)	0.090 (2.5)
Polystyrene	0.3 (2)	–	0.34	38.9 (70.0)	0.038 (1.05)
Polyvinyl Chloride (PVC)	<0.6 (<4)	–	–	28.0 (50.4)	0.047 (1.3)
Alumina Fiber	58 (400)	–	–	–	0.141 (3.9)
Aramide Fiber	18.1 (125)	–	–	–	0.047 (1.3)
Boron Fiber	58 (400)	–	–	–	0.083 (2.3)
Beryllium Fiber	43.5 (300)	–	–	–	0.069 (1.9)
BeO Fiber	58 (400)	–	–	–	0.108 (3.0)
Carbon Fiber	101.5 (700)	–	–	–	0.083 (2.3)
Silicon Carbide Fiber	58 (400)	–	–	–	0.116 (3.2)

Source: Hibbeler, R.C., *Mechanics of Materials*, 4th ed., 2000. Pearson Education, Inc., New York, NY.

Average Mechanical Properties of Typical Engineering Materials (U.S. Customary Units)[a]

(Use these values for the specific alloys and temper listed. For all other materials refer to Table 1 above.)

Materials		Specific Weight γ (lb/in^3)	Modulus of Elasticity, E (10^3 ksi)	Modulus of Rigidity, G (10^3 ksi)	Yield Strength (ksi) σy			Ultimate Strength (ksi) σu			% Elongation in 2 in. Specimen	Poisson's Ratio ν	Coeff. of Therm. Expansion α 10^{-6}/°F
					Tens.	Comp.[b]	Shear	Tens.	Comp. [b]	Shear			
Metallic													
Aluminum Wrought Alloys	2014-T6	0.101	10.6	3.9	60	60	25	68	68	42	10	0.35	12.8
	6061-T6	0.098	10.0	3.7	37	37	19	42	42	27	12	0.35	13.1
Cast Iron Alloys	Gray ASTM 20	0.260	10.0	3.9	–	–	–	26	97	–	0.6	0.28	6.70
	Malleable ASTM A-197	0.263	25.0	9.8	–	–	–	40	83	–	5	0.28	6.60
Copper Alloys	Red Brass C83400	0.316	14.6	5.4	11.4	11.4	–	35	35	–	35	0.35	9.80
	Bronze C86100	0.319	15.0	5.6	50	50	–	95	95	–	20	0.34	9.60
Magnesium Alloy	[Am 1004-T611]	0.066	6.48	2.5	22	22	–	40	40	22	1	0.30	14.3
Steel Alloys	Structural A36	0.284	29.0	11.0	36	36	–	58	58	–	30	0.32	6.60
	Stainless 304	0.284	28.0	11.0	30	30	–	75	75	–	40	0.27	9.60
	Tool L2	0.295	29.0	11.0	102	102	–	116	116	–	22	0.32	6.50
Titanium Alloy	[Ti-6Al-4V]	0.160	17.4	6.4	134	134	–	145	145	–	16	0.36	5.20
Nonmetallic													
Concrete	Low Strength	0.086	3.20	–	–	–	1.8	–	–	–	–	0.15	6.0
	High Strength	0.086	4.20	–	–	–	5.5	–	–	–	–	0.15	6.0
Plastic Reinforced	Kevlar 49	0.0524	19.0	–	–	–	–	104	70	10.2	2.8	0.34	–
	30% Glass	0.0524	10.5	–	–	–	–	13	19	–	–	0.34	–
Wood Select Structural Grade	Douglas Fir	0.017	1.90	–	–	–	–	0.30[c]	3.78[d]	0.90[d]	–	0.29[c]	–
	White Spruce	0.130	1.40	–	–	–	–	0.36[c]	5.18[d]	0.97[d]	–	0.31[c]	–

[a] Specific values may vary for a particular material due to alloy or mineral composition, mechanical working of the specimen, or heat treatment. For a more exact value, consult reference books for the material.

[b] The yield and ultimate strengths for ductile materials can be assumed equal for both tension and compression.

[c] Measured perpendicular to the grain.

[d] Measured parallel to the grain.

Source: Hibbeler, R.C., *Mechanics of Materials*, 4 ed., Pearson Education, Inc., 2000, New York, NY.

11.2 Thermodynamics

Thermal and Physical Properties of Gases at Room Temperature

Substance	Mol. Wt.	c_p		c_v		k	R	
		kJ/kg•K	Btu/lbm-°R	kJ/kg•K	Btu/lbm-°R		kJ/kg•K	ft-lbf/lbm-°R
Air	29	1.00	0.240	0.718	0.171	1.40	0.2870	53.34
Argon	40	0.520	0.125	0.312	0.0756	1.67	0.2081	38.68
Butane	58	1.72	0.415	1.57	0.381	1.09	0.1430	26.58
Carbon dioxide	44	0.846	0.203	0.657	0.158	1.29	0.1889	35.10
Carbon monoxide	28	1.04	0.249	0.744	0.178	1.40	0.2968	55.16
Ethane	30	1.77	0.427	1.49	0.361	1.18	0.2765	51.38
Helium	4	5.19	1.25	3.12	0.753	1.67	2.0769	386.0
Hydrogen	2	14.3	3.43	10.2	2.44	1.40	4.1240	766.4
Methane	16	2.25	0.532	1.74	0.403	1.30	0.5182	96.35
Neon	20	1.03	0.246	0.618	0.148	1.67	0.4119	76.55
Nitrogen	28	1.04	0.248	0.743	0.177	1.40	0.2968	55.15
Octane vapor	114	1.71	0.409	1.64	0.392	1.04	0.0729	13.53
Oxygen	32	0.918	0.219	0.658	0.157	1.40	0.2598	48.28
Propane	44	1.68	0.407	1.49	0.362	1.12	0.1885	35.04
Steam	18	1.87	0.445	1.41	0.335	1.33	0.4615	85.76

Thermal and Physical Properties of Selected Liquids and Solids at Room Temperature

Substance	c_p		Density	
	kJ/kg•K	Btu/lbm-°R	kg/m^3	lbm/ft^3
Liquids				
Ammonia	4.80	1.146	602	38
Mercury	0.139	0.033	13,560	847
Water	4.18	1.000	997	62.4
Solids				
Aluminum	0.900	0.215	2,700	170
Copper	0.386	0.092	8,900	555
Ice (0°C; 32°F)	2.11	0.502	917	57.2
Iron	0.450	0.107	7,840	490
Lead	0.128	0.030	11,310	705

Source: Howell, John, R. and Richard O. Bukins, *Fundamentals of Engineering Thermodynamics*, 2nd ed., McGraw-Hill, 1992, p. 896.

11.3 Physical and Combustion Properties of Selected Fuels

Fuel	Mol. Wt.	Spec. Grav.	T_{Boil} (°C)	Heat of Vap. (kJ/kg)	Heat of Comb. (MJ/kg)	Stoichiometry		Flammability Limits (% stoichio.)		Spont. Ign. Temp. (°C) [b]	Fuel for Max. Flame Speed (% stoichio.)	Max. Flame Speed (cm/s)	Flame Temp. at Max. Fl. Speed (K)	Ignition Energy (10^{-5} cal.)		Quenching Dist. (mm)	
						% Vol.	f [a]	Lean	Rich					Stoich.	Min.	Stoich.	Min.
Acetaldehyde	44.1	0.783	–56.7	569.4	–	0.0772	0.1280	–	–	–	–	–	–	8.99	–	2.29	–
Acetone	58.1	0.792	56.7	523.0	30.8	0.0497	0.1054	59	233	561.1	131	50.18	2,121	27.48	–	3.81	–
Acetylene	26.0	0.621	–83.9	–	48.2	0.0772	0.0755	31	–	305.0	133	155.25	–	0.72	–	0.76	–
Acrolein	56.1	0.841	52.8	–	–	0.0564	0.1163	48	752	277.8	100	61.75	–	4.18	–	1.52	–
Acrylonitrile	53.1	0.797	78.3	–	–	0.0528	0.1028	87	–	481.1	105	46.75	2,461	8.60	3.82	2.29	1.52
Ammonia	17.0	0.817	–33.3	1,373.6	–	0.2181	0.1645	–	–	651.1	–	–	2,600	–	–	–	–
Aniline	93.1	1.022	184.4	432.6	–	0.0263	0.0872	–	–	593.3	–	–	–	–	–	–	–
Benzene	78.1	0.885	80.0	431.8	39.9	0.0277	0.0755	43	336	591.7	108	44.60	2,365	13.15	5.38	2.79	1.78
Benzyl alcohol	108.1	1.050	205.0	–	–	0.0240	0.0923	–	–	427.8	–	–	–	–	–	–	–
1,2-Butadiene (methylallene)	54.1	0.658	11.1	–	45.5	0.0366	0.0714	–	–	–	117	63.90	2,419	5.60	–	1.30	–
n-Butane	58.1	0.584	–0.5	385.8	45.7	0.0312	0.0649	54	330	430.6	113	41.60	2,256	18.16	6.21	3.05	1.78
Butanone (methyl-ethyl ketone)	72.1	0.805	79.4	–	–	0.0366	0.0951	–	–	–	100	39.45	–	12.67	6.69	2.54	2.03
1-Butene	56.1	0.601	–6.1	443.9	45.3	0.0377	0.0678	53	353	443.3	116	47.60	2,319	–	–	–	–
d-Camphor	152.2	0.990	203.4	–	–	0.0153	0.0818	–	–	466.1	–	–	–	–	–	–	–
Carbon disulfide	76.1	1.263	46.1	351.0	–	0.0652	0.1841	18	1,120	120.0	102	54.46	–	0.36	–	0.51	–
Carbon monoxide	28.0	–	–190.0	211.7	–	0.2950	0.4064	34	676	608.9	170	42.88	–	–	–	–	–
Cyclobutane	56.1	0.703	12.8	–	–	0.0377	0.0678	–	–	–	115	62.18	2,308	–	–	–	–
Cyclohexane	84.2	0.783	80.6	258.1	43.8	0.0227	0.0678	48	401	270.0	117	42.46	2,250	32.98	5.33	4.06	1.78
Cyclohexene	82.1	0.810	82.8	–	–	0.0240	0.0701	–	–	–	–	44.17	–	20.55	–	3.30	–
Cyclopentane	70.1	0.751	49.4	388.3	44.2	0.0271	0.0678	–	–	385.0	117	41.17	2,264	19.84	–	3.30	–
Cyclopropane	42.1	0.720	–34.4	–	–	0.0444	0.0678	58	276	497.8	113	52.32	2,328	5.74	5.50	1.78	1.78
trans-Decalin	138.2	0.874	187.2	–	–	0.0142	0.0692	–	–	271.7	109	33.88	2,222	–	–	–	–
n-Decane	142.3	0.734	174.0	359.8	44.2	0.0133	0.0666	45	356	231.7	105	40.31	2,286	–	–	2.06	–
Diethyl ether	74.1	0.714	34.4	351.6	–	0.0337	0.0896	55	2,640	185.6	115	43.74	2,253	11.71	6.69	2.54	2.03
Ethane	30.1	–	–88.9	488.3	47.4	0.0564	0.0624	50	272	472.2	112	44.17	2,244	10.04	5.74	2.29	1.78
Ethyl acetate	88.1	0.901	77.2	–	–	0.0402	0.1279	61	236	486.1	100	35.59	–	33.94	11.47	4.32	2.54
Ethanol	46.1	0.789	78.5	836.8	26.8	0.0652	0.1115	–	–	392.2	–	–	–	–	–	–	–
Ethylamine	45.1	0.706	16.7	611.3	–	0.0528	0.0873	–	–	–	–	–	–	57.36	–	5.33	–
Ethylene oxide	44.1	1.965	10.6	581.1	–	0.0772	0.1280	–	–	428.9	125	11.35	2,411	2.51	1.48	1.27	1.02
Furan	68.1	0.936	32.2	400.0	–	0.0444	0.1098	–	–	–	–	–	–	5.40	–	1.78	–
n-Heptane	100.2	0.688	98.5	364.9	44.4	0.0187	0.0661	53	450	247.2	122	42.46	2,214	27.49	5.74	3.81	1.78

Fuel	Mol. Wt.	Spec. Grav.	T_{Boil} (°C)	Heat of Vap. (kJ/kg)	Heat of Comb. (MJ/kg)	Stoichiometry		Flammability Limits (% stoichio.)		Spont. Ign. Temp. (°C) [b]	Fuel for Max. Flame Speed (% stoichio.)	Max. Flame Speed (cm/s)	Flame Temp. at Max. Fl. Speed (K)	Ignition Energy		Quenching Dist.	
						% Vol.	*f* [a]	Lean	Rich					Stoich.	Min.	Stoich.	Min.
														(10^{-5} cal.)		(mm)	
n-Hexane	86.2	0.664	68.0	364.9	44.7	0.0216	0.0659	51	400	260.6	117	42.46	2,239	22.71	5.50	3.56	1.78
Hydrogen	2.0	–	–252.7	451.0	119.9	0.2950	0.0290	–	–	571.1	170	291.19	2,380	0.36	0.36	0.51	0.51
iso-Propanol	60.1	0.785	82.2	664.8	–	0.0444	0.0969	–	–	455.6	100	38.16	–	15.54	–	2.79	–
Kerosene	154.0	0.825	250.0	290.8	43.1	–	–	–	–	–	–	–	–	–	–	–	–
Methane	16.0	–	–161.7	509.2	50.0	0.0947	0.0581	46	164	632.2	106	37.31	2,236	7.89	6.93	2.54	2.03
Methanol	32.0	0.793	64.5	1,100.9	19.8	0.1224	0.1548	48	408	470.0	101	52.32	–	5.14	3.35	1.78	1.52
Methyl formate	60.1	0.975	31.7	472.0	–	0.0947	0.2181	–	–	–	–	–	–	14.82	–	2.79	–
n-Nonane	128.3	0.772	150.6	288.3	44.6	0.0147	0.0665	47	434	238.9	–	–	–	–	–	–	–
n-Octane	114.2	0.707	125.6	300.0	44.8	0.0165	0.0633	51	425	240.0	–	–	2,251	–	–	–	–
n-Pentane	72.1	0.631	36.0	364.4	45.3	0.0255	0.0654	54	359	284.4	115	42.46	2,250	19.60	5.26	3.30	1.78
1-Pentene	70.1	0.646	30.0	–	45.0	0.0271	0.0678	47	370	298.3	114	46.75	2,314	–	–	–	–
Propane	44.1	0.508	–42.2	425.5	46.3	0.0402	0.0640	51	283	504.4	114	42.89	2,250	7.29	–	2.03	1.78
Propene	42.1	0.522	–47.7	437.2	45.8	0.0444	0.0678	48	272	557.8	114	48.03	2,339	6.74	–	2.03	–
n-Propanol	60.1	0.804	97.2	685.8	–	0.0444	0.0969	–	–	433.3	–	–	–	–	–	–	–
Toluene	92.1	0.872	110.6	362.8	40.9	0.0227	0.0743	43	322	567.8	105	38.60	2,344	–	–	–	–
Triethylamine	101.2	0.723	89.4	–	–	0.0210	0.0753	–	–	–	–	–	–	27.48	–	3.81	–
Turpentine	–	–	–	–	–	–	–	–	–	252.2	–	–	–	–	–	–	–
Xylene	106.0	0.870	130.0	334.7	43.1	–	–	–	–	–	–	–	–	–	–	–	–
Gasoline 73 octane	120.0	0.720	155.0	338.9	44.1	–	–	–	–	298.9	–	–	–	–	–	–	–
Gasoline 100 octane	–	–	–	–	–	–	–	–	–	468.3	106	37.74	–	–	–	–	–
Jet fuel JP1	150.0	0.810	–	–	43.0	0.0130	0.0680	–	–	248.9	107	36.88	–	–	–	–	–
JP3	112.0	0.760	–	–	43.5	0.0170	0.0680	–	–	–	–	–	–	–	–	–	–
JP4	126.0	0.780	–	–	43.5	0.0150	0.0680	–	–	261.1	107	38.17	–	–	–	–	–
JP5	170.0	0.830	–	–	43.0	0.0110	0.0690	–	–	242.2	–	–	–				

[a] *f* is the stoichiometric air/fuel ratio; i.e., $f = 1/r$.

[b] For additional information, see Table C.5 and Chapter 18, "Ignition of Liquids," in the SFPE *Handbook of Fire Protection Engineering*, fifth edition.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.4 Heat of Combustion

11.4.1 Selected Fuels

Heat of Combustion for Selected Fuels at 25°C (298 K)

Fuel[a]	ΔH_c kJ/mol	ΔH_c kJ/g	ΔH_c[c] kJ/g (O_2)	ΔH_c kJ/g (air)
Carbon monoxide (CO)	283	10.10	17.69	4.10
Methane (CH_4)	800	50.00	12.54	2.91
Ethane (C_2H_6)	1,423	47.45	11.21	2.96
Ethene (C_2H_4)	1,411	50.53	14.74	3.42
Ethyne (C_2H_2)	1,253	48.20	15.73	3.65
Propane (C_3H_8)	2,044	46.45	12.80	2.97
n-Butane (n-C_4H_{10})	2,650	45.69	12.80	2.97
n-Pentane (n-C_5H_{12})	3,259	45.27	12.80	2.97
n-Hexane	3,861	44.90		
c-Hexane (c-C_6H_{12})	3,680	43.81	12.80	2.97
n-Octane (n-C_8H_{18})	5,104	44.77	12.80	2.97
Benzene (C_6H_6)	3,120	40.00	13.06	3.03
Methanol (CH_3OH)	635	19.83	13.22	3.07
Ethanol (C_2H_5OH)	1,232	26.78	12.88	2.99
Acetone (CH_3COCH_3)	1,786	30.79	14.00	3.25
D-glucose ($C_6H_{12}O_6$)	2,772	15.40	13.27	3.08
Cellulose [b]	–	16.09	13.59	3.15
Polyethylene	–	43.28	12.65	2.93
Polypropylene	–	43.31	12.66	2.94
Polystyrene	–	39.85	12.97	3.01
Polyvinylchloride	–	16.43	12.84	2.98
Polymethylmethacrylate	–	24.89	12.98	3.01
Polyacrylonitrile	–	30.80	13.61	3.16
Polyoxymethylene	–	15.46	14.50	3.36
Polyethyleneterephthalate	–	22.00	13.21	3.06
Polycarbonate	–	29.72	13.12	3.04
Nylon 6,6	–	29.58	12.67	2.94
Polyester	–	23.8	–	–
Wool	–	20.5	–	–
Wood (European Beech)	–	19.5	–	–
Wood volatiles (European Beech)	–	16.6	–	–
Wood char (European Beech)	–	34.3	–	–
Wood (Ponderosa Pine)	–	19.4	–	–

[a] Apart from the solids (D-glucose, etc.), the initial state of the fuel and of all the products is taken to be gaseous.

[b] Cotton and rayon are virtually pure cellulose and can be assumed to have the same heat of combustion.

[c] $\Delta H_c(O_2)$ = 13.1 kJ/g is used in the oxygen consumption method for calculating rate of heat release.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.4.2 Net Heats of Combustion Per Unit Mass of Fuel[a]

Fuel [d]	Formula [b]	ΔH_T^c (kJ/g)	ΔH_O^* (kJ/g)	ΔH_{CO_2} (kJ/g)	ΔH_{CO}^* (kJ/g)
Normal Alkanes					
Methane	CH_4	50.1	12.5	(18.2)	(18.6)
Ethane	C_2H_6	47.1	12.7	16.2	15.4
Propane	C_3H_8	46.0	12.9	15.3	14.0
Butane	C_4H_{10}	45.4	12.7	15.1	13.7
Pentane	C_5H_{12}	45.0	12.6	14.7	13.2
Hexane	C_6H_{14}	44.8	12.7	14.6	12.9
Heptane	C_7H_{16}	44.6	12.7	14.5	12.8
Octane	C_8H_{18}	44.5	12.6	14.4	12.7
Nonane	C_9H_{20}	44.3	12.7	14.3	12.5
Decane	$C_{10}H_{22}$	44.4	12.7	14.3	12.4
Undecane	$C_{11}H_{24}$	44.3	12.7	14.3	12.4
Dodecane	$C_{12}H_{26}$	44.2	12.7	14.2	12.3
Tridecane	$C_{13}H_{28}$	44.2	12.7	14.2	12.3
Kerosene	$C_{14}H_{30}$	44.1	12.7	14.1	12.2
Hexadecane	$C_{16}H_{34}$	44.1	12.7	14.2	12.3
		Average	**12.7**	**14.6**	**12.9**
Substituted Alkanes					
Methylbutane	C_5H_{12}	45.0	12.6	14.7	13.1
Dimethylbutane	C_6H_{14}	44.8	12.7	14.6	13.0
Methylpentane	C_6H_{14}	44.8	12.7	14.6	12.9
Dimethylpentane	C_7H_{16}	44.6	12.7	14.5	12.9
Methylhexane	C_7H_{16}	44.6	12.6	14.4	12.7
Isooctane	C_8H_{18}	44.5	12.6	14.4	12.7
Methylethylpentane	C_8H_{18}	44.5	12.6	14.4	12.7
Ethylhexane	C_8H_{18}	44.5	12.6	14.4	12.7
Dimethylhexane	C_8H_{18}	44.5	12.7	14.5	12.8
Methylheptane	C_8H_{18}	44.5	12.6	14.4	12.7
		Average	**12.6**	**14.6**	**12.8**
Cyclic Alkanes					
Cyclopentane	C_5H_{10}	44.3	12.8	13.9	11.9
Methylcyclopentane	C_6H_{12}	43.8	12.7	13.9	11.9
Cyclohexane	C_6H_{12}	43.8	12.7	13.8	11.7
Methylcyclohexane	C_7H_{14}	43.4	12.7	13.8	11.7
Ethylcyclohexane	C_8H_{16}	43.2	12.7	13.8	11.7
Dimethylcyclohexane	C_8H_{16}	43.2	12.7	13.8	11.7
Cyclooctane	C_8H_{16}	43.2	12.7	13.9	11.9
Decalin	$C_{10}H_{18}$	42.8	12.7	13.4	11.0
Bicyclohexyl	$C_{12}H_{22}$	42.6	12.6	13.3	11.0
		Average	**12.7**	**13.8**	**11.6**

Fuel [d]	Formula [b]	ΔH_T^c (kJ/g)	ΔH_O^* (kJ/g)	ΔH_{CO_2} (kJ/g)	ΔH_{CO}^* (kJ/g)
Normal Alkenes					
Ethylene	C_2H_4	48.0	13.8	15.0	13.6
Propylene	C_3H_6	46.4	13.4	14.6	12.9
Butylene	C_4H_8	45.6	14.3	14.3	12.5
Pentene	C_5H_{10}	45.2	14.3	14.3	12.5
Hexene	C_6H_{12}	44.9	12.9	14.1	12.2
Heptene	C_7H_{14}	44.6	12.9	14.1	12.2
Octene	C_8H_{16}	44.5	12.9	14.1	12.1
Nonene	C_9H_{18}	44.3	12.9	14.1	12.1
Decene	$C_{10}H_{20}$	44.2	12.9	14.1	12.2
Dodecene	$C_{12}H_{24}$	44.1	12.9	14.1	12.2
Tridecene	$C_{13}H_{26}$	44.0	12.9	14.1	12.2
Tetradecene	$C_{14}H_{28}$	44.0	12.9	14.1	12.2
Hexadecene	$C_{16}H_{32}$	43.9	12.9	14.1	12.1
Octadecene	$C_{18}H_{36}$	43.8	12.9	14.1	12.1
		Average	**13.2**	**14.2**	**12.4**
Cyclic Alkenes					
Cyclohexene	C_6H_{10}	43.0	13.0	13.4	11.0
Methylcyclohexene	C_7H_{12}	43.1	12.9	13.4	11.1
		Average	**13.0**	**13.4**	**11.1**
Dienes					
1,3-Butadiene	C_4H_6	44.6	13.7	13.7	11.5
Cyclooctadiene	C_8H_{12}	43.2	13.3	13.3	10.9
		Average	**13.5**	**13.5**	**11.2**
Normal Alkynes					
Acetylene	C_2H_2	47.8	(15.6)	14.3	12.4
Heptyne	C_7H_{12}	44.8	13.4	13.9	11.8
Octyne	C_8H_{14}	44.7	13.3	14.0	11.9
Decyne	$C_{10}H_{18}$	44.5	13.2	13.9	11.9
Dodecyne	$C_{12}H_{22}$	44.3	13.2	14.0	12.0
		Average	**13.3**	**14.0**	**12.0**
Arenes					
Benzene	C_6H_6	40.1	13.0	11.9	8.7
Toluene	C_7H_8	39.7	12.9	12.1	9.0
Styrene	C_8H_8	39.4	13.1	12.0	8.8
Ethylbenzene	C_8H_{10}	39.4	12.9	12.3	9.4
Xylene	C_8H_{10}	39.4	13.0	12.4	9.5
Propylbenzene	C_9H_{12}	39.4	12.9	12.5	9.6
Trimethylbenzene	C_9H_{12}	39.2	12.9	12.5	9.7
Cumene	C_9H_{12}	39.2	12.9	12.9	9.6
Naphthalene	$C_{10}H_8$	39.0	12.9	11.3	7.7

Fuel [d]	Formula [b]	ΔH_T^c (kJ/g)	ΔH_O^* (kJ/g)	ΔH_{CO_2} (kJ/g)	ΔH_{CO}^* (kJ/g)
Arenes (cont'd)					
Tetralin	$C_{10}H_{12}$	39.0	12.9	12.2	9.2
Butylbenzene	$C_{10}H_{14}$	39.0	12.9	12.7	9.9
Diethylbenzene	$C_{10}H_{14}$	39.0	13.7	13.5	11.1
p-Cymene	$C_{10}H_{14}$	39.0	13.0	12.5	9.6
Methylnaphthalene	$C_{11}H_{10}$	38.9	12.9	11.5	8.1
Pentylbenzene	$C_{11}H_{16}$	38.8	13.0	12.8	10.2
Triethylbenzene	$C_{12}H_{18}$	38.7	12.7	12.7	10.0
		Average	**13.0**	**12.4**	**9.4**
Alcohols					
Methyl alcohol	CH_4O	20.0	13.4	14.5	12.9
Ethyl alcohol	C_2H_6O	27.7	13.2	14.5	12.7
n-Propyl alcohol	C_3H_8O	31.8	13.3	14.5	12.7
Isopropyl alcohol	C_3H_8O	31.8	13.3	14.5	12.7
Allyl alcohol	C_3H_6O	31.4	14.2	13.8	11.7
n-Butyl alcohol	$C_4H_{10}O$	34.4	13.3	14.5	12.8
Isobutyl alcohol	$C_4H_{10}O$	34.4	13.3	14.5	12.8
Sec-butyl alcohol	$C_4H_{10}O$	34.4	13.3	14.5	12.8
Ter-butyl alcohol	$C_4H_{10}O$	34.4	13.3	14.5	12.8
n-Amyl alcohol	$C_5H_{12}O$	36.2	13.3	14.5	12.8
Isobutyl carbinol	$C_5H_{12}O$	36.2	13.3	14.5	12.8
Sec-butyl carbinol	$C_5H_{12}O$	36.2	13.3	14.5	12.8
Methylpropylcarbinol	$C_5H_{12}O$	36.2	13.3	14.5	12.8
Dimethylethylcarbinol	$C_5H_{12}O$	36.2	13.3	14.5	12.8
n-Hexyl alcohol	$C_6H_{14}O$	37.4	13.3	14.5	12.7
Dimethylbutylalcohol	$C_6H_{14}O$	37.4	13.3	14.5	12.7
Ethylbutyl alcohol	$C_6H_{12}O$	37.4	13.3	14.5	12.7
Cyclohexanol	$C_6H_{12}O$	37.3	13.7	14.1	12.2
Benzyl alcohol	C_7H_8O	32.4	13.0	11.4	8.0
n-Heptyl alcohol	$C_7H_{16}O$	39.8	13.7	15.0	13.6
n-Octyl alcohol	$C_8H_{18}O$	40.6	13.7	15.0	13.6
n-Nonyl alcohol	$C_9H_{20}O$	40.3	13.4	14.7	13.0
		Average	**13.3**	**14.5**	**12.8**
Aldehydes					
Formaldehyde	CH_2O	18.7	(17.5)	12.7	10.1
Acetaldehyde	C_2H_4O	25.1	13.8	12.6	9.7
Butyraldehyde	C_4H_8O	33.8	13.9	13.9	11.7
Crotonaldehyde	C_4H_6O	34.8	15.2	13.8	11.8
Benzaldehyde	C_7H_6O	32.4	13.4	11.2	7.5
Ethyl hexaldehyde	$C_8H_{16}O$	39.4	13.7	12.7	9.9
		Average	**14.2**	**13.3**	**10.6**

Fuel [d]	**Formula** [b]	ΔH_T^c **(kJ/g)**	ΔH_O^* **(kJ/g)**	ΔH_{CO_2} **(kJ/g)**	ΔH_{CO}^* **(kJ/g)**
Ketones					
Acetone	C_3H_6O	29.7	13.4	13.1	10.5
Methylethyl ketone	C_4H_8O	32.7	13.4	13.4	11.0
Diethyl ketone	$C_5H_{10}O$	33.7	12.9	13.2	10.7
Cyclohexanone	$C_6H_{10}O$	35.9	13.8	13.3	11.0
Methyl butyl ketone	$C_6H_{12}O$	35.2	12.9	13.3	11.0
Di-acetone alcohol	$C_6H_{12}O_2$	37.3	(16.9)	(16.4)	(15.7)
Dipropyl ketone	$C_7H_{14}O$	38.6	13.8	14.3	12.5
Phenylbutyl ketone	$C_{11}H_{14}O$	34.8	12.6	11.6	(8.4)
		Average	**13.2**	**13.2**	**11.1**
Acids					
Formic acid	CH_2O_2	5.7	16.4	5.96	0
Acetic acid	$C_2H_4O_2$	14.6	13.7	9.95	5.65
Benzoic acid	$C_7H_6O_2$	24.4	12.4	9.66	5.18
Cresylic acid	$C_8H_80_2$	34.0	(16.0)	13.1	10.6
Esters					
Ethyl formate	$C_2H_6O_2$	20.2	13.3	11.3	7.8
n-Propyl formate	$C_4H_8O_2$	23.9	13.2	12.0	8.8
n-Butyl formate	$C_5H_{10}O_2$	26.6	13.0	12.3	9.4
Methyl acetate	$C_3H_6O_2$	20.2	13.3	11.3	7.8
Ethyl acetate	$C_4H_8O_2$	23.9	13.2	12.0	8.8
n-Propyl acetate	$C_5H_{10}O_2$	26.6	13.0	12.3	9.4
n-Butyl acetate	$C_6H_{12}O_2$	28.7	13.0	12.6	9.8
Isobutyl acetate	$C_6H_{12}O_2$	28.7	13.0	12.6	9.8
Amyl acetate	$C_7H_{14}O_2$	30.3	13.0	12.8	10.1
Cyclohexyl acetate	$C_8H_{14}O_2$	31.5	13.3	12.7	10.0
Octyl acetate	$C_{10}H_{20}O_2$	33.6	12.9	13.1	10.6
Ethylacetoacetate	$C_6H_{10}O_3$	30.3	(17.6)	(14.9)	(13.5)
Methyl propionate	$C_4H_8O_2$	23.9	13.2	12.0	7.4
Ethyl propionate	$C_5H_{10}O_2$	26.6	13.0	12.3	9.4
n-Butyl propionate	$C_7H_{14}O_2$	30.3	13.0	12.8	10.1
Isobutyl propionate	$C_7H_{14}O_2$	30.3	13.0	12.8	10.1
Amyl propionate	$C_8H_{18}O_2$	31.6	12.9	12.9	10.3
Methyl butyrate	$C_5H_{10}O_2$	26.6	13.0	12.3	9.4
Ethyl butyrate	$C_6H_{12}O_2$	28.7	13.0	12.6	9.8
Propyl butyrate	$C_7H_{14}O_2$	30.3	13.0	12.8	10.1
n-Butyl butyrate	$C_8H_{16}O_2$	31.6	12.9	12.9	10.3
Isobutyl butyrate	$C_8H_{16}O_2$	31.6	12.9	12.9	10.3
Ethyl laurate	$C_{14}H_{28}O_2$	37.2	13.3	13.8	11.6
Ethyl lactate	$C_5H_{10}O_3$	30.8	(18.9)	(16.5)	(16.0)
Butyl lactate	$C_7H_{14}O_3$	33.3	(16.8)	(15.8)	(14.8)

Fuel [d]	**Formula** [b]	**ΔH_T^c (kJ/g)**	**ΔH_O^* (kJ/g)**	**ΔH_{CO_2} (kJ/g)**	**ΔH_{CO}^* (kJ/g)**
Esters (cont'd)					
Amyl lactate	$C_8H_{16}O_3$	34.3	(16.4)	(15.6)	(14.5)
Ethyl benzoate	$C_9H_{10}O_2$	34.5	(15.4)	13.1	10.5
Ethyl carbonate	$C_5H_{10}O_3$	30.8	(18.9)	(16.5)	(16.0)
Ethyl oxalate	$C_6H_{10}O_4$	28.7	(20.2)	(16.6)	(20.2)
Ethyl malonate	$C_5H_8O_4$	32.2	(17.9)	(19.3)	(20.4)
		Average	**13.0**	**12.5**	**9.7**
Others					
Camphor	$C_{10}H_{16}O$	38.8	13.7	13.4	11.1
Cresol	C_7H_8O	34.6	13.7	12.1	9.1
Resorcinol	$C_6H_6O_2$	26.0	13.7	10.8	5.9
Acrolein	C_3H_4O	29.1	14.6	12.3	9.4
C-H-N Fuels					
Acrylonitrile	C_3H_3N	24.5	8.5	9.8	5.4
Diethylamine	$C_4H_{11}N$	38.0	11.2	15.8	14.8
n-Butylamine	$C_4H_{11}N$	38.0	11.2	15.8	14.8
sec-Butylamine	$C_4H_{11}N$	38.0	11.2	15.8	14.8
Pyridine	C_5H_9N	32.2	11.0	11.6	8.2
Aniline	C_6H_7N	33.8	11.2	11.9	8.7
Picoline	C_6H_7N	33.8	11.2	11.9	8.7
Triethylamine	$C_6H_{15}N$	39.6	11.6	15.2	13.8
Toluidine	C_7H_9N	34.9	11.3	12.1	9.1
Dimethylaniline	$C_8H_{11}N$	35.7	11.5	12.3	9.3
Di-*n*-butylamine	$C_8H_{19}N$	40.6	11.9	14.9	13.4
Quinoline	C_9H_7N	36.1	12.4	11.8	8.5
Quinaldine	$C_{10}H_9N$	36.7	12.4	11.9	8.7
Butylaniline	$C_{10}H_{15}N$	37.0	11.7	12.5	9.7
Tri-*n*-butylamine	$C_{12}H_{27}N$	41.6	12.1	14.6	12.9
		Average	**11.5**	**15.4**	**14.1**
C-H-S Fuels					
Carbon disulfide	CS_2	13.6	10.8	(23.5)	(27.0)
Thiophene	C_4H_4S	31.9	14.0	15.2	14.0
Methylthiophene	C_5H_6S	33.2	13.6	14.8	13.2
Thiophenol	C_6H_6S	34.1	13.8	14.2	12.3
Hexyl mercaptan	$C_6H_{14}S$	33.0	11.6	14.8	13.2
Thiocresol	C_7H_8S	34.9	13.5	14.1	12.1
Heptyl mercaptan	$C_7H_{16}S$	33.7	11.6	14.4	12.7
Cresolmethylsulfide	$C_8H_{11}S$	36.2	13.4	15.9	15.0
Decylmercaptan	$C_{10}H_{22}S$	34.9	11.5	13.8	11.7
Dodecyl mercaptan	$C_{12}H_{26}S$	35.5	11.5	13.6	11.4
Hexyl sulfide	$C_{12}H_{26}S$	35.5	11.5	13.6	11.4

Fuel [d]	**Formula** [b]	**ΔH_T^c (kJ/g)**	**ΔH_O^* (kJ/g)**	**ΔH_{CO_2} (kJ/g)**	**ΔH_{CO}^* (kJ/g)**
C-H-S Fuels (cont'd)					
Heptyl sulfide	$C_{14}H_{30}S$	35.9	11.5	13.4	11.1
Octyl sulfide	$C_{16}H_{34}S$	36.3	11.5	13.3	10.9
Decyl sulfide	$C_{20}H_{42}S$	36.8	11.4	13.1	10.7
		Average	**11.3**	**13.1**	**11.5**
Carbon-Hydrogen Atoms in the Structure					
Polyethylene	CH_2	43.6	12.8	13.9	11.8
Polypropylene	CH	43.4	12.7	13.8	11.7
Polyisobutylene	CH_2	43.7	12.7	13.9	11.9
Polybutadiene	$CH_{1.5}$	42.8	13.1	13.1	10.7
Polystyrene	CH	39.2	12.7	12.2	9.2
Expanded polystyrene:					
GM47	$CH_{1.1}$	38.1	12.4	11.3	7.7
GM49	$CH_{1.1}$	38.1	12.4	11.3	7.7
GM51	CH	35.6	11.6	10.8	7.0
GM53	$CH_{1.1}$	37.6	12.4	11.3	7.7
		Average	**12.5**	**12.4**	**9.5**
Carbon-Hydrogen-Oxygen-Nitrogen Atoms in the Structure					
Polyoxy-methylene	CH_2O	15.4	14.4	10.5	6.6
Polymethyl-methacrylate	$CH_{1.6}O_{0.4}$	25.2	13.1	11.5	8.0
Polyester	$CH_{1.4}O_{0.22}$	32.5	13.9	12.5	9.6
Epoxy	$CH_{1.3}O_{0.20}$	28.8	12.1	10.8	6.9
Polycarbonate	$CH_{0.88}O_{0.19}$	29.7	13.1	10.7	6.9
Cellulose triacetate	$CH_{1.3}O_{0.67}$	17.6	13.3	9.6	5.1
Polyethylene-terephthalate	$CH_{0.80}O_{0.40}$	22.0	13.2	9.6	5.1
Rigid phenolic foam	$CH_{1.1}O_{0.24}$	36.4	(16.8)	(14.0)	(12.0)
Polyacrylonitrile (PAN)	$CHN_{0.33}$	30.8	10.7	12.3	9.4
Red oak	$CH_{1.7}O_{0.72}N_{0.001}$	17.1	13.2	10.2	6.0
Douglas fir	$CH_{1.7}O_{0.742}N_{0.002}$	16.4	12.4	9.5	5.0
Nylon	$CH_{1.8}O_{0.17}N_{0.17}$	30.8	11.9	13.3	10.8
Flexible polyurethane foams:					
GM21	$CH_{1.8}O_{0.30}N_{0.05}$	26.2	12.1	11.5	8.0
GM23	$CH_{1.8}O_{0.35}N_{0.06}$	27.2	13.7	12.5	9.7
GM25	$CH_{1.7}O_{0.32}N_{0.07}$	24.6	12.0	11.1	7.5
GM27	$CH_{1.7}O_{0.03}N_{0.08}$	23.2	11.2	10.4	6.2
Rigid polyurethane foams:					
GM29	$CH_{1.1}O_{0.23}N_{0.10}$	26.0	12.6	10.7	6.8
GM31	$CH_{1.2}O_{0.22}N_{0.10}$	25.0	11.9	10.2	6.1
GM37	$CH_{1.2}O_{0.20}N_{0.08}$	28.0	12.7	11.2	7.5

Fuel [d]	Formula [b]	ΔH_T^c (kJ/g)	ΔH_O^* (kJ/g)	ΔH_{CO_2} (kJ/g)	ΔH_{CO}^* (kJ/g)
Carbon-Hydrogen-Oxygen-Nitrogen Atoms in the Structure (cont'd)					
Rigid polyisocyanurate foams:					
GM41	$CH_{1.0}O_{0.19}N_{0.11}$	26.2	12.5	10.4	6.4
GM43	$CH_{0.93}O_{0.20}N_{0.11}$	22.2	10.8	8.9	(4.0)
		Average	**12.5**	**10.9**	**7.2**
Carbon-Hydrogen-Chlorine Atoms in the Structure					
Polyethylene with:					
25% chlorine	$CH_{1.9}Cl_{0.13}$	31.6	12.7	13.4	10.8
36% chlorine	$CH_{1.8}Cl_{0.22}$	26.3	12.8	12.9	10.2
48% chlorine	$CH_{1.7}Cl_{0.36}$	20.6	12.8	12.3	9.4
Polychloroprene	$CH_{1.3}Cl_{0.30}$	25.3	13.3	12.7	9.5
Polyvinylchloride	$CH_{1.5}Cl_{0.50}$	16.4	11.7	11.7	8.2
Polyvinyl-idenechloride	CHCl	9.0	13.5	9.8	(5.5)
		Average	**12.8**	**12.1**	**9.6**
Carbon-Hydrogen-Fluorine Atoms in the Structure					
Teflon TFE	CF_2	6.2	9.7	(7.1)	(1.1)
Teflon FEP	$CF_{1.8}$	4.8	(6.9)	(5.0)	(0)
Tefzel ETFE	CHF	12.6	12.6	9.2	(4.4)
Teflon PFA	$CF_{1.7}O_{0.01}$	5.0	(8.0)	(5.3)	(0)
Kel-F (CTFE)	$CF_{1.5}Cl_{0.50}$	6.5	11.8	8.6	(3.5)
Halar (E-CTFE)	$CHF_{0.75}Cl_{0.25}$	12.0	9.8	9.8	(5.4)
Kynar (PVF_2)	CHF	13.3	12.4	9.1	(4.2)
Tedlar (PVF)	$CH_{1.5}F_{0.50}$	13.5	(6.5)	(7.1)	(1.1)
Carbon-Hydrogen-Oxygen-Silicone Atoms in the Structure					
Silicone-1	$CH_{1.3}O_{0.25}Si_{0.18}$	21.7	12.6	11.0	7.4
Silicone-2	$CH_{1.5}O_{0.30}Si_{0.26}$	21.3	13.9	12.4	9.4
Silicone-3	$CH_3O_{0.50}Si_{0.50}$	25.1	14.5	21.0	23.0

Note: Numbers in parentheses not used for averaging.

[a] From the data measured in the FM Global Research Flammability Laboratory.

[b] From the data for the elemental composition of the polymeric materials measured in the FM Global Research Flammability Laboratory.

[c] From the data measured by the FM Global Research Flammability Laboratory in the oxygen bomb calorimeter and corrected for water as a gas and for the residue.

[d] Trade names from Harper, C.A., Ed. *Handbook of Plastics and Elastomers*. 1975: McGraw-Hill Book Company, New York.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.4.3 Pure Substances

Heat of Combustion and Related Properties of Pure Substances

Material	Composition	Molecular Weight, W	Gross, Δh_c^u (MJ/kg)	Net, Δh_c^l (MJ/kg)	$\frac{\Delta h_c^l}{r_o}$ (MJ/kg of O_2)	Oxygen Fuel Mass Ratio, r_o	Boiling Temp., T_b (°C)	Latent Heat of Vaporization, Δh_v (kJ/kg)	Liquid Heat Capacity, C_{pl} (kJ/kg•°C)	Vapor Heat Capacity, C_{pv} (kJ/kg•°C)
Acetaldehyde	C_2H_4O	44.05	27.07	25.07	13.81	1.816	20.8	–	1.94	1.24
Acetic acid	$C_2H_4O_2$	60.05	14.56	13.09	12.28	1.066	118.1	395		1.11
Acetone	C_3H_6O	58.08	30.83	28.56	12.96	2.204	56.5	501	2.12	1.29
Acetylene	C_2H_2	26.04	49.91	48.22	15.70	3.072	–84.0	–	–	1.69
Acrolein	C_3H_4O	56.06	29.08	27.51	13.77	1.998	52.5	505	–	1.17
Acrylonitrile	C_3H_3N	53.06	33.16	31.92	14.11	2.262	77.3	615	2.10	1.20
(Allene) → propadiene										
Ammonium perchlorate*	NH_4ClO_4	117.49	2.35	2.16	3.97	0.545	–	–	–	
iso-Amyl alcohol	$C_5H_{12}O$	88.15	37.48	34.49	12.67	2.723	132.0	501	2.90	1.50
Aniline	C_6H_7N	93.12	36.44	34.79	13.06	2.663	184.4	478	2.08	1.16
Benzaldehyde	C_7H_6O	106.12	33.25	32.01	13.27	2.412	179.2	385	1.61	
Benzene	C_6H_6	78.11	41.83	40.14	13.06	3.073	80.1	389	1.72	1.05
Benzoic acid*	$C_7H_6O_2$	122.12	26.43	25.35	12.90	1.965	250.8	415	–	0.85
Benzyl alcohol	C_7H_8O	108.13	34.56	32.93	13.09	2.515	205.7	467	2.00	1.19
Bicyclohexyl	$C_{12}H_{22}$	166.30	45.35	42.44	12.61	3.367	236.0	263		
1,2-Butadiene	C_4H_6	54.09	47.95	45.51	13.99	3.254	10.8	–	–	1.48
1,3-Butadiene	C_4H_6	54.09	46.99	44.55	13.69	3.254	–4.4	–	–	1.47
(1,3-Butadiyne) → diacetylene										
n-Butane	C_4H_{10}	58.12	49.50	45.72	12.77	3.579	–0.5	–	2.30	1.68
iso-Butane	C_4H_{10}	58.12	48.95	45.17	12.62	3.579	–11.8	–	–	1.67
1-Butene	C_4H_8	56.10	48.44	45.31	13.24	3.422	–6.2	–	–	1.53
n-Butylamine	$C_4H_{11}N$	73.14	41.75	38.45	12.84	2.994	77.8	372	2.57	1.62
d-Camphor*	$C_{10}H_{16}O$	152.23	38.75	36.44	12.84	2.838	203.4	–	–	0.82
Carbon*	C	12.01	32.80	32.80	12.31	2.664	4,200.0	–	–	0.71
Carbon disulfide	CS_2	76.13	6.34	6.34	5.03	1.261	46.5	351	1.00	0.60
Carbon monoxide	CO	28.01	10.10	10.10	17.69	0.571	–191.3	–	–	1.04
Cellulose*	$C_6H_{10}O_5$	162.14	17.47	16.12	13.61	1.184	–	–	1.16	–
(Chloroethylene) → vinyl chloride										
(Chloroform) → trichloromethane										
Chlorotrifluoroethylene	C_2F_3Cl	116.47	2.00	2.00	3.64	0.549	–28.3	188	1.34	0.72
m-Cresol	C_7H_8O	108.13	34.26	32.64	12.98	2.515	202.2	399	2.00	1.13
Cumene	C_9H_{12}	120.19	43.40	41.20	12.90	3.195	152.3	312	1.77	1.26
Cyanogen	C_2N_2	52.04	21.06	21.06	17.12	1.230	–21.2	–	–	1.12
Cyclobutane	C_4H_8	56.10	48.91	45.77	13.38	3.422	12.9	–	–	1.29
Cyclohexane	C_6H_{12}	84.16	46.58	43.45	12.70	3.422	80.7	357	1.84	1.26
Cyclohexene	C_6H_{10}	82.14	45.67	42.99	12.99	3.311	82.8	371	1.80	1.28
Cyclohexylamine	$C_6H_{13}N$	99.18	41.05	38.17	12.79	2.984	134.5			
Cyclopentane	C_5H_{10}	70.13	46.93	43.80	12.80	3.422	49.3	389	2.23	1.18
Cyclopropane	C_3H_6	42.08	49.70	46.57	13.61	3.422	–32.9	–	1.92	1.33
(Decahydronaphthalene) → *cis*-decalin										
cis-Decalin	$C_{10}H_{18}$	138.24	45.49	42.63	12.70	3.356	195.8	309	1.67	1.21
n-Decane	$C_{10}H_{22}$	142.28	47.64	44.24	12.69	3.486	174.1	276	2.19	1.85
Diacetylene	C_4H_2	50.06	46.60	45.72	15.89	2.877	10.3	–	–	1.47
(Diamine) → hydrazine										
Diborane	H_6B_2	27.69	79.80	79.80	23.02	3.467	–92.5	–	–	1.75

Material	Composition	Molecular Weight, W	Gross, Δh_c^u (MJ/kg)	Net, Δh_c^l (MJ/kg)	$\frac{\Delta h_c^l}{r_o}$ (MJ/kg of O_2)	Oxygen Fuel Mass Ratio, r_o	Boiling Temp., T_b (°C)	Latent Heat of Vaporization, Δh_v (kJ/kg)	Liquid Heat Capacity, C_{pl} (kJ/kg•°C)	Vapor Heat Capacity, C_{pv} (kJ/kg•°C)
Dichloromethane	CH_2Cl_2	84.94	6.54	6.02	10.65	0.565	39.7	330	1.18	0.80
Diethyl cyclohexane	$C_{10}H_{20}$	140.26	46.30	43.17	12.58	3.422	174.0		1.87	
Diethyl ether	$C_4H_{10}O$	74.12	36.75	33.79	13.04	2.590	34.6	360	2.34	1.52
(2,4 Diisocyanotoulene) → toluene diisocyanate										
(Diisopropyl ether) → iso-propyl ether										
Dimethylamine	C_2H_7N	45.08	38.66	35.25	13.24	2.662	6.9	–	–	1.80
(Dimethyl aniline) → xylidene										
Dimethyldecalin	$C_{12}H_{22}$	166.30	45.70	42.79	13.15	3.254	220.0	260		
(Dimethyl ether) → methyl ether										
1,1-Dimethyl-hydrazine (UDMH)	$C_2H_8N_2$	60.10	32.95	30.03	14.10	2.130	25.0	578	2.73	
Dimethyl sulfoxide	C_2H_6SO	78.13	29.88	28.19	15.30	1.843	189.0	677	1.89	1.14
1,3 Dioxane	$C_4H_8O_2$	88.10	26.57	24.58	9.66	2.543	105.0	404		
1,4 Dioxane	$C_4H_8O_2$	88.10	26.83	24.84	9.77	2.543	101.1	406	1.74	1.07
Ethane	C_2H_6	30.07	51.87	47.49	12.75	3.725	–88.6	–	–	1.75
Ethanol	C_2H_6O	46.07	29.67	26.81	12.87	2.084	78.5	837	2.43	1.42
(Ethene) → ethylene										
Ethyl acetate	$C_4H_8O_2$	88.10	25.41	23.41	12.89	1.816	77.2	367	1.94	1.29
Ethyl acrylate	$C_5H_8O_2$	100.12	27.44	25.69	13.39	1.918	100.0	290		1.14
Ethylamine	C_2H_7N	45.08	38.63	35.22	13.23	2.662	16.5	–	2.89	1.61
Ethyl benzene	C_8H_{10}	106.16	43.00	40.93	12.93	3.165	136.1	339	1.75	1.21
Ethylene	C_2H_4	28.05	50.30	47.17	13.78	3.422	–103.9	–	2.38	1.56
Ethylene glycol	$C_2H_6O_2$	62.07	19.17	17.05	13.22	1.289	197.5	800	2.43	1.56
Ethylene oxide	C_2H_4O	44.05	29.65	27.65	15.23	1.816	10.7	–	1.97	1.10
(Ethylene trichloride) → trichloroethylene										
(Ethyl ether) → diethyl ether										
Formaldehyde	CH_2O	30.03	18.76	17.30	16.23	1.066	–19.3	–	–	1.18
Formic acid	CH_2O_2	46.03	5.53	4.58	13.15	0.348	100.5	476	2.15	0.98
Furan	C_4H_4O	68.07	30.61	29.32	13.86	2.115	31.4	398	1.69	0.96
a-D-glucose*	$C_6H_{12}O_6$	180.16	15.55	14.08	13.21	1.066	–	–	–	–
(Glycerine) → glycerol										
Glycerol	$C_3H_8O_3$	92.10	17.95	16.04	13.19	1.216	290.0	800	2.42	1.25
(Glycerol trinitrate) → nitroglycerin										
n-Heptane	C_7H_{16}	100.20	48.07	44.56	12.68	3.513	98.4	316	2.20	1.66
n-Heptene	C_7H_{14}	98.18	47.44	44.31	12.95	3.422	93.6	317	2.17	1.58
Hexadecane	$C_{16}H_{34}$	226.43	47.25	43.95	12.70	3.462	286.7	226	2.22	1.64
Hexamethyldisiloxane	$C_6H_{18}Si_2O$	162.38	38.30	35.80	15.16	2.364	100.1	192	2.01	–
(Hexamethylenetetramine) → methenamine										
n-Hexane	C_6H_{14}	86.17	48.31	44.74	12.68	3.528	68.7	335	2.24	1.66
n-Hexene	C_6H_{12}	84.16	47.57	44.44	12.99	3.422	63.5	333	2.18	1.57
Hydrazine	H_4N_2	32.05	52.08	49.34	49.40	0.998	113.5	1,180	3.08	1.65
Hydrazoic acid	HN_3	43.02	15.28	14.77	79.40	0.186	35.7	690	–	1.02
Hydrogen	H_2	2.00	141.79	130.80	16.35	8.000	–252.7	–	–	14.42
(Hydrogen azide) → hydrazoic acid										
Hydrogen cyanide	HCN	27.03	13.86	13.05	8.82	1.480	25.7	933	2.61	1.33
Hydrogen sulfide	H_2S	34.08	48.54	47.25	16.77	2.817	–60.3	548	–	1.00
Maleic anhydride*	$C_4H_2O_3$	74.04	18.77	18.17	14.01	1.297	202.0	–	–	–
Melamine*	$C_3H_6N_6$	126.13	15.58	14.54	12.73	1.142	–	–	–	–

Material	Composition	Molecular Weight, W	Gross, Δh_c^u (MJ/kg)	Net, Δh_c^l (MJ/kg)	$\frac{\Delta h_c^l}{r_o}$ (MJ/kg of O_2)	Oxygen Fuel Mass Ratio, r_o	Boiling Temp., T_b (°C)	Latent Heat of Vaporization, Δh_v (kJ/kg)	Liquid Heat Capacity, C_{pl} (kJ/kg•°C)	Vapor Heat Capacity, C_{pv} (kJ/kg•°C)
Methane	CH_4	16.04	55.50	50.03	12.51	4.000	–161.5	–	–	2.23
Methanol	CH_4O	32.04	22.68	19.94	13.29	1.500	64.8	1,101	2.37	1.37
Methenamine*	$C_6H_{12}N_4$	140.19	29.97	28.08	13.67	2.054	–	–	–	–
2-Methoxy-ethanol	$C_3H_8O_2$	76.09	24.23	21.92	13.03	1.682	124.4	583	2.23	–
Methylamine	CH_5N	31.06	34.16	30.62	13.21	2.318	–6.3	–	–	1.61
(2-Methyl 1-butanol) → iso-amyl alcohol										
(Methyl chloride) → dichloromethane										
Methyl ether	C_2H_6O	46.07	31.70	28.84	13.84	2.084	–24.9	–	–	1.43
Methyl ethyl ketone	C_4H_8O	72.10	33.90	31.46	12.89	2.441	79.6	434	2.30	1.43
1-Methylnaphthalene	$C_{11}H_{10}$	142.19	40.88	39.33	12.95	3.038	244.7	323	1.58	1.12
Methyl meth-acrylate	$C_5H_8O_2$	100.11	27.37	25.61	12.33	2.078	101.0	360	1.91	–
Methyl nitrate	CH_3NO_3	77.04	8.67	7.81	75.10	0.104	64.6	409	2.04	0.99
(2-Methyl propane) → iso-butane										
Naphthalene*	$C_{10}H_8$	128.16	40.21	38.84	12.96	2.996	217.9	–	1.18	1.03
Nitrobenzene	$C_6H_5NO_2$	123.11	25.11	24.22	14.90	1.625	210.7	330	1.52	–
Nitroglycerin	$C_3H_5N_3O_9$	227.09	6.82	6.34	–	–	Unstable	462	1.49	–
Nitromethane	CH_3NO_2	61.04	11.62	10.54	15.08	0.699	101.1	567	1.74	0.94
n-Nonane	C_9H_{20}	128.25	47.76	44.33	12.69	3.493	150.6	295	2.10	1.65
Octamethyl-cyclotetrasiloxane	$C_8H_{24}Si_4O_4$	296.62	26.90	25.10	14.56	1.725	175.0	127	1.88	–
n-Octane	C_8H_{18}	114.22	47.90	44.44	12.69	3.502	125.6	301	2.20	1.65
iso-Octane	C_8H_{18}	114.22	47.77	44.31	12.65	3.502	117.7	272	2.15	1.65
1-Octene	C_8H_{10}	112.21	47.33	44.20	12.92	3.422	121.3	301	2.19	1.59
(1-Octylene) → 1-octene										
1,2-Pentadiene	C_5H_8	68.11	47.31	44.71	13.60	3.288	44.9	405	2.21	1.55
n-Pentane	C_5H_{12}	72.15	48.64	44.98	12.68	3.548	36.0	357	2.33	1.67
1-Pentene	C_5H_{10}	70.13	47.77	44.64	13.04	3.422	30.0	359	2.16	1.56
Phenol*	C_6H_6O	94.11	32.45	31.05	13.05	2.380	181.8	433	1.43	1.10
Phosgene	$COCl_2$	98.92	1.74	1.74	10.74	0.162	8.3	247	1.02	0.58
Propadiene	C_3H_4	40.06	48.54	46.35	14.51	3.195	–34.6	–	–	1.44
Propane	C_3H_8	44.09	50.35	46.36	12.78	3.629	–42.2	–	2.23	1.67
n-Propanol	C_3H_8O	60.09	33.61	30.68	12.81	2.396	97.2	686	2.50	1.45
iso-Propanol	C_3H_8O	60.09	33.38	30.45	12.71	2.396	80.3	663	2.42	1.48
Propene	C_3H_6	42.08	48.92	45.79	13.38	3.422	–47.7	–	–	1.52
(*iso*-Propylbenzene) → cumene										
(Propylene) → propene										
iso-Propyl ether	$C_6H_{14}O$	102.17	39.26	36.25	12.86	2.819	67.8	286	2.14	1.55
Propyne	C_3H_4	40.06	48.36	46.17	14.45	3.195	–23.3	–	–	1.51
Styrene	C_8H_8	104.14	42.21	40.52	13.19	3.073	145.2	356	1.76	1.17
Sucrose*	$C_{12}H_{22}O_{11}$	342.30	16.49	15.08	13.44	1.122	–	–	1.24	–
(1,2,3,4-Tetrahydronaphthalene) → tetralin										
Tetralin	$C_{10}H_{12}$	132.20	42.60	40.60	12.90	3.147	207.0	425	1.64	1.19
Tetranitro-methane	CN_4O_8	196.04	2.20	2.20	–	–	125.7	196	–	–
Toluene	C_7H_8	92.13	42.43	40.52	12.97	3.126	110.4	360	1.67	1.12
Toluene diisocyanate	$C_9H_6N_2O_2$	174.16	24.32	23.56	13.50	1.746	120.0	–	1.65	–
Triethanolamine	$C_6H_{15}NO_3$	149.19	29.29	27.08	15.30	1.770	360.0	–	–	–
Triethylamine	$C_6H_{15}N$	101.19	43.19	39.93	12.95	3.083	89.5	303	2.22	1.59
1,1,2-Trichloroethane	$C_2H_3Cl_3$	133.42	7.77	7.28	11.02	0.660	114.0	260	1.11	0.67

Material	Composition	Molecular Weight, W	Gross, Δh_c^u (MJ/kg)	Net, Δh_c^l (MJ/kg)	$\frac{\Delta h_c^l}{r_o}$ (MJ/kg of O_2)	Oxygen Fuel Mass Ratio, r_o	Boiling Temp., T_b (°C)	Latent Heat of Vaporization, Δh_v (kJ/kg)	Liquid Heat Capacity, C_{pl} (kJ/kg•°C)	Vapor Heat Capacity, C_{pv} (kJ/kg•°C)
Trichloro-ethylene	C_2HCl_3	131.40	6.77	6.60	12.05	0.548	86.9	245	1.07	0.61
Trichloro-methane	$CHCl_3$	119.39	3.39	3.21	9.60	0.335	61.7	249	0.97	0.55
Trinitromethane	CHN_3O_6	151.04	3.41	3.25	–	–	Unstable	–	–	–
Trinitrotoluene*	$C_7H_5N_3O_6$	227.13	15.12	14.64	19.80	0.740	240.0	322	1.40	–
Trioxane	$C_3H_6O_3$	90.08	16.57	15.11	14.17	1.066	114.5	450	–	–
Urea*	CH_4ON_2	60.06	10.52	9.06	11.34	0.799	–	–	–	1.55
Vinyl acetate	$C_4H_6O_2$	86.09	24.18	22.65	13.54	1.673	72.5	167	2.00	1.05
Vinyl acetylene	C_4H_4	52.07	47.05	45.36	14.76	3.073	5.1	–	–	1.41
Vinyl bromide	C_2H_3Br	106.96	12.10	11.48	13.95	0.823	15.6	–	2.42	0.53
Vinyl chloride	C_2H_3Cl	62.50	20.02	16.86	11.97	1.408	–13.8	–	–	0.86
(Vinyl trichloride) → 1,1,2-trichlorolthane										
Xylenes	C_8H_{10}	106.16	42.89	40.82	12.90	3.165	138–144	343	1.72	1.21
Xylidene	$C_8H_{11}N$	121.22	38.28	36.29	12.79	2.838	192.7	366	1.77	–

*Denotes substance in crystalline solid form; otherwise, liquid if $T_b > 25°C$, gaseous if $T_b > 25°C$.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.4.4 Plastics

Heats of Combustion and Related Properties of Plastics

Material	Unit Composition	Molecular Weight, W	Gross, Δh_c^u (MJ/kg)	Net, Δh_c^l (MJ/kg)	$\frac{\Delta h_c^l}{r_o}$ (MJ/kg of O_2)	Oxygen Fuel Mass Ratio, r_o	Heat Capacity Solid, C_{ps} (kJ/kg•°C)
Acrylonitrile-butadiene styrene copolymer	–	–	35.25	33.75			1.41–1.59
Bisphenol A epoxy	$C_{11.85}H_{20.37}O_{2.83}N_{0.3}$	212.10	33.53	31.42	13.41	2.343	
Butadiene-acrylonitrile 37% copolymer	–	–	39.94				
Butadiene/styrene 8.58% copolymer	$C_{4.18}H_{6.09}$	56.30	44.84	42.49	13.11	3.241	1.94
Butadiene/styrene 25.5% copolymer	$C_{4.60}H_{6.29}$	61.55	44.19	41.95	13.07	3.209	1.82
Cellulose acetate (triacetate)	$C_{12}H_{16}O_8$	288.14	18.88	17.66	13.25	1.333	1.34
Cellulose acetate-butyrate	$C_{12}H_{18}O_7$	274.27	23.70	22.30	14.67	1.517	1.70
Epoxy, unhardened	$C_{31}H_{36}O_{5.5}$	496.63	32.92	31.32	13.05	2.400	
Epoxy, hardened	$C_{39}H_{40}O_{8.5}$	644.74	30.27	28.90	13.01	2.221	
Melamine formaldehyde (Formica™)	$C_6H_6N_6$	162.08	19.33	18.52	12.51	1.481	1.46
Nylon 6	$C_6H_{11}NO$	113.08	30.1–31.7	28.0–29.6	12.30	2.335	1.52
Nylon 6,6	$C_{12}H_{22}N_2O_2$	226.16	31.6–31.7	29.5–29.6	12.30	2.405	1.70
Nylon 11 (Rilsan)	$C_{11}H_{21}NO$	183.14	36.99	34.47	12.33	2.796	1.70–2.30
Phenol formaldehyde	$C_{15}H_{12}O_2$	224.17	27.9–31.6	26.7–30.4	11.80	2.427	1.70
foam			21.6–27.4	20.2–26.2			
Polyacenaphthalene	$C_{12}H_8$	152.14	39.23	38.14	12.95	2.945	
Polyacrylonitrile	C_3H_3N	53.04	32.22	30.98	13.70	2.262	1.50
Polyallylphthalate	$C_{14}H_{14}O$	198.17	27.74	26.19	9.54	2.745	
(Polyamides) → nylon							
Poly-1,4-butadiene	C_4H_6	54.05	45.19	42.75	13.13	3.256	
Poly-1-butene	C_4H_8	56.05	46.48	43.35	12.65	3.426	1.88
Polycarbonate	$C_{16}H_{14}O_3$	254.19	30.99	29.78	13.14	2.266	1.26
Polycarbon suboxide	C_3O_2	68.03	13.78	13.78	14.64	0.941	
Polychlorotrifluorethylene	C_2F_3Cl	116.47	1.12	1.12	2.04	0.549	0.92
Polydiphenylbutadiene	$C_{16}H_{10}$	202.18	39.30	38.20	13.05	2.928	

Material	Unit Composition	Molecular Weight, W	Gross, Δh_c^u (MJ/kg)	Net, Δh_c^l (MJ/kg)	$\frac{\Delta h_c^l}{r_o}$ (MJ/kg of O_2)	Oxygen Fuel Mass Ratio, r_o	Heat Capacity Solid, C_{ps} (kJ/kg•°C)
Polyester, unsaturated	$C_{5.77}H_{6.25}O_{1.63}$	101.60	21.6–29.8	20.3–28.5	11.90	2.053	1.20–2.30
Polyether, chlorinated	$C_5H_8OCl_2$	154.97	17.84	16.71	12.45	1.342	
Polyethylene	C_2H_4	28.03	46.2–46.5	43.1–43.4	12.63	3.425	1.83–2.30
Polyethylene oxide	C_2H_4O	44.02	26.65	24.66	13.57	1.817	
Polyethylene terephthalate	$C_{10}H_8O_4$	192.11	22.18	21.27	12.77	1.666	1.00
Polyformaldehyde	CH_2O	30.01	16.93	15.86	14.88	1.066	1.46
Poly-1-hexene sulfone	$C_6H_{12}SO_2$	148.13	29.78	28.00	14.40	1.944	
Polyhydrocyanic acid	HCN	27.02	23.26	22.45	15.17	1.480	
(Polyisobutylene) → poly-1-butene							
Polyisocyanurate foam	–		26.30	22.2–26.2			
Polyisoprene	C_5H_8	68.06	44.90	42.30	12.90	3.291	
Poly-3-methyl-1-butene	C_5H_{10}	70.06	46.55	43.42	12.67	3.426	
Polymethyl methacrylate	$C_5H_8O_2$	100.06	26.64	24.88	12.97	1.919	1.44
Poly-4-methyl-1-pentene	C_6H_{12}	84.08	46.52	43.39	12.67	3.425	2.18
Poly-α-methylstyrene	C_9H_{10}	118.11	42.31	40.45	13.00	3.116	
Polynitroethylene	$C_2H_3O_2N$	73.03	15.96	15.06	19.64	0.767	
Polyoxymethylene	CH_2O	30.01	16.93	15.65	14.68	1.066	
Polyoxytrimethylene	C_3H_6O	58.04	31.52	29.25	13.27	2.205	
Poly-1-pentene	C_5H_{10}	70.06	45.58	42.45	12.39	3.426	
Polyphenylacetylene	C_8H_6	102.09	40.00	38.70	13.00	2.978	
Polyphenylene oxide	C_8H_8O	120.09	34.59	33.13	13.09	2.531	1.34
Polypropene sulfone	$C_3H_6SO_2$	106.10	23.82	22.58	16.64	1.357	
Poly-β-propiolactone	$C_3H_4O_2$	72.14	19.35	18.13	13.62	1.331	
Polypropylene	C_3H_6	42.04	46.37	43.23	12.62	3.824	2.10
Polypropylene oxide	C_3H_6O	58.04	31.17	28.90	13.11	2.205	
Polystyrene	C_8H_8	104.10	41.4–42.5	39.7–39.8	12.93	3.074	1.40
Polystyrene-foam	–		39.70	35.6–40.8			
Polystyrene-foam, FR	–		41.2–42.9				
Polysulfones, butene	$C_4H_8SO_2$	120.11	24.04–26.47	22.25–25.01	14.79	1.598	1.30
Polysulfur	S	32.06	9.72	9.72	9.74	0.998	
Polytetrafluoroethylene	C_2F_4	100.02	5.00	5.00	7.81	0.640	1.02
Polytetrahydrofuran	C_4H_8O	72.05	34.39	31.85	13.04	2.443	
Polyurea	$C_{15}H_{18}O_4N_4$	318.20	24.91	23.67	13.45	1.760	
Polyurethane	$C_{6.3}H_{7.1}NO_{2.1}$	130.30	23.90	22.70	13.16	1.725	1.75–1.84
Polyurethane-foam	–		26.1–31.6	23.2–28.0			
Polyurethane-foam, FR	–		24.0–25.0				
Polyvinyl acetate	$C_4H_6O_2$	86.05	23.04	21.51	12.86	1.673	
Polyvinyl alcohol	C_2H_4	44.03	25.00	23.01	12.66	1.817	1.70
Polyvinyl butyral	$C_8H_{14}O_2$	142.10	32.90	30.70	13.00	2.365	
Polyvinyl chloride	C_2H_3Cl	62.48	17.95	16.90	12.00	1.408	0.90–1.20
Polyvinyl-foam	–		22.83				1.30–2.10
Polyvinyl fluoride	C_2H_3F	46.02	21.70	20.27	10.60	1.912	
Polyvinylidene chloride	$C_2H_2Cl_2$	96.93	10.52	10.07	12.21	0.825	1.34
Polyvinylidene fluoride	$C_2H_2F_2$	64.02	14.77	14.08	11.26	1.250	1.38
Urea formaldehyde	$C_3H_6O_2N_2$	102.05	15.90	14.61	13.31	1.098	1.60–2.10
Urea formaldehyde-foam	–	–	14.80				

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.4.5 Miscellaneous Materials

Heats of Combustion of Miscellaneous Materials

Material	Gross, Δh_c^u (MJ/kg)	Net, Δh_c^l (MJ/kg)
Acetate (see cellulose acetate)		
Acrylic fiber	30.6–30.8	
Blasting powder	2.1–2.4	
Butter	38.5	
Celluloid (cellulose nitrate and camphor)	17.5–20.6	16.4–19.2
Cellulose acetate fiber, $C_8H_{12}O_6$	17.8–18.4	16.4–17.0
Cellulose diacetate fiber, $C_{10}H_{14}O_7$	18.7	
Cellulose nitrate, $C_6H_9N_1O_7/C_6H_8N_2O_9/C_6H_7N_3O_{11}$	9.11–13.48	
Cellulose triacetate fiber, $C_{12}H_{16}O_8$	18.8	17.6
Charcoal	33.7–34.7	33.2–34.2
Coal–anthracite	30.9–34.6	30.5–34.2
–bituminous	24.7–36.3	
Coke	28.0–31.0	23.6–35.2
Cork	26.1	28.0–31.0
Cotton	16.5–20.4	
Dynamite	5.4	
Epoxy, $C_{11.9}H_{20.4}O_{2.8}N_{0.3}/C_{6.064}H_{7.550}O_{1.222}$	32.8–33.5	31.1–31.4
Fat, animal	39.8	
Flint powder	3.0–3.1	
Fuel oil–No. 1	46.1	
–No. 6	42.5	
Gasketing–chlorosulfonated polyethylene (Hypalon)	28.5	
–vinylidene fluoride/ hexafluoropropylene (Fluorel, Viton A)	14.0–15.1	
Gasoline	46.8	43.7
Jet fuel–JP1		43.0
–JP3		43.5
–JP4	46.6	43.5
–JP5	45.9	43.0
Kerosene (jet fuel A)	46.4	43.3
Lanolin (wool fat)	40.8	
Lard	40.1	
Leather	18.2–19.8	
Lignin, $C_{2.6}H_3O$	24.7–26.4	23.4–25.1
Lignite	22.4–33.3	
Modacrylic fiber	24.7	
Naphtha	43.0–47.1	40.9–43.9
Neoprene, C_5H_5Cl–gum	24.3	
–foam	9.7–26.8	

Material	Gross, Δh_c^u (MJ/kg)	Net, Δh_c^l (MJ/kg)
Nomex™ (polymethaphenylene isophthalamide) fiber, $C_{14}H_{10}O_2N_2$	27.0–28.7	
Oil–castor	37.1	
–linseed	39.2–39.4	
–mineral	45.8–46.0	
–olive	39.6	
–solar	41.8	
Paper–brown	16.3–17.9	
–magazine	12.7	
–newsprint	19.7	
–wax	21.5	
Paraffin wax	46.2	43.1
Peat	16.7–21.6	
Petroleum jelly, $C_{7.118}H_{12.957}O_{0.091}$	45.9	
Rayon fiber	13.6–19.5	
Rubber–buna N	34.7–35.6	
–butyl	45.8	
–isoprene (natural), C_5H_8	44.9	42.3
–latex foam	33.9–40.6	
–GRS	44.2	
–tire, auto	32.6	
Silicone rubber (SiC_2H_6O)	15.5–16.8	
–foam	14.0–19.5	
Sisal	15.9	
Spandex fiber	31.4	
Starch	17.6	16.2
Straw	15.6	
Sulfur–rhombic		9.28
–monoclinic		9.29
Tobacco	15.8	
Wheat	15.0	
Wood–beech	20.0	18.7
–birch	20.0	18.7
–Douglas fir	21.0	19.6
–maple	19.1	17.8
–red oak	20.2	18.7
–spruce	21.8	20.4
–white pine	19.2	17.8
–hardboard	19.9	
Woodflour	19.8	
Wool	20.7–26.6	

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.4.6 Selected Metals and Nonmetallic Elements

Heats of Combustion of Selected Metals and Nonmetallic Elements

Element Symbol	Element Name	Oxide Formed	Δh_c (MJ/kg)
Al	Aluminum	Al_2O_3	31.06
B	Boron	B_2O_3	58.83
Ba	Barium	BaO	4.03
Be	Beryllium	BeO	67.48
Ca	Calcium	CaO	15.58
Cd	Cadmium	CdO	2.30
Ce	Cerium	CeO_2	7.77
Cr	Chromium	Cr_2O_3	10.78
Cu	Copper	CuO	2.48
Fe	Iron	FeO	4.87
Hf	Hafnium	HfO_2	6.42
Li	Lithium	Li_2O	43.08
Mg	Magnesium	MgO	24.73
Na	Sodium	Na_2O	9.00
Sr	Strontium	SrO	6.76
Th	Thorium	ThO_2	5.29
Ti	Titanium	TiO_2	19.6
U	Uranium	UO_2	4.56
W	Tungsten	WO_3	4.59
Zn	Zinc	ZnO	5.37
Zr	Zirconium	ZrO_2	12.03

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.5 Autoignition Temperatures for Liquids

Autoignition Temperatures for Liquids

Fuel	Autoignition Temperature (°C)
Acetaldehyde	185.0
Acetone	537.8
Acetylene	305.0
Acrolein	233.9
Acrylonitrile (564)	481.1
Ammonia	651.1
Aniline	617.2
Benzene	562.2
Benzyl alcohol	436.1
1,2-Butadiene	428.9
Butanone (methyl ethyl ketone)	515.6
1-Butene	383.9
n-Butene	405.0

Fuel	Autoignition Temperature (°C)
d-Camphor	466.1
Carbon disulfide	90.0
Carbon monoxide	608.9
Cyclobutane	426.7
Cyclohexane	260.0
Cyclohexene	265.0
Cyclopentane	361.1
Cyclopropane	497.8
n-Decane	207.8
Diethyl ether	180.0
Ethane	515.0
Ethanol	422.8
Ethyl acetate	426.7
Ethylamine	383.9
Ethylene oxide	428.9
n-Heptane	222.8
n-Hexane	408.9
Hydrogen	400.0
iso-Propanol	398.9
Methane	600.0
Methanol	463.9
Methyl formate	456.1
n-Nonane	206.1
n-Octane	220.0
n-Pentane	260.0
1-Pentene	217.2
Propane	450.0
n-Propanol	371.1
Propene	455.0
Toluene	536.1
m-Xylene	527.8
o-Xylene	463.9
p-Xylene	528.9

For more information, see Table C.1 and Chapter 18, "Ignition of Liquids," in the SFPE *Handbook of Fire Protection Engineering*, fifth edition.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.6 Critical Heat Flux and Thermal Response Parameter of Materials

Material	CHF (kW/m^2)		TRP (kW•s$^{1/2}$/m^2)	
	ASTM E2058 FPA	ASTM E1354 Cone	ASTM E2058 FPA	ASTM E1354 Cone
Natural Materials				
Flour	10	–	218	–
Sugar	10	–	255	–
Tissue paper	10	–	95	–
Newspaper	10	–	108	–
Wood (red oak)	10	–	134	–
Wood (Douglas fir)	10	–	138	–
Wood (Douglas fir)/fire retarded (FR)	10	–	251	–
Wood (hemlock)	–	–	–	175
Corrugated paper (light)	10	–	152	–
Corrugated paper (heavy), with:				
No coating	10	–	189	–
Coating (10% by weight)	15	–	435	–
Coating (15% by weight)	15	–	526	–
Coating (20% by weight)	15	–	714	–
Wool 100%	–	–	–	252
Synthetics (Ordinary Polymers)				
Acrylic fiber 100%	–	–	–	180
Acrylic (modified)/FR	–	–	–	526
Acrylonitrile-butadiene- styrene (ABS)	–	9–15	–	317–365
ABS-FR	–	13	–	330
Butyl rubber (BR, polyisobutylene)	–	19	–	211
Epoxy (EP)	13	20	162	–
Isophthalic polyester	–	–	–	296
Nitrile-butadiene (Buna-N, NBR)	–	26	–	308
Polyamide (PA, Nylon) 6	15	15–20	154–270	379–461
PA 66	–	15–21	–	352
PA 11	–	15–21	–	352
PPO-PS	–	–	–	455
Polyethylenephthalate (PEN)	–	24	–	545
Polyethyleneterephthalate (PET)	10	–	174	–
Polyethylene (PE) high density (HD)	15	15	321–454	343
PE (cross-linked)	15	–	224–301	442
PE (cross-linked)/nonhalogenated FR	15	–	652–700	581
Polyisoprene (natural rubber, NR)	10	17	174	294
Polymethylmethacrylate (PMMA)	10	6–23	274	274
Polymethylpentene (PMP)	–	–	–	–
Polyoxymethylene (POM)	13	–	250–269	–

Material	CHF (kW/m^2)		TRP (kW•s$^{1/2}$/m^2)	
	ASTM E2058 FPA	ASTM E1354 Cone	ASTM E2058 FPA	ASTM E1354 Cone
Polypropylene (PP)	10–15	15	277–333	193–336
PP/FR panel	15	–	315	–
Polyphenyleneether (PPE)	–	–	–	323
Polystyrene (PS)	13	–	162	–
PS-FR	–	–	221–667	–
Polyvinyl ester	–	–	–	263
Polyvinyl ester panels	13–15	–	440–700	–
Styrene-butadiene rubber (SBR)	–	10–15	–	198
Unsaturated polyester (UPT)	–	–	343	–
Vinyl ester (VE)	–	–	–	285
Vinyl thermoplastic elastomer	–	–	294	–
Foams (Wall, Ceiling Insulation Materials, etc.)				
Polyurethanes	13–40	–	55–221	–
Polystyrenes	10–15	–	111–317	–
Latex	16	–	113–172	–
Phenolic	20	–	610	–
Synthetic High-Temperature Engineered Polymers				
Melamine formaldehyde (MF)	–	25	–	324
Phenol formaldehyde (PF)	–	15–26	–	537
Polyamideimide (PAI, Torlon®)	–	40–50	–	378
Polybenzimidazole (PBI)	–	~60	–	–
Polybenzoylphenylene (PX)	–	–	–	626
Polycarbonate (PC)	15	15–20	357–455	455
PC panel	16	–	420	–
PC/ABS (70/30)	–	–	–	344
PC/ABS-FR	–	–	–	391
Polydimethylphenyleneoxide (PPO)	–	19	–	342
Polyethylenephthalate (PEN)	–	–	545	–
Polyethersulfone (PESU, Radel-A®)	–	19–30	–	360
Polyether ether ketone (PEEK)	30	30–40	550	623
Polyetherimide (PEI)	25	25–40	435	435
Polyphenyleneether (PPE)	–	–	–	323
Polyphenylenesulfide (PPS)	–	35–38	–	395
Polyphenylsulfone (Radel-R® PPSU)	–	32–35	512	512
Polyphenyleneether (PPE)	–	–	–	323
Polysulfone (PSU)	30	26	469	424
Polydimethylsiloxane (SIR)	–	34	–	429

Material	CHF (kW/m^2)		TRP (kW•s$^{1/2}$/m^2)	
	ASTM E2058 FPA	ASTM E1354 Cone	ASTM E2058 FPA	ASTM E1354 Cone
Halogenated				
Polychloroprene (neoprene, CR)	–	20–37	–	245
Polytetrafluoroethylene-perfluoroether (PFA)	–	–	–	787
Polytetrafluoroethylene (PTFE)	50	–	680	–
Polytrifluoroethylene (P3FE)	–	–	–	504
Polyvinylidenefluoride (PVDF)	–	–	609	–
Polyvinylfluoride (PVF)	–	–	–	303
Polychlorotrifluoroethylene (CTFE)	–	30	–	460
Polyethylene-tetrafluoroethyl-ene (ETFE, Tefzel®)	25	17–27	481	478
Polyethylenechlorotrifluoro-ethylene (ECTFE)	38	38–74	450	410
Fluorinated ethylene propylene (FEP, Teflon®)	38–50	–	680	–
FEP fabric	50	–	299	–
FEP coated on metal	20	–	488	–
Polytrifluoroethylene (P3FE)	–	–	–	504
Polyvinylchloride (PVC, flexible)	10	21	215–263	194
PVC flexible (LOI = 0.20)	–	–	–	285
PVC flexible (LOI = 0.25)	–	–	–	401
PVC flexible, FR (alkyl aryl phosphate, LOI = 0.28)	–	–	–	401
PVC flexible, FR (Sb2O3, LOI = 0.30)	–	–	–	397
PVC flexible, FR (tertiary phosphate, LOI = 0.34)	–	–	–	345
PVC flexible, FR	–	–	–	222–263
PVC, rigid	15	15–28	357	357–418
PVC, rigid (LOI = 0.50)	–	–	–	388
PVC sheets	15	–	446–590	–
PVC panel	17	–	321	–
PVC fabric	26	–	217	–
Chlorinated PVC (CPVC)	40	40	435	590–1,111
Polyvinylfluoride (PVF)	–	–	–	303
Composite and Fiber Reinforced (Glass–Gl and Graphite–Gr):				
Acrylic/Gl	–	–	–	180
Bismaleimide (BMI)/Gr	–	–	–	513–608
Cyanate ester/Gl	–	–	–	302
Epoxy (EP)/Gl (thin sheet)	10	–	156	198
EP/Gl	10–15	–	388–540	288–665
EP/Gr	15	–	395–481	395–554
EP/Gr/intumescent coating (IC)	–	–	962	–
EP/Gr/ceramic coating (CC)	–	–	2,273	–
EP/Gr/CC/IC	–	–	1,786	–
EP/Kevlar (thin sheet)	–	–	–	120

Material	CHF (kW/m^2)		TRP (kW•s$^{1/2}$/m^2)	
	ASTM E2058 FPA	ASTM E1354 Cone	ASTM E2058 FPA	ASTM E1354 Cone
Graphite composite	40	–	400	–
Isophthalic polyester/Gl (77%)	–	–	–	426
Polyarylsulfone/Gr	–	–	–	360
Polyamide (PA6)/Gl (10%)	–	–	–	303
PA6/Gl (20%)	–	–	–	315
PA6/Gl (30%)	–	–	–	318
PA6/Gl (50%)	–	–	–	359–371
Polybutyleneterephthalate (PBT)/Gl (10%)	–	–	–	317
PBT/Gl (20%)	–	–	–	308
PBT/Gl (30%)	–	–	–	325
PBT/Gl (50%)	–	–	–	381
Polycarbonate (PC)/Gl (10%)	–	–	–	383
PC/Gl (20%)	–	–	–	362
PC/Gl (30%)	–	–	–	373
PC/Gl (50%)	–	–	–	402
Polyether ether ketone (PEEK)/Gl (30%)	–	–	–	301
PEEK/Gr	–	–	–	514
Polyester (PEST)/Gl	10–15	–	275–406	–
Polyether ketoneketone (PEKK)/Gl	–	–	–	710
Polyethersulfone (PESU)/Gl (30%)	–	–	–	256
Polyethersulfone (PESU)/Gr	–	–	–	352
Polyimide/Gl	–	–	844	–
Phenol formaldehyde (PF)/Gl	20	–	–	610
Phenol/Gl (thin sheet)	33	–	105	172
Phenol/Gl (thick sheet)	20	–	610	–
Phenolic/Gl	–	–	–	382–998
Phenolic/Gl (45%)	–	–	–	683
Phenolic/Gr	20	–	333	398–982
Phenolic/PE fibers	–	–	–	267
Phenolic/aramid fibers	–	–	–	287
Phenolic/Kevlar (thin sheet)	20	–	185	258
Phenolic/Kevlar (thick sheet)	15	–	403	–
Phenolic/Gr/ceramic coating	–	–	807	–
Phenolic/Gr/intumescent coating	–	–	1,563	–
Phenolic laminate/Gl (45%)	–	–	–	683
Polypropylene (PP)/Gl panel	–	–	–	315–377
Polyvinylester/Gl	–	–	281	312–429
Polyvinylester/Gl (69%)	–	–	–	444
Polyvinylester/Gl/ceramic coating (CC)	–	–	676	–

Material	CHF (kW/m^2)		TRP (kW•$s^{1/2}$/m^2)	
	ASTM E2058 FPA	ASTM E1354 Cone	ASTM E2058 FPA	ASTM E1354 Cone
Polyvinylester/Gl/intumescent coating (IC)	–	–	1,471	–
Polyvinylester/Gl/IC/CC	–	–	1,923	–
Polyphenylenesulfide (PPS)/Gl	–	–	–	588–623
PPS/Gr	–	–	–	330–510
Materials with Fiberweb, Netlike, and Multiplex Structures				
Polypropylenes	8–15	–	108–417	–
Polyester-polypropylene	10	–	139	–
Wood pulp-polypropylene	8	–	90	–
Polyester	8–18	–	94–383	–
Rayon	14–17	–	161–227	–
Polyester-rayon	13–17	–	119–286	–
Wool-nylon	15	–	293	–
Nylon	13–16	–	149–217	–
Cellulose	15	–	264	–
Cellulose-polyester	13	–	159	–
Electrical Cables–Power				
PVC/PVC	13–25	–	156–341	–
PE/PVC	15	–	221–244	–
PVC/PE	15	–	263	–
Silicone (Si)/PVC	19	–	212	–
Si/cross-linked Polyolefin (XLPO)	25–30	–	435–457	–
Ethylene-propylene rubber (EPR)/EPR	20–23	–	467–567	–
Cross-linked PE (XLPE)/XLPE	20–25	–	273–386	–
XLPE/ethyl-vinyl acetate (EVA)	12–22	–	442–503	–
XLPE/neoprene	15	–	291	–
XLPO/XLPO	16–25	–	461–535	–
XLPO/polyvinylidine fluoride (PVF)/XLPO	14–17	–	413–639	–
EPR/chlorosulfonated PE	14–19	–	283–416	–
EPR, FR	14–28	–	289–448	–
Electrical Cables–Communications				
PVC/PVC	15	–	131	–
PE/PVC	20	–	183	–
XLPE/XLPO	20	–	461–535	–
Si/XLPO	20	–	457	–
EPR-FR	19	–	295	–
Chlorinated PE	12	–	217	–
Polyethylene-tetrafluoroethylene (ETFE)/EVA	22	–	454	–
PVC/PVF	30	–	264	
Fluorinated ethylene propylene (FEP)/FEP	36	–	638–652	–

Material	CHF (kW/m^2)		TRP (kW•s$^{1/2}$/m^2)	
	ASTM E2058 FPA	ASTM E1354 Cone	ASTM E2058 FPA	ASTM E1354 Cone
Conveyor Belts				
Styrene-butadiene rubber (SBR)	10–15	–	336–429	–
Chloroprene rubber (CR)	20	–	760	–
CR/SBR	15	–	400	–
PVC	15–20	–	343–640	–

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.7 Thermal Properties and Thermal Response Properties of Polymers

Material	T_{ig} (°C)	ρ (10^{-3} kg/m^3)	c_P (kJ/kg•K)	k (10^{-3} kW/m•K)	TRP (kW•s$^{1/2}$/m^2)	
					Measured	Calculated
Synthetic (Ordinary Polymers)						
Acrylonitrile-butadiene-styrene (ABS)	394	1.05	1.50	0.26	317–365	212
Polybutadiene (BDR)	378	0.97	1.96	0.22	–	205
Butyl rubber (BR, polyisobutylene)	330	0.92	1.96	0.13	211	133
Cellulose acetate (CA)	348	1.25	1.67	0.25	–	210
Cellulose acetate butyrate (CAB)	–	1.20	1.46	0.25	–	–
Cellulose acetate propionate (CAP)	–	1.21	1.46	0.25	–	–
Cyanate ester (typical) (CE)	468	1.23	1.11	0.19	–	202
Cellulose nitrate (CN)	–	1.38	1.46	0.23	–	–
Cellulose propionate (CP)	–	1.30	1.46	0.20	–	–
Diallylphthalate (DAP)	–	1.35	1.32	0.21	–	–
DAP/glass fibers	–	1.80	1.69	0.42	–	–
Ethylene-acrylic acid salt (EAA ionomer)	–	0.95	1.62	0.26	–	–
Epoxy (EP)	427	1.20	1.70	0.19	162	225
EP/Gl	–	1.80	1.60	0.42	–	–
Epoxy novolac (EPN)	–	1.21	1.26	0.19	–	–
Ethylene-propylene diene (EPDM)	–	0.93	2.00	0.20	–	–
Ethylene vinyl acetate (EVA)	–	0.93	1.37	0.34	–	–
Nitrile-butadiene (Buna-N, NBR)	–	1.35	1.33	0.25	308	–
Polyamide (PA, nylon) 6	432–497	1.13–1.20	1.55–2.19	0.24	154–461	236–336
PA 6/glass fibers	390	1.38	1.34	0.22	–	–
PA 66	456	1.14	1.57	0.23	352	248
PA 11	–	1.12	1.74	0.28	352	–
PA 11/glass fibers	–	1.35	1.76	0.37	–	–
PA 12	–	1.04–1.01	1.69–1.79	0.18–0.25	–	–
PA 610	–	1.10	1.51	0.23	–	–
PA 612	–	1.08	1.59	0.22	–	–
Polyacrylonitrile (PAN)	460	1.15	1.30	0.26	–	243
Polyarylate (PAR)	–	1.21	1.20	0.18	–	–

Material	T_{ig} (°C)	ρ (10^{-3} kg/m^3)	c_P (kJ/kg•K)	k (10^{-3} kW/m•K)	TRP (kW•s$^{1/2}$/m^2)	
					Measured	**Calculated**
Polyamideimide (PAI)	526	1.42	1.00	0.24	–	262
Polybutene (PB)	–	0.92	2.09	0.22	–	–
Polybutyleneterephthalate (PBT)	382	1.35	1.61	0.22	–	222
Polyimide (PI)	–	1.40	1.10	0.11	–	–
Polyethyleneterephthalate (PET)	407	1.35	1.15	0.20	174	191
PET/glass fibers	–	1.70	1.20	0.29	–	–
Polyethylene (PE) high density (HD)	380–443	0.94–0.96	2.00–2.15	0.42–0.43	321–454	283–353
PE low density	377	0.93	1.55	0.30–0.38	–	208–234
PE medium density	–	0.93	1.70	0.40	–	–
Polyethyleneoxide (PEO)	–	1.13	2.01	0.21	–	–
Polyisoprene (natural rubber, NR)	297	0.92	1.55	0.14	174–294	110
Polyethylmethacrylate (PEMA)	–	1.13	1.47	0.18	–	–
Polymethylmethacrylate (PMMA)	378–383	1.19	2.09	0.27	274	264
Polymethylpentene (PMP)	–	0.83	1.73	0.17	–	–
Polymethyl styrene (PMS)	–	1.02	1.28	0.20	–	–
Polyoxymethylene (POM)	374	1.42	1.92	0.27	250–269	269
Polypropylene (PP)	443	0.96	2.16	0.20	193–336	242
Polystyrene (PS)	356	1.05	1.25	0.14	162	128
PS/glass fibers	–	1.29	1.05	0.13	–	–
Polyisocyanurate (PU) rigid	378	1.27	1.67	0.21	–	–
Polyurethane rubber (PUR)	356	1.10	1.76	0.19	–	181
Polyurethane thermoplastic (TPU)	271	1.27	1.67	0.21	–	149
Polyvinyl acetate (PVAC)	–	1.19	1.33	0.16	–	–
Polyvinylalcohol (PVOH)	–	1.35	1.55	0.20	–	–
Styrene-butadiene rubber (SBR)	–	1.10	1.88	0.17	198	–
Styrene-acrylonitrile (SAN)	368	1.07	1.38	0.15	–	145
Unsaturated polyester (UPT)	380	1.23	1.30	0.17	343	166
UPT/glass fibers	–	1.65	1.05	0.42	–	–
Vinyl ester (VE)	–	1.11	1.30	0.25	285	–
Synthetic High-Temperature Engineered Polymers						
Melamine formaldehyde (MF)	350	1.25	1.67	0.25	324	211
MF/glass fibers	–	1.75	1.67	0.44	–	–
Phenol formaldehyde (PF)	429	1.30	1.42	0.25	537	246
PF/glass fibers	580	1.85	1.26	0.40	610	479
Polyamideimide (PAI, Torlon®)	526	1.42	1.00	0.24	378	262
Polybenzimidazole (PBI)	–	1.30	0.93	0.41	–	–
Polybenzoylphenylene (PX)	–	1.22	1.30	0.32	626	–
Polycarbonate (PC)	500–580	1.20	1.20–1.22	0.20–0.21	357–455	228–296
PC/glass fibers	–	1.43	1.10	0.21	402	–
Polyethersulfone (PESU, Radel-A®)	502	1.40	1.12	0.18	360	227

Material	T_{ig} (°C)	ρ (10^{-3} kg/m^3)	c_P (kJ/kg•K)	k (10^{-3} kW/m•K)	TRP (kW•s$^{1/2}$/m^2)	
					Measured	**Calculated**
Polyaryl ether ketone (PAEK)	–	1.30	1.02	0.30	–	–
Polyether ether ketone (PEEK)	570–580	1.31–1.32	1.70–1.80	0.20–0.25	550	325–383
Polyetherketoneketone (PEKK)	–	1.28	1.00	0.22	–	–
Polyetherimide (PEI)	528–540	1.27	1.22–1.40	0.22–0.23	435	262–295
Polyphthalamide (PPA)	–	1.17	1.40	0.15	–	–
Polyphenyleneether (PPE)	426	1.10	1.19	0.23	323	198
Polydimethyleneoxide (PPO)	418	1.11	1.25	0.16	342	166
PPO/glass fibers	–	1.32	1.31	0.17	–	–
Polyphenylenesulfide (PPS)	575	1.30	1.02	0.29	395	305
Polyphenylsulfone (Radel-R® PPSU)	575	1.32	1.01	0.18	512	241
Polyphenyleneether (PPE)	426	1.10	1.19	0.23	323	–
Polysulfone (PSU)	510–580	1.24	1.11–1.30	0.26–0.28	424–469	259–334
Polydimethylsiloxane (SI)	–	1.24	1.30	0.28	–	–
Silicone/glass fibers (Si/G)	–	1.90	1.17	0.30	–	–
Silicone rubber (SIR)	407	0.97	1.59	0.23	429	204
Urea formaldehyde (UF)	–	1.25	1.55	0.25	–	–
Halogenated Polymers						
Polychloroprene (neoprene, CR)	406	1.42	1.12	0.19	245	188
Polytetrafluoroethylene-perfluoroether (PFA)	–	2.15	1.00	0.25	787	–
PFA/glass fibers	–	1.85	1.26	0.40	–	–
Polytetrafluoroethylene (PTFE)	630–700	2.15–2.18	1.00–1.05	0.25	680	396–456
Polytrifluoroethylene (P3FE)	–	1.83	1.08	0.31	504	–
Polyvinylidenefluoride (PVDF)	643	1.76	1.30	0.13	609	301
Polyvinylfluoride (PVF)	476	1.48	1.30	0.13	303	202
Polychlorotrifluoroethylene (CTFE)	580	1.67–2.11	0.90–0.92	0.22–0.23	460	285–332
Polyethylene-tetrafluoroethylene (ETFE, Tefzel®)	540	1.70	0.90–1.00	0.23–0.24	478–481	273–294
Polyethylenechlorotrifluoroethylene (ECTFE)	613	1.69	1.00–1.17	0.15–0.16	410–450	264–296
Fluorinated ethylene propylene (FEP, Teflon®)	630–700	2.15	1.17–1.20	0.25	680	428–484
Polyvinylchloride (PVC, flexible)	318–374	1.26–1.95	1.14–1.38	0.17–0.26	194–263	130–263
PVC, rigid 395		1.42	0.98	0.19	357–418	171
Chlorinated PVC (CPVC)	643	1.50	0.78	0.22	435	280
Polyvinylidenechloride (PVDC)	468	1.70	1.07	0.13	–	193

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.8 Yields of Fire Products and Heats of Combustion for Well-Ventilated Fires[a]

Yields of Fire Products and Chemical, Convective, and Radiative Heats of Combustion for Well-Ventilated Fires

Material	ΔH_T (kJ/g)	y_{CO_2}	y_{CO}	y_{ch}	y_S	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				(kJ/g)		
Common Gases								
Methane	50.1	2.72	–	–	–	49.6	42.6	7.0
Ethane	47.1	2.85	0.001	0.001	0.013	45.7	34.1	11.6
Propane	46.0	2.85	0.005	0.001	0.024	43.7	31.2	12.5
Butane	45.4	2.85	0.007	0.003	0.029	42.6	29.6	13.0
Ethylene	48.0	2.72	0.013	0.005	0.043	41.5	27.3	14.2
Propylene	46.4	2.74	0.017	0.006	0.095	40.5	25.6	14.9
1,3-Butadiene	44.6	2.46	0.048	0.014	0.125	33.6	15.4	18.2
Acetylene	47.8	2.60	0.042	0.013	0.096	36.7	18.7	18.0
Common Liquids								
Methyl alcohol	20.0	1.31	0.001	–	–	19.1	16.1	3.0
Ethyl alcohol	27.7	1.77	0.001	0.001	0.008	25.6	19.0	6.5
Isopropyl alcohol	31.8	2.01	0.003	0.001	0.015	29.0	20.6	8.5
Acetone	29.7	2.14	0.003	0.001	0.014	27.9	20.3	7.6
Methylethyl ketone	32.7	2.29	0.004	0.001	0.018	30.6	22.1	8.6
Heptane	44.6	2.85	0.010	0.004	0.037	41.2	27.6	13.6
Octane	44.5	2.84	0.011	0.004	0.038	41.0	27.3	13.7
Kerosene	44.1	2.83	0.012	0.004	0.042	40.3	26.2	14.1
Benzene	40.1	2.33	0.067	0.018	0.181	27.6	11.0	16.5
Toluene	39.7	2.34	0.066	0.018	0.178	27.7	11.2	16.5
Styrene	39.4	2.35	0.065	0.019	0.177	27.8	11.2	16.6
Hydrocarbon	43.9	2.64	0.019	0.007	0.059	36.9	24.5	12.4
Mineral oil	41.5	2.37	0.041	0.012	0.097	31.7	–	–
Polydimethyl siloxane	25.1	0.93	0.004	0.032	0.232	19.6	–	–
Silicone	25.1	0.72	0.006	0.008	–	15.2	12.7	2.5
Chemicals and Solvents								
Tetrahydrofuran (C_4H_8O)	32.2	2.29	0.021	–	–	30.3	–	–
Phenol (C_6H_6O)	31.0	2.63	0.057	–	0.099	27.6	13.3	14.3
Acetonitrile (C_2H_3N)	29.6	2.04	0.025	–	0.026	29.0	23.0	6.0
Ethylisonicotate ($C_8H_9O_2N$)	26.3	2.37	0.029	–	0.142	24.3	12.8	11.5
Adiponitrile ($C_6H_8N_2$)	33.1	2.35	0.045	–	0.045	31.1	22.1	9.0
Hexamethylenediamine ($C_6H_{16}N_2$)	35.3	2.28	0.029	–	0.045	32.6	15.7	16.9
Toluenediisocyanate ($C_9H_6O_2N_2$)	23.6	1.77	0.052	–	0.141	19.3	11.1	8.2
Diphenylmethanediisocyanate MDI ($C_{15}H_{10}O_2N_2$)	27.1	0.95	0.042	–	0.154	19.6	13.7	5.9
Polymeric MDI ($C_{23}H_{19}O_3N_3$)	29.6	1.22	0.032	–	0.165	23.3	15.0	8.3
Isoproturon ($C_{12}H_{18}ON_2$)	32.8	1.70	0.056	–	0.115	23.9	14.0	9.9
3-Chloropropene (C_3H_5Cl)	23.0	0.75	0.076	–	0.179	10.8	6.9	3.9
Monochlorobenzene (C_6H_5Cl)	26.4	0.86	0.083	–	0.232	11.2	–	–

Material	ΔH_T (kJ/g)	y_{CO_2}	y_{CO}	y_{ch}	y_S	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				(kJ/g)		
Dichloromethane (CH_2Cl_2)	6.0	0.11	0.088	–	0.081	2.0	–	–
1,3-Dichloropropene ($C_3H_4Cl_2$)	14.2	0.35	0.090	–	0.169	5.6	–	–
Ethylmonochloroacetate ($C_4H_7O_2Cl$)	15.7	1.24	0.019	–	0.138	14.1	10.1	4.0
Chloronitrobenzoic acid ($C_7H_4O_4NCl$)	15.9	0.39	0.057	–	–	4.4	–	–
Aclonifen ($C_{12}H_9O_3N_2Cl$)	19.7	0.68	0.063	–	0.186	7.0	–	–
2,6-Dichlorobenzonitrile (dichlobenil) ($C_7H_3NCl_2$)	17.8	0.39	0.068	–	–	4.3	–	–
Diuron ($C_9H_{10}ON_2Cl_2$)	20.3	0.76	0.080	–	0.159	10.2	7.7	2.5
Trifluoromethylbenzene ($C_6H_5CF_3$)	18.7	1.19	0.069	–	0.185	10.8	5.1	5.7
Metatrifluoromethylphenylacetonitrile ($C_9H_6NF_3$)	16.0	0.89	0.058	–	0.168	7.3	4.0	3.3
Tetramethylthiurammonosulfide ($C_6H_{12}N_2S_3$)	22.6	1.06	0.041	–	–	19.6	–	–
Methylthiopropionylaldehyde (C_4H_8OS)	25.0	1.62	0.001	–	0.005	23.8	18.8	5.0
Pesticides								
2,4-D acid (herbicide, $C_8H_6O_3Cl_2$)	11.5	0.50	0.074	–	0.163	4.5	3.0	1.5
Mancozeb ($(C_4H_6N_2S_4Mn)_iZn_{0,4}$)	14.0	0.50	–	–	–	9.5	–	–
Folpel ($C_9H_4O_2NSCl_3$)	9.1	0.37	0.072	–	0.205	3.6	–	–
Chlorfenvinphos ($C_{12}H_{24}O_4Cl_3P$)	18.0	0.43	0.011	–	0.288	7.7	–	–
Chlormephos ($C_5H_{12}O_2S_2CIP$)	19.1	0.51	0.075	–	0.055	13.9	–	–
Natural Materials								
Tissue paper	–	–	–	–	–	11.4	6.7	4.7
Newspaper	–	–	–	–	–	14.4	–	–
Wood (red oak)	17.1	1.27	0.004	0.001	0.015	12.4	7.8	4.6
Wood (Douglas fir)	16.4	1.31	0.004	0.001	–	13.0	8.1	4.9
Wood (pine)	17.9	1.33	0.005	0.001	–	12.4	8.7	3.7
Corrugated paper	–	–	–	–	–	13.2	–	–
Wood (hemlock) [b]	–	–	–	–	0.015	13.3	–	–
Wool 100% [b]	–	–	–	–	0.008	19.5	–	–
Synthetic Materials—Solids (abbreviations/names in the nomenclature)								
ABS [b]	–	–	–	–	0.105	30.0	–	–
POM	15.4	1.40	0.001	0.001	–	14.4	11.2	3.2
PMMA	25.2	2.12	0.010	0.001	0.022	24.2	16.6	7.6
PE	43.6	2.76	0.024	0.007	0.060	38.4	21.8	16.6
PP	43.4	2.79	0.024	0.006	0.059	38.6	22.6	0
PS	39.2	2.33	0.060	0.014	0.164	27.0	11.0	16.0
Silicone	21.7	0.96	0.021	0.006	0.065	10.6	7.3	3.3
Polyester-1	32.5	1.65	0.070	0.020	0.091	20.6	10.8	9.8
Polyester-2	32.5	1.56	0.080	0.029	0.089	19.5	–	–
Epoxy-1	28.8	1.59	0.080	0.030	–	17.1	8.5	8.6
Epoxy-2	28.8	1.16	0.086	0.026	0.098	12.3	–	–

Material	ΔH_T (kJ/g)	y_{CO_2}	y_{CO}	y_{ch}	y_S	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				**(kJ/g)**		
Nylon	30.8	2.06	0.038	0.016	0.075	27.1	16.3	10.8
Polyamide-6 [b]	–	–	–	–	0.011	28.8	–	–
IPST [b]	–	–	–	–	0.080	23.3	–	–
PVEST [b]	–	–	–	–	0.076	22.0	–	–
Silicone rubber	21.7	0.96	0.021	0.005	0.078	10.9	–	–
Polyether ether ketone (PEEK-$CH_{0.63}O_{0.16}$)	31.3	1.6	0.029	–	0.008	17.5	–	–
Polysulfone (PSO-$CH_{0.81}O_{0.15}S_{0.04}$)	29.0	1.8	0.034	–	0.020	24.3	–	–
Polyethersulfone (PES-$CH_{0.67}O_{0.21}S_{0.08}$)	25.2	1.5	0.040	–	0.021	20.4	–	–
Polyetherimide (PEI-$CH_{0.68}N_{0.05}O_{0.14}$)	30.1	2.0	0.026	–	0.014	27.2	–	–
Polycarbonate (PC-$CH_{0.88}O_{0.13}$)	31.6	1.5	0.054	–	0.112	18.4	–	–
Polyurethane (Flexible) Foams								
GM21	26.2	1.55	0.010	0.002	0.131	17.8	8.6	9.2
GM23	27.2	1.51	0.031	0.005	0.227	19.0	10.3	8.7
GM25	24.6	1.50	0.028	0.005	0.194	17.0	7.2	9.8
GM27	23.2	1.57	0.042	0.004	0.198	16.4	7.6	8.8
Polyurethane (Rigid) Foams								
GM29	26.0	1.52	0.031	0.003	0.130	16.4	6.8	9.6
GM31	25.0	1.53	0.038	0.002	0.125	15.8	7.1	8.8
GM35	28.0	1.58	0.025	0.001	0.104	17.6	7.8	9.8
GM37	28.0	1.63	0.024	0.001	0.113	17.9	8.7	9.2
GM41	26.2	1.18	0.046	0.004	–	15.7	5.7	10.0
GM43	22.2	1.11	0.051	0.004	–	14.8	6.4	8.4
Polystyrene Foams								
GM47	38.1	2.30	0.060	0.014	0.180	25.9	11.4	14.5
GM49	38.2	2.30	0.065	0.016	0.210	25.6	9.9	15.7
GM51	35.6	2.34	0.058	0.013	0.185	24.6	10.4	14.2
GM53	37.6	2.34	0.060	0.015	0.200	25.9	11.2	14.7
Polyethylene Foams								
1	41.2	2.62	0.020	0.004	0.056	34.4	20.2	14.2
2	40.8	2.78	0.026	0.008	0.102	36.1	20.6	15.5
3	40.8	2.60	0.020	0.004	0.076	33.8	18.2	15.6
4	40.8	2.51	0.015	0.005	0.071	32.6	19.1	13.5
Phenolic Foams								
1 [b]	–	–	–	–	0.002	10.0	–	–
2 [b]	–	–	–	–	–	10.0	–	–
Halogenated Materials (abbreviations/names in the nomenclature)								
Polyethylene with:								
25% chlorine	31.6	1.71	0.042	0.016	0.115	22.6	10.0	12.6
36% chlorine	26.3	0.83	0.051	0.017	0.139	10.6	6.4	4.2
48% chlorine	20.6	0.59	0.049	0.015	0.134	7.2	3.9	3.3
PVC	16.4	0.46	0.063	0.023	0.172	5.7	3.1	2.6

Material	ΔH_T (kJ/g)	y_{CO_2}	y_{CO}	y_{ch}	y_S	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				(kJ/g)		
PVC-1b (LOI = 0.50)	–	–	–	–	0.098	7.7	–	–
PVC-2b (LOI = 0.50)	–	–	–	–	0.076	8.3	–	–
PVCb (LOI = 0.20)	–	–	–	–	9.099	11.3	–	–
PVCb (LOI = 0.25)	–	–	–	–	0.078	9.8	–	–
PVCb (LOI = 0.30)	–	–	–	–	0.098	10.3	–	–
PVC (LOI = 0.35)	–	–	–	–	0.088	10.8	–	–
PVC panel	–	–	–	–	–	7.3	–	–
CPVC ($CH_{1.3}Cl_{0.70}$)	12.8	0.48	0.052	–	0.043	4.4	–	–
PVDF (CHF)	13.3	0.53	0.055	–	0.037	3.8	–	–
ECTFE ($CHF_{0.75}Cl_{0.25}$)	12.0	0.41	0.095	–	0.038	4.6	–	–
ETFE (Tefzel, CHF)	12.6	0.78	0.035	–	0.028	7.3	–	–
PFA (Teflon, $CF_{1.6}O_{0.01}$)	5.0	0.42	0.099	–	0.002	2.2	–	–
FEP (Teflon, $CF_{1.8}$)	4.8	0.25	0.116	–	0.003	1.3	–	–
TFE (Teflon, $CF_{1.8}$)	6.2	0.38	0.092	–	0.003	2.0	–	–
Building Products [c]								
Particleboard (PB)	–	1.2	0.004	–	–	14.0	–	–
Fiberboard (FB)	–	1.4	0.015	–	–	14.0	–	–
Medium-density FB	–	1.2	0.002	–	–	14.0	–	–
Wood panel	–	1.2	0.002	–	–	15.0	–	–
Melamine-faced PB	–	0.8	0.025	–	–	10.7	–	–
Gypsumboard (GB)	–	0.3	0.027	–	–	4.3	–	–
Paper on GB	–	0.4	0.028	–	–	5.6	–	–
Plastic on GB	–	0.4	0.028	–	–	14.3	–	–
Textile on GB	–	0.4	0.025	–	–	13.0	–	–
Textile on rock wool	–	1.8	0.091	–	–	25.0	–	–
Paper on PB	–	1.2	0.003	–	–	12.5	–	–
Rigid PU	–	1.1	0.200	–	–	13.0	–	–
EPS	–	1.9	0.054	–	–	28.0	–	–
Composite and Fiberglass-Reinforced Materials (FGR) (abbreviations/names in the nomenclature)								
PEEK/FGR [b]	–	–	–	–	0.042	20.5	–	–
IPST/FGR [b]	–	–	–	–	0.032	27.0	–	–
PES/FGR [b]	–	–	–	–	0.049	27.5	–	–
PEST1/FGR [b]	–	–	–	–	–	16.0	–	–
PEST2/FGR [b]	–	–	–	–	–	12.9	–	–
PEST1/FGR	–	–	–	–	–	19.0	–	–
PEST2/FGR	–	–	–	–	–	13.9	–	–
PEST3/FGR	–	1.47	0.055	0.007	0.070	17.9	10.7	7.2
PEST4/FGR	–	1.24	0.039	0.004	0.054	16.0	9.9	6.1
PEST5/FGR	–	0.71	0.102	0.019	0.068	9.3	6.5	2.8
Epoxy/FG [b]	–	–	–	–	0.056	27.5	–	–
PVEST/FGR	–	–	–	–	0.079	26.0	–	–

Material	ΔH_T (kJ/g)	y_{CO_2}	y_{CO}	y_{ch}	y_S	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				(kJ/g)		
Kevlar/phenolic	–	1.27	0.025	0.002	0.041	14.8	11.1	3.7
Phenolic-1/FGR	–	0.98	0.066	0.003	0.023	11.9	8.9	3.0
Phenolic-2/FGR [b]	–	–	–	–	0.016	22.0	–	–
Aircraft Panel Materials								
Epoxy/FGR/paint	–	0.828	0.114	0.016	0.166	11.3	6.2	5.1
Epoxy/Kevlar/paint	–	0.873	0.091	0.016	0.126	11.4	6.3	5.1
Phenolic/FGR/paint	–	1.49	0.027	0.002	0.059	22.9	11.5	11.4
Phenolic/Kevlar/paint	–	1.23	0.088	0.011	0.094	18.6	8.9	9.7
Phenolic/graphite/paint	–	1.67	0.026	0.003	0.062	24.6	14.0	10.6
Polycarbonate	–	–	–	–	–	20.5	–	–
Electric Cables (abbreviations/names in the nomenclature)								
Polyethylene/Polyvinylchloride								
1	–	2.08	0.100	0.021	0.076	31.3	11.6	19.7
2	–	1.75	0.050	0.013	0.115	25.1	11.1	14.0
3	–	1.67	0.048	0.012	–	24.0	13.0	11.0
4	–	1.39	0.166	0.038	–	22.0	14.0	8.1
5	–	1.29	0.147	0.042	0.136	20.9	10.7	10.2
EPR/Hypalon								
1	–	1.95	0.072	0.014	–	29.6	15.8	13.9
2	–	1.74	0.076	0.022	–	26.8	17.0	9.8
3	–	1.21	0.072	0.014	–	19.0	12.3	6.7
4	–	0.99	0.090	0.085	0.082	17.4	6.6	10.8
5	–	0.95	0.122	0.024	–	17.3	7.5	9.8
6	–	0.89	0.121	0.022	0.164	13.9	9.2	4.7
Silicone								
1	–	1.65	0.011	0.001	–	25.0	17.5	7.3
2	–	1.47	0.029	0.001	–	24.0	20.0	4.0
XLPE/XLPE								
1	–	1.78	0.114	0.029	0.120	28.3	12.3	16.0
2	–	0.83	0.110	0.024	0.120	12.5	7.5	5.0
XLPE/Neoprene								
1	–	0.68	0.122	0.031	–	12.6	5.9	6.7
2	–	0.63	0.082	0.014	0.175	10.3	4.9	5.5
Silicone/PVC								
1	16.4	0.76	0.110	0.015	0.111	10.0	–	–
2	16.4	1.19	0.065	0.005	0.119	15.6	–	–
PVC/Nylon/PVC-Nylon								
1	–	0.63	0.084	0.024	–	10.2	5.0	5.2
2	–	0.49	0.082	0.032	0.115	9.2	4.8	4.4
PTFE								
1	–	0.180	0.091	0.012	0.011	3.2	2.7	0.4

Material	ΔH_T **(kJ/g)**	y_{CO_2}	y_{CO}	y_{ch}	y_S	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				**(kJ/g)**		
2	6.2	0.383	0.103	–	0.005	5.7	–	–
Materials with Fiberweb, Netlike, and Multiplex Structure (abbreviations/names in the nomenclature)								
Olefin	–	1.49	0.006	–	–	16.5	13.3	3.2
PP-1	–	1.25	0.0029	–	–	14.0	10.8	3.2
PP-2	–	1.56	0.0048	–	–	17.2	10.5	6.7
Polyester-1	–	2.21	0.015	–	–	24.6	8.9	15.7
Polyester-2	–	1.51	0.0079	–	–	16.8	9.1	7.7
Polyester-3	–	2.55	0.020	–	–	28.5	22.6	5.9
Polyester-4	–	1.92	0.014	–	–	21.4	12.4	9.0
Rayon-1	–	1.80	0.043	–	–	20.3	14.1	6.2
Rayon-2	–	1.91	0.043	0.002	–	21.5	13.3	8.2
Rayon-3	–	1.18	0.047	–	–	13.5	8.3	5.2
Polyester-rayon	–	1.52	0.005	–	–	16.8	9.1	7.7
Polyester-polyamide	–	1.82	0.008	–	–	20.2	10.4	9.8
Two to Eight 100-mm × 100-mm × 100-mm Corrugated Paper Boxes with and without the Polymers with Three-Dimensional Arrangement (abbreviations/names in the nomenclature) [d]								
Empty	–	1.53	0.023	0.001	–	14.2	10.7	3.5
With PVC (62% thick)	–	1.01	0.073	0.007	0.119	10.7	9.5	1.2
With PC (59% thick)	–	1.73	0.047	0.002	0.061	18.4	13.5	4.9
With PS (58% thick)	–	1.40	0.138	0.026	0.285	16.2	12.5	3.7
With PS (60% thin)	–	1.88	0.068	0.020	0.140	19.4	10.1	9.3
With PS (40% thin)	–	1.74	0.042	0.005	0.167	18.0	11.7	6.7
With ABS (59% thick)	–	1.53	0.089	0.006	0.143	16.1	12.7	3.4
With PET (41% thin)	–	1.87	0.050	0.006	0.053	19.9	11.8	8.1
With PU (40% foam)	–	1.56	0.024	–	–	14.4	8.6	5.8
High-Pressure Liquid Spray Combustion[e]								
Hydraulic Fluids								
Organic polyol esters								
1	36.6	–	–	–	–	35.5	–	–
2	35.7	–	–	–	–	35.1	–	–
3	40.3	–	–	–	–	37.2	–	–
4	37.0	–	–	–	–	35.7	–	–
Phosphate esters								
1	31.8	–	–	–	–	29.3	–	–
2	32.0	–	–	–	–	29.6	–	–
Water-in-oil emulsions								
1	27.6	–	–	–	–	2.5	–	–
Polyglycol-in-water								
1	11.0	–	–	–	–	10.4	–	–
2	11.9	–	–	–	–	11.1	–	–

Material	ΔH_T (kJ/g)	y_{CO_2}	y_{CO}	y_{ch}	y_S	ΔH_{ch}	ΔH_{con}	ΔH_{rad}
		(g/g)				(kJ/g)		
3	14.7	–	–	–	–	12.2	–	–
4	12.1	–	–	–	–	10.6	–	–
Liquid fuels								
Mineral oil	46.0	–	–	–	–	44.3	–	–
Methanol	20.0	–	–	–	–	19.8	–	–
Ethanol	27.7	–	–	–	–	26.2	–	–
Heptane	44.4	–	–	–	–	40.3	–	–

Note: Dashes = either not measured or less than 0.001.

[a] Data measured in the ASTM E2058 fire propagation apparatus. Data measured in the cone calorimeter are identified by superscripts [b] and [c]. Some of the data are corrected to reflect well-ventilated fire conditions. All the data are reported for turbulent fires, that is, materials exposed to higher external heat flux values.

[b] Calculated from the data measured in the cone calorimeter.

[c] Calculated from the data measured in the cone calorimeter.

[d] 100-mm × 100-mm × 100-mm corrugated paper boxes with and without the 99-mm × 99-mm × 99-mm polymer boxes or pieces on corrugated paper compartments. The boxes are arranged in one and two layers, about 12 mm apart, with one to four boxes in each layer, separated by about 12 mm. All the boxes are placed on a very light metal frame made of rods with screen base. Measurements made in the ASTM E2058 fire propagation apparatus; numbers in parentheses are the weight percents.

[e] Data measured in high-pressure liquid spray combustion in the fire products collector (5,000-kW scale apparatus).

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.9 Combustion Properties of Fuels

(Shaded cells show measurements by Tewarson; refer to SFPE *Handbook of Fire Protection Engineering*, fifth edition, for reference information.)

Fuel	Formula	L_{sp} (m)	M (g/mol)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
					ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
Normal Alkanes										
Ethane	C_2H_6	0.243	30	16.0	47.1	47.0	37.4	9.6	<0.001	0.002
n-Propane	C_3H_8	0.162	44	15.6	46.0	44.1	31.6	12.5	0.005	0.019
n-Butane	C_4H_{10}	0.160	58	15.4	45.4	43.5	31.0	12.4	0.005	0.020
n-Pentane	C_5H_{12}	0.155	72	15.3	45.0	42.3	29.3	13.1	0.006	0.022
n-Hexane	C_6H_{14}	0.125	86	15.2	44.8	41.7	28.2	13.4	0.009	0.031
n-Heptane	C_7H_{16}	0.110	100	15.1	44.6	41.2	27.6	13.6	0.012	0.042
n-Octane	C_8H_{18}	0.118	114	15.1	44.5	41.3	27.5	13.8	0.010	0.034
n-Nonane	C_9H_{20}	0.110	128	15.0	44.4	40.9	26.9	14.1	0.012	0.037
n-Decane	$C_{10}H_{22}$	0.110	142	15.0	44.3	40.9	26.8	14.0	0.012	0.037
n-Undecane	$C_{11}H_{24}$	0.110	156	15.0	44.3	40.9	26.8	14.0	0.012	0.037
n-Dodecane	$C_{12}H_{26}$	0.108	170	14.9	44.2	40.7	26.6	14.1	0.012	0.038
n-Tridecane	$C_{13}H_{28}$	0.106	184	14.9	44.2	40.6	26.5	14.1	0.012	0.039
n-Tetradecane	$C_{14}H_{30}$	0.109	198	14.9	44.1	40.6	26.6	14.0	0.012	0.037
Hexadecane	$C_{16}H_{34}$	0.118	226	14.9	44.1	41.0	27.3	13.7	0.010	0.034
Branched Alkanes										
Methylbutane	C_5H_{12}	0.113	72	15.3	45.0	41.6	27.5	14.1	0.011	0.035
Dimethylbutane	C_6H_{14}	0.089	86	15.2	44.8	40.4	25.5	15.0	0.015	0.046
Methylpentane	C_6H_{14}	0.094	86	15.2	44.8	40.7	25.9	14.8	0.014	0.043
Dimethylpentane	C_7H_{16}	0.096	100	15.1	44.6	40.6	25.9	14.6	0.014	0.043
Methylhexane	C_7H_{16}	0.109	100	15.1	44.6	41.1	26.9	14.2	0.012	0.037
Isooctane (trimethylpentane)	C_8H_{18}	0.080	114	15.1	44.5	40.5	26.7	13.8	0.016	0.051
Methylethylpentane	C_8H_{18}	0.082	114	15.1	44.5	39.9	24.7	15.1	0.016	0.049
Ethylhexane	C_8H_{18}	0.093	114	15.1	44.5	40.4	25.6	14.7	0.014	0.044
Dimethylhexane	C_8H_{18}	0.089	114	15.1	44.5	40.2	25.3	14.9	0.015	0.046
Methylheptane	C_8H_{18}	0.101	114	15.1	44.5	40.7	26.3	14.4	0.013	0.040
Cyclic Alkanes										
Cyclo-pentane	C_5H_{10}	0.067	70	14.7	44.3	38.9	23.2	15.6	0.020	0.059
Methylcyclopentane	C_6H_{12}	0.052	84	14.7	43.8	37.5	21.5	16.0	0.025	0.070
Cyclohexane	C_6H_{12}	0.085	84	14.7	43.8	39.9	24.5	15.3	0.016	0.049
Methylcyclohexane	C_7H_{14}	0.075	98	14.7	43.4	38.5	23.5	15.0	0.018	0.054
Ethylcyclohexane	C_8H_{16}	0.082	112	14.7	43.2	38.7	24.0	14.7	0.017	0.050
Dimethylcyclohexane	C_8H_{16}	0.057	112	14.7	43.2	37.3	21.7	15.6	0.023	0.066
Cyclooctane	C_8H_{16}	0.085	112	14.7	43.2	38.8	24.2	14.6	0.016	0.049
Decalin	$C_{10}H_{18}$	–	138	14.4	42.8	34.2	17.9	16.3	0.015	0.097
Bicyclohexyl	$C_{12}H_{22}$	–	166	14.5	42.6	36.2	20.9	15.3	0.010	0.071

Fuel	Formula	L_{sp} (m)	M (g/mol)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
					ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
Alkenes										
Ethylene	C_2H_4	0.106	28	14.7	48.0	44.2	29.8	14.4	0.013	0.045
Propylene	C_3H_6	0.029	42	14.7	46.4	37.6	19.0	18.6	0.036	0.103
Butylene	C_4H_8	0.019	56	14.7	45.6	35.3	17.3	18.0	0.042	0.115
Pentene	C_5H_{10}	0.053	70	14.7	45.2	38.7	22.3	16.5	0.024	0.070
Hexene	C_6H_{12}	0.063	84	14.7	44.9	39.2	23.2	16.0	0.021	0.062
Heptene	C_7H_{14}	0.073	98	14.7	44.6	39.5	24.0	15.5	0.019	0.055
Octene	C_8H_{16}	0.080	112	14.7	44.5	39.8	24.5	15.2	0.017	0.051
Nonene	C_9H_{18}	0.084	126	14.7	44.3	39.8	24.8	15.0	0.016	0.049
Decene	$C_{10}H_{20}$	0.079	140	14.7	44.2	39.4	24.3	15.2	0.017	0.052
Dodecene	$C_{12}H_{24}$	0.080	168	14.7	44.1	39.4	24.3	15.1	0.017	0.051
Tridecene	$C_{13}H_{26}$	0.084	182	14.7	44.0	39.5	24.6	14.9	0.016	0.049
Tetradecene	$C_{14}H_{28}$	0.079	196	14.7	44.0	39.3	24.2	15.1	0.017	0.052
Hexadecene	$C_{16}H_{32}$	0.080	224	14.7	43.9	39.2	24.2	15.0	0.017	0.051
Octadecene	$C_{18}H_{36}$	0.075	252	14.7	43.8	38.9	23.7	15.2	0.018	0.054
Polyethylene	$(C_2H_4)n$	0.045	601	14.7	43.6	37.9	21.8	16.1	0.024	0.060
Polypropylene	$(C_3H_6)n$	0.050	720	14.7	43.4	37.0	21.1	15.9	0.024	0.058
Cyclic Alkenes										
Cyclohexene	C_6H_{10}	0.044	82	14.2	43.0	36.2	20.2	16.0	0.028	0.080
Methylcyclohexene	C_7H_{12}	0.043	96	14.3	43.1	36.2	20.1	16.1	0.028	0.080
Pinene	$C_{10}H_{16}$	0.024	136	14.1	36.0	28.5	14.5	14.0	0.039	0.108
Alkynes and Butadiene										
Acetylene	C_2H_2	0.019	26	13.2	47.8	37.0	18.2	18.8	0.045	0.124
Heptyne	C_7H_{12}	0.035	96	14.3	44.8	36.8	19.8	17.0	0.032	0.090
Octyne	C_8H_{14}	0.030	110	14.4	44.7	36.2	19.0	17.2	0.035	0.096
Decyne	$C_{10}H_{18}$	0.043	138	14.4	44.5	37.4	20.7	16.6	0.028	0.080
Dodecyne	$C_{12}H_{22}$	0.030	166	14.5	44.3	35.9	18.8	17.0	0.034	0.096
1,3-Butadiene	C_4H_6	0.015	54	14.0	44.6	33.7	16.0	17.7	0.048	0.130
Arenes										
Benzene	C_6H_6	0.007	78	13.2	40.1	28.1	11.9	16.2	0.064	0.171
Toluene	C_7H_8	0.005	92	13.4	39.7	27.0	11.1	15.9	0.064	0.173
Styrene	C_8H_8	0.006	104	13.2	39.4	27.2	11.2	16.0	0.066	0.178
Ethylbenzene	C_8H_{10}	0.005	106	13.6	39.4	26.7	10.7	16.0	0.069	0.184
Xylene	C_8H_{10}	0.006	106	13.6	39.4	27.2	11.2	16.0	0.065	0.175
Indene	C_9H_8	0.008	116	13.0	39.2	27.8	12.0	15.8	0.062	0.166
Propylbenzene	C_9H_{12}	0.009	120	13.7	39.2	28.1	12.4	15.8	0.057	0.155
Trimethylbenzene	C_9H_{12}	0.006	120	13.7	39.2	27.0	11.2	15.9	0.065	0.174
Cumene	C_9H_{12}	0.006	120	13.7	39.2	27.0	11.2	15.9	0.065	0.174
Naphthalene	$C_{10}H_8$	0.005	128	12.9	39.0	26.4	10.6	15.8	0.071	0.190
Tetralin	$C_{10}H_{12}$	0.006	132	13.5	39.0	26.9	11.1	15.8	0.065	0.176

Fuel	Formula	L_{sp} (m)	M (g/mol)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
					ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
Butylbenzene	$C_{10}H_{14}$	0.007	134	13.8	39.0	27.3	11.5	15.8	0.062	0.166
Diethylbenzene	$C_{10}H_{14}$	0.007	134	13.8	39.0	27.3	11.5	15.8	0.062	0.166
p-Cymene	$C_{10}H_{14}$	0.007	134	13.8	39.0	27.3	11.5	15.8	0.062	0.166
Methylnaphthalene	$C_{11}H_{10}$	0.006	142	13.0	38.9	26.8	11.1	15.8	0.067	0.180
Pentylbenzene	$C_{11}H_{16}$	0.009	148	13.9	38.8	27.9	12.2	15.6	0.057	0.154
Dimethylnaphthalene	$C_{12}H_{12}$	0.006	156	13.2	38.8	26.8	11.0	15.7	0.066	0.178
Cyclohexylbenzene	$C_{12}H_{16}$	0.007	160	13.7	38.7	27.1	11.5	15.6	0.062	0.167
Diisopropylbenzene	$C_{12}H_{18}$	0.007	162	14.0	38.7	27.1	11.5	15.6	0.061	0.165
Triethylbenzene	$C_{12}H_{18}$	0.006	162	14.0	38.7	26.7	11.0	15.7	0.064	0.172
Triamylbenzene	$C_{21}H_{36}$	0.007	288	14.3	38.1	26.7	11.3	15.4	0.060	0.162
Polystyrene	$(C_8H_8)n$	0.015	200	13.2	39.2	27.0	11.0	16.1	0.060	0.166
Aliphatic Esters										
Ethyl formate	$C_3H_6O_2$	0.137	74	6.5	20.2	19.0	13.1	5.9	0.005	0.016
n-Propyl formate	$C_4H_8O_2$	0.114	88	7.8	23.9	22.1	14.6	7.5	0.007	0.023
n-Butyl formate	$C_5H_{10}O_2$	0.099	102	8.8	26.6	24.3	15.6	8.7	0.009	0.029
Methyl acetate	$C_3H_6O_2$	0.137	74	6.5	20.2	19.0	13.1	5.9	0.005	0.016
Ethyl acetate	$C_4H_8O_2$	0.114	88	7.8	23.9	22.1	14.6	7.5	0.007	0.023
n-Propyl acetate	$C_5H_{10}O_2$	0.099	102	8.8	26.6	24.3	15.6	8.7	0.009	0.029
n-Butyl acetate	$C_6H_{12}O_2$	0.093	116	9.5	28.7	26.0	16.5	9.5	0.011	0.032
Isobutyl acetate	$C_6H_{12}O_2$	0.093	116	9.5	28.7	26.0	16.5	9.5	0.011	0.032
Amyl acetate	$C_7H_{14}O_2$	0.086	130	10.0	30.3	27.3	17.1	10.2	0.012	0.036
Cyclohexyl acetate	$C_8H_{14}O_2$	0.083	142	10.2	31.5	28.2	17.6	10.7	0.013	0.039
Octyl acetate	$C_{10}H_{20}O$	0.077	172	11.2	33.6	29.9	18.3	11.6	0.015	0.043
Ethyl acetoacetate	$C_6H_{10}O_3$	0.086	130	7.4	30.3	27.3	17.1	10.2	0.010	0.031
Methyl propionate	$C_4H_8O_2$	0.114	88	7.8	23.9	22.1	14.6	7.5	0.007	0.023
Ethyl propionate	$C_5H_{10}O_2$	0.099	102	8.8	26.6	24.3	15.6	8.7	0.009	0.029
n-Butyl propionate	$C_7H_{14}O_2$	0.086	130	10.0	30.3	27.3	17.1	10.2	0.012	0.036
Isobutyl propionate	$C_7H_{14}O_2$	0.086	130	10.0	30.3	27.3	17.1	10.2	0.012	0.042
Amyl propionate	$C_8H_{16}O_2$	0.082	144	10.5	31.6	28.3	17.5	10.8	0.013	0.024
Methyl butyrate	$C_5H_{10}O_2$	0.099	102	8.8	26.6	24.3	15.6	8.7	0.009	0.035
Ethyl butyrate	$C_6H_{12}O_2$	0.093	116	9.5	28.7	26.0	16.5	9.5	0.011	0.038
Propyl butyrate	$C_7H_{14}O_2$	0.086	130	10.0	30.3	27.3	17.1	10.2	0.012	0.042
n-Butyl butyrate	$C_8H_{16}O_2$	0.082	144	10.5	31.6	28.3	17.5	10.8	0.013	0.039
Isobutyl butyrate	$C_8H_{16}O_2$	0.082	144	10.5	31.6	28.3	17.5	10.8	0.013	0.069
Ethyl laurate	$C_{14}H_{28}O_2$	0.196	228	12.0	37.2	36.3	27.3	9.1	0.002	0.004
Ethyl oxalate	$C_6H_{10}O_4$	0.224	146	6.1	28.7	33.0	25.7	7.3	<0.001	0.003
Ethyl malonate	$C_5H_8O_4$	0.210	132	7.7	32.2	31.7	24.2	7.5	<0.001	0.005
Ethyl lactate	$C_5H_{10}O_3$	0.214	118	7.0	30.8	30.4	23.3	7.0	<0.001	0.005
Butyl lactate	$C_7H_{14}O_3$	0.206	146	8.5	33.3	32.7	24.9	7.8	0.001	0.007
Amyl lactate	$C_8H_{16}O_3$	0.203	160	9.0	34.3	33.6	25.5	8.1	0.001	0.007

Fuel	Formula	L_{sp} (m)	M (g/mol)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
					ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
Ethyl carbonate	$C_5H_{10}O_3$	0.214	118	7.0	30.8	30.4	23.3	7.0	<0.001	0.005
Aliphatic Alcohols										
Methyl alcohol	CH_4O	0.305	32	6.4	20.0	19.4	16.6	2.8	0.001	<0.001
Ethyl alcohol	C_2H_6O	0.225	46	9.0	27.7	26.9	20.5	6.4	0.001	0.008
n-Propyl alcohol	C_3H_8O	0.155	60	10.3	31.8	30.3	21.5	8.8	0.004	0.016
Isopropyl alcohol	C_3H_8O	0.148	60	10.3	31.8	29.9	20.7	9.2	0.003	0.017
n-Butyl alcohol	$C_4H_{10}O$	0.141	74	11.1	34.4	32.5	22.5	10.0	0.006	0.020
Isobutyl alcohol	$C_4H_{10}O$	0.141	74	11.1	34.4	32.5	22.5	10.0	0.006	0.020
Sec butyl alcohol	$C_4H_{10}O$	0.141	74	11.1	34.4	32.5	22.5	10.0	0.006	0.020
Ter butyl alcohol	$C_4H_{10}O$	0.141	74	11.1	34.4	32.5	22.5	10.0	0.006	0.020
n-Amyl alcohol	$C_5H_{12}O$	0.131	88	11.7	36.2	34.0	23.2	10.8	0.007	0.024
Isobutyl carbinol	$C_5H_{12}O$	0.131	88	11.7	36.2	34.0	23.2	10.8	0.007	0.024
Sec butyl carbinol	$C_5H_{12}O$	0.131	88	11.7	36.2	34.0	23.2	10.8	0.007	0.024
Methylpropyl carbinol	$C_5H_{12}O$	0.131	88	11.7	36.2	34.0	23.2	10.8	0.007	0.024
Dimethylethyl carbinol	$C_5H_{12}O$	0.131	88	11.7	36.2	34.0	23.2	10.8	0.007	0.024
n-Hexyl alcohol	$C_6H_{14}O$	0.125	102	12.1	37.4	34.9	23.6	11.4	0.008	0.026
Dimethylbutyl alcohol	$C_6H_{14}O$	0.125	102	12.1	37.4	34.9	23.6	11.4	0.008	0.026
Ethylbutyl alcohol	$C_6H_{14}O$	0.125	102	12.1	37.4	34.9	23.6	11.4	0.008	0.026
Allyl alcohol	C_3H_6O	0.159	58	9.5	31.4	30.0	21.4	8.6	0.004	0.015
Cyclohexanol	$C_6H_{12}O$	0.124	100	11.7	37.3	34.8	23.5	11.4	0.008	0.027
Aliphatic Ketones										
Acetone	C_3H_6O	0.205	58	9.5	29.7	28.5	21.7	6.8	0.001	0.009
Methyl ethyl ketone	C_4H_8O	0.169	72	10.5	32.7	31.5	22.8	8.7	0.003	0.014
Cyclohexanone	$C_6H_{10}O$	0.164	98	11.2	35.9	34.5	24.7	9.7	0.004	0.017
Di-acetone alcohol	$C_6H_{12}O_2$	0.161	116	9.5	37.3	35.7	25.5	10.2	0.004	0.015
Other Aliphatic Fuels										
Monoethyl ether	$C_4H_{10}O_2$	0.232	90	8.4	26.7	26.5	20.8	5.7	<0.001	0.003
Monoethylether acetate	$C_6H_{12}O_3$	0.204	132	7.8	32.2	31.6	24.0	7.6	0.001	0.006
Monoethylether diacetate	$C_6H_{10}O_4$	0.208	146	6.1	33.3	32.7	25.0	7.8	<0.001	0.005
Glycerol triacetate	$C_9H_{14}O_6$	0.195	218	6.0	36.9	36.0	27.0	9.0	0.001	0.007
Other Aromatic Fuels										
Benzaldehyde	C_7H_6O	0.010	106	10.4	32.4	23.5	10.5	13.0	0.049	0.132
Benzyl alcohol	C_7H_8O	0.010	108	10.8	32.6	23.7	10.6	13.1	0.048	0.130
Cresylic acid	C_8H_8O	0.015	136	9.1	34.0	25.7	12.2	13.5	0.038	0.103
Ethyl benzoate	$C_9H_{10}O_2$	0.029	150	9.6	34.5	27.8	14.6	13.3	0.029	0.081
Aliphatic Fuels with Carbon, Hydrogen, and Nitrogen										
Diethylamine	$C_4H_{11}N$	0.089	73	14.6	38.0	34.3	21.6	12.7	0.012	0.036
n-Butylamine	$C_4H_{11}N$	0.089	73	14.6	38.0	34.3	21.6	12.7	0.012	0.036
Sec-Butylamine	$C_4H_{11}N$	0.089	73	14.6	38.0	34.3	21.6	12.7	0.012	0.036
Triethylamine	$C_6H_{15}N$	0.085	101	14.6	39.6	35.6	22.2	13.4	0.013	0.041

Fuel	Formula	L_{sp} (m)	M (g/mol)	S	Heat of Combustion (kJ/g)				Yield (g/g)	
					ΔH_T	ΔH_{ch}	ΔH_{con}	ΔH_{rad}	CO	Smoke
Di-*n*-butylamine	$C_8H_{19}N$	0.083	129	14.6	40.6	36.4	22.6	13.8	0.014	0.043
Tri-*n*-butylamine	$C_{12}H_{27}N$	0.082	185	14.7	41.6	37.3	23.1	14.2	0.015	0.046
Aromatic Fuels with Carbon, Hydrogen, and Nitrogen										
Pyridine	C_5H_5N	0.022	79	12.6	32.2	25.3	12.7	12.6	0.035	0.096
Aniline	C_6H_7N	0.018	93	12.9	33.8	26.0	12.7	13.3	0.039	0.106
Picoline	C_6H_7N	0.018	93	12.9	33.8	26.0	12.7	13.3	0.039	0.106
Toluidine	C_7H_9N	0.014	107	13.2	34.9	26.2	12.3	13.9	0.043	0.118
Dimethylaniline	$C_8H_{11}N$	0.013	121	13.3	35.7	26.6	12.4	14.2	0.045	0.122
Quinoline	C_9H_7N	0.012	129	12.5	36.1	26.7	12.2	14.4	0.049	0.132
Quinaldine	$C_{10}H_9N$	0.011	143	12.7	36.7	26.9	12.2	14.7	0.050	0.136
Butylaniline	$C_{10}H_{15}N$	0.009	149	13.6	37.0	26.6	11.7	14.9	0.051	0.139
Aliphatic Fuels with Carbon, Hydrogen, and Sulphur										
Hexyl mercaptan	$C_6H_{14}S$	0.062	118	12.2	33.0	28.7	16.9	11.8	0.015	0.045
Heptyl mercaptan	$C_7H_{16}S$	0.063	132	12.5	33.7	29.4	17.4	12.0	0.016	0.046
Decyl mercaptan	$C_{10}H_{22}S$	0.062	174	13.0	34.9	30.4	17.9	12.5	0.017	0.050
Dodecyl mercaptan	$C_{12}H_{26}S$	0.063	202	13.3	35.5	31.0	18.3	12.7	0.018	0.052
Hexyl sulfide	$C_{12}H_{26}S$	0.063	202	13.3	35.5	31.0	18.3	12.7	0.018	0.052
Heptyl sulfide	$C_{14}H_{30}S$	0.061	230	13.4	35.9	31.2	18.4	12.9	0.019	0.054
Octyl sulfide	$C_{16}H_{34}S$	0.061	258	13.6	36.3	31.6	18.6	13.0	0.019	0.055
Decyl sulfide	$C_{20}H_{42}S$	0.062	314	13.8	36.8	32.0	18.9	13.1	0.019	0.056
Aromatic Fuels with Carbon, Hydrogen, and Sulphur										
Thiophene	C_4H_4S	0.016	84	9.8	31.9	24.3	11.6	12.6	0.030	0.082
Methylthiophene	C_5H_6S	0.014	98	10.5	33.2	24.9	11.7	13.2	0.034	0.092
Thiophenol	C_6H_6S	0.013	110	10.6	34.1	25.4	11.8	13.6	0.037	0.101
Thiocresol	C_7H_8S	0.011	124	11.1	34.9	25.6	11.6	14.0	0.041	0.110
Cresolmethyl sulfide	$C_8H_{11}S$	0.011	155	11.6	36.2	26.5	12.0	14.5	0.041	0.112

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.10 Flammability Limits of Premixed and Diffusion Flames

Limits of Flammability (vol %)

Combustible	LFL [y]	UFL [y]	T_L (°C)	AIT (°C)
Acetal	1.6	10	37	230
Acetaldehyde	4.0	60	–	175
Acetic acid	5.4 [a]	–	40	465
Acetic anhydride	2.7 [b]	10 [c]	47	390
Acetanilide	1.0 [d]	–	–	545
Acetone	2.6	13	–	465
Acetophenone	1.1 [d]	–	–	570
Acetylacetone	1.7 [d]	–	–	340
Acetyl chloride	5.0 [d]	–	–	390

Combustible	LFL [y]	UFL [y]	T_L (°C)	AIT (°C)
Acetylene	2.5	100	–	305
Acrolein	2.8	31	–	235
Acrylonitrile	3.0	–	–6	–
Acetone-cyanohydrin	2.2	12	–	–
Adipic acid	1.6 [d]	–	–	420
Aldol	2.0 [d]	–	–	250
Allyl alcohol	2.5	18	22	–
Allyl amine	2.2	22	–	375
Allyl bromide	2.7 [d]	–	–	295
Allyl chloride	2.9	–	–32	485
o-Aminodiphenyl	0.66	4.1	–	450
Ammonia	15.0	28	–	–
n-Amyl acetate	1.0 [a]	7.1 [a]	25	360
n-Amyl alcohol	1.4 [a]	10 [a]	38	300
tert-Amyl alcohol	1.4 [d]	–	–	435
n-Amyl chloride	1.6 [e]	8.6 [a]	–	260
tert-Amyl chloride	1.5 [f]	–	–12	345
n-Amyl ether	0.7 [d]	–	–	170
Amyl nitrite	1.0 [d]	–	–	210
n-Amyl propionate	1.0 [d]	–	–	380
Amylene	1.4	8.7	–	275
Aniline	1.2 [g]	8.3 [g]	–	615
Anthracene	0.65 [d]	–	–	540
n-Amyl nitrate	1.1	–	–	195
Benzene	1.3 [a]	7.9 [a]	–	560
Benzyl benzoate	0.7 [d]	–	–	480
Benzyl chloride	1.2 [d]	–	–	585
Bicyclohexyl	0.65 [a]	5.1 [h]	74	245
Biphenyl	0.70 [i]	–	110	540
2-Biphenylamine	0.8 [d]	–	–	450
Bromobenzene	1.6 [d]	–	–	565
Butadiene (1,3)	2.0	12	–	420
n-Butane	1.8	8.4	–72	405
1,3-Butandiol	1.9 [d]	–	–	395
Butene-1	1.6	10	–	385
Butene-2	1.7	9.7	–	325
n-Butyl acetate	1.4 [e]	8.0 [a]	–	425
n-Butyl alcohol	1.7 [a]	12 [a]	–	–
sec-Butyl alcohol	1.7 [a]	9.8 [a]	21	405
tert-Butyl alcohol	1.9 [a]	9.0 [a]	11	480
tert-Butyl amine	1.7 [a]	8.9 [a]	–	380
n-Butyl benzene	0.82 [a]	5.8 [a]	–	410

Combustible	LFL [y]	UFL [y]	T_L (°C)	AIT (°C)
sec-Butyl benzene	0.77 [a]	5.8 [a]	–	420
tert-Butyl benzene	0.77 [a]	5.8 [a]	–	450
n-Butyl bromide	2.5 [a]	–	–	265
Butyl cellosolve	1.1 [h]	11 [j]	–	245
n-Butyl chloride	1.8	10 [a]	–	–
n-Butyl formate	1.7	8.2	–	–
n-Butyl stearate	0.3 [d]	–	–	355
Butyric acid	2.1 [d]	–	–	450
α-Butryolactone	2.0 [h]	–	–	–
Carbon disulfide	1.3	50	–	90
Carbon monoxide	12.5	74	–	–
Chlorobenzene	1.4	–	21	640
m-Cresol	1.1 [h]	–	–	–
Crotonaldehyde	2.1	16 [k]	–	–
Cumene	0.88 [a]	6.5 [a]	–	425
Cyanogen	6.6	–	–	–
Cycloheptane	1.1	6.7	–	–
Cyclohexane	1.3	7.8	–	245
Cyclohexanol	1.2 [d]	–	–	300
Cyclohexene	1.2 [a]	–	–	–
Cyclohexyl acetate	1.0 [d]	–	–	335
Cyclopropane	2.4	10.4	–	500
Cymene	0.85 [a]	6.5 [a]	–	435
Decaborane	0.2	–	–	–
Decalin	0.74 [a]	4.9 [a]	57	250
n-Decane	0.75 [l]	5.6 [m]	46	210
Deuterium	4.9	75	–	–
Diborane	0.8	88	–	–
Diesel fuel (60 cetane)	–	–	–	225
Diethyl amine	1.8	10	–	–
Diethyl analine	0.8 [d]	–	80	630
1,4-Diethyl benzene	0.8 [a]	–	–	430
Diethyl cyclohexene	0.75	–	–	240
Diethyl ether	1.9	36	–	160
3,3-Diethyl pentane	0.7 [a]	–	–	290
Diethyl ketone	1.6	–	–	450
Diisobutyl carbinol	0.82 [a]	6.1 [j]	–	–
Diisobutyl ketone	0.79 [a]	6.2 [a]	–	–
2-4,Diisocyanate	–	–	120	–
Diisopropyl ether	1.4	7.9	–	–
Dimethyl amine	2.8	–	–	400
2,2-Dimethyl butane	1.2	7.0	–	–

Combustible	LFL [y]	UFL [y]	T_L (°C)	AIT (°C)
2,3-Dimethyl butane	1.2	7.0	–	–
Dimethyl decalin	0.69 [a]	5.3 [i]	–	235
Dimethyl dichlorosilane	3.4	–	–	–
Dimethyl ether	3.4	27	–	350
n,n-Dimethyl formamide	1.8 [a]	14 [a]	57	435
2,3-Dimethyl pentane	1.1	6.8	–	335
2,2-Dimethyl propane	1.4	7.5	–	450
Dimethyl sulfide	2.2	20	–	205
Dimethyl sulfoxide	–	–	84	–
Dioxane	2.0	22	–	265
Dipentene	0.75 [h]	6.1 [h]	45	237
Diphenylamine	0.7 [d]	–	–	635
Diphenyl ether	0.8 [d]	–	–	620
Diphenyl methane	0.7 [d]	–	–	485
Divinyl ether	1.7	27	–	–
n-Dodecane	0.60 [d]	–	74	205
Ethane	3.0	12.4	–130	515
Ethyl acetate	2.2	11	–	–
Ethyl alcohol	3.3	19 [k]	–	365
Ethyl amine	3.5	–	–	385
Ethyl benzene	1.0 [a]	6.7 [a]	–	430
Ethyl chloride	3.8	–	–	–
Ethyl cyclobutane	1.2	7.7	–	210
Ethyl cyclohexane	2.0 [n]	6.6 [n]	–	260
Ethyl cyclopentane	1.1	6.7	–	260
Ethyl formate	2.8	16	–	455
Ethyl lactate	1.5	–	–	400
Ethyl mercaptan	2.8	18	–	300
Ethyl nitrate	4.0	–	–	–
Ethyl nitrite	3.0	50	–	–
Ethyl propionate	1.8	11	–	440
Ethyl propyl ether	1.7	9	–	–
Ethylene	2.7	36	–	490
Ethyleneimine	3.6	46	–	320
Ethylene glycol	3.5 [d]	–	–	400
Ethylene oxide	3.6	100	–	–
Furfural alcohol	1.8 [o]	16 [p]	72	390

Combustible	LFL [y]	UFL [y]	T_L (°C)	AIT (°C)
Gasoline:				
100/130	1.3	7.1	–	440
115/145	1.2	7.1	–	470
Glycerine	–	–	–	370
n-Heptane	1.05	6.7	–4	215
n-Hexadecane	0.43 [d]	–	126	205
n-Hexane	1.2	7.4	–26	225
n-Hexyl alcohol	1.2 [a]	–	–	–
n-Hexyl ether	0.6 [d]	–	–	185
Hydrazine	4.7	100	–	–
Hydrogen	4.0	75	–	400
Hydrogen cyanide	5.6	40	–	–
Hydrogen sulfide	4.0	44	–	–
Isoamyl acetate	1.1	7.0 [a]	25	360
Isoamyl alcohol	1.4	9.0 [a]	–	350
Isobutane	1.8	8.4	–81	460
Isobutyl alcohol	1.7 [a]	11 [a]	–	–
Isobutyl benzene	0.82 [a]	6.0 [j]	–	430
Isobutyl formate	2.0	8.9	–	–
Isobutylene	1.8	9.6	–	465
Isopentane	1.4	–	–	–
Isophorone	0.84	–	–	460
Isopropylacetate	1.7 [d]	–	–	–
Isopropyl alcohol	2.2	–	–	–
Isopropyl biphenyl	0.6 [d]	–	–	440
Jet fuel:				
JP-4	1.3	8	–	240
JP-6	–	–	–	230
Kerosene	–	–	–	210
Methane	5.0	15.0	–187	540
Methyl acetate	3.2	16	–	–
Methyl acetylene	1.7	–	–	–
Methyl alcohol	6.7	36 [k]	–	385
Methyl amine	4.2 [d]	–	–	430
Methyl bromide	10	15	–	–
3-Methyl butene-1	1.5	9.1	–	–
Methyl butyl ketone	51.2	8.0 [a]	–	–
Methyl cellosolve	2.5 [q]	20 [g]	–	380
Methyl cellosolve acetate	1.7 [h]	–	46	–
Methyl ethyl ether	2.2 [d]	–	–	–
Methyl chloride	7 [d]	–	–	–
Methyl cyclohexane	1.1	6.7	–	250

Combustible	LFL[y]	UFL[y]	T_L (°C)	AIT (°C)
Methyl cyclopentadiene	1.3[a]	7.6[a]	49	445
Methyl ethyl ketone	1.9	10	–	–
Methyl ethyl ketone peroxide	–	–	40	390
Methyl formate	5.0	23	–	465
Methyl cyclohexanol	1.0[d]	–	–	295
Methyl isobutyl carbinol	1.3[d]	–	40	–
Methyl isopropenyl ketone	1.8[e]	9.0[e]	–	–
Methyl lactate	2.2[a]	–	–	–
α-Methyl naphthalene	0.8[d]	–	–	530
2,Methyl pentane	1.2[d]	–	–	–
Methyl propionate	2.4	13	–	–
Methyl propyl ketone	1.6	8.2	–	–
Methyl styrene	1.0[d]	–	49	495
Methyl vinyl ether	2.6	39	–	–
Methylene chloride	–	–	–	615
Monoisopropyl bicyclohexyl	0.52	4.1[r]	124	230
2-Monoisopropyl biphenyl	0.53[j]	3.2[r]	141	435
Monomethylhydrazine	4	–	–	–
Naphthalene	0.88[s]	5.9[t]	–	526
Nicotine	0.75[a]	–	–	–
Nitroethane	3.4	–	30	–
Nitromethane	7.3	–	33	–
1-Nitropropane	2.2	–	34	–
2-Nitropropane	2.5	–	27	–
n-Nonane	0.85[u]	–	31	205
n-Octane	0.95	–	13	220
Paraldehyde	1.3	–	–	–
Pentaborane	0.42	–	–	–
n-Pentane	1.4	7.8	–48	260
Pentamethylene glycol	–	–	–	335
Phthalic anhydride	1.2[g]	9.2[v]	140	570
3-Picoline	1.4[d]	–	–	500
Pinane	0.74[w]	7.2[w]	–	–
Propadiene	2.16	–	–	–
Propane	2.1	9.5	–102	450
1,2-Propandiol	2.5[d]	–	–	410
b-Propiolactone	2.9[c]	–	–	–
Propionaldehyde	2.9	17	–	–
n-Propyl acetate	1.8	8	–	–
n-Propyl alcohol	2.2[k]	14[a]	–	440
Propyl amine	2.0	–	–	–
Propyl chloride	2.4[d]	–	–	–

Combustible	LFL [y]	UFL [y]	T_L (°C)	AIT (°C)
n-Propyl nitrate	1.8 [q]	100 [q]	21	175
Propylene	2.4	11	–	460
Propylene dichloride	3.1 [d]	–	–	–
Propylene glycol	2.6 [x]	–	–	–
Propylene oxide	2.8	37	–	–
Pyridine	1.8 [k]	12 [y]	–	–
Propargyl alcohol	2.4 [e]	–	–	–
Quinoline	1.0 [d]	–	–	–
Styrene	1.1 [z]	–	–	–
Sulfur	2.0 [aa]	–	247	–
p-Terphenyl	0.96 [d]	–	–	535
n-Tetradecane	0.5 [d]	–	–	200
Tetrahydrofurane	2.0	–	–	–
Tetralin	0.84 [a]	5.0 [h]	71	385
2,2,3,3-Tetramethyl pentane	0.8	–	–	430
Tetramethylene glycol	–	–	–	390
Toluene	1.2 [a]	7.1 [a]	–	480
Trichloroethane	–	–	–	500
Trichloroethylene	12 [bb]	40 [y]	30	420
Triethyl amine	1.2	8.0	–	–
Triethylene glycol	0.9 [g]	9.2 [bb]	–	–
2,2,3-Trimethyl butane	1.0	–	–	420
Trimethyl amine	2.0	12	–	–
2,2,4-Trimethyl pentane	0.95	–	–	415
Trimethylene glycol	1.7 [d]	–	–	400
Trioxane	3.2 [d]	–	–	–
Turpentine	0.7 [a]	–	–	–
Unsymmetrical dimethylhydrazine	2.0	95	–	–
Vinyl acetate	2.6	–	–	–
Vinyl chloride	3.6	33	–	–
m-Xylene	1.1 [a]	6.4 [a]	–	530
o-Xylene	1.1 [a]	6.4 [a]	–	465
p-Xylene	1.1 [a]	6.6 [a]	–	530

[a] T = 100°C
[b] T = 75°C
[c] T = 75°C
[d] Calculated
[e] T = 50°C
[f] T = 85°C
[g] T = 140°C
[h] T = 150°C
[i] T = 110°C
[j] T = 175°C
[k] T = 60°C
[l] T = 53°C
[m] T = 86°C
[n] T = 130°C
[o] T = 72°C
[p] T = 117°C
[q] T = 125°C
[r] T = 200°C
[s] T = 78°C
[t] T = 122°C
[u] T = 43°C
[v] T = 195°C
[w] T = 160°C
[x] T = 96°C
[y] T = 70°C
[z] T = 29°C
[aa] T = 247°C
[bb] T = 30°C

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.11 Limiting Oxygen Concentrations

Limiting Oxygen Concentrations at Normal Temperature and Pressure

Gas or Vapor	Limiting Oxidant Concentration N_2/Air (volume % O_2 above which deflagration can take place)	Limiting Oxidant Concentration CO_2/Air (volume % O_2 above which deflagration can take place)
Ethane	11	13.5
Propane	11.5	14.5
n-Butane	12	14.5
Isobutane	12	15
n-Pentane	12	14.5
Isopentane	12	14.5
n-Hexane	12	14.5
n-Heptane	11.5	14.5
Ethylene	10	11.5
Propylene	11.5	14
1-Butene	11.5	14
Isobutylene	12	15
Butadiene	10.5	13
3-Methyl-1-butene	11.5	14
Benzene	11.4	14
Gasoline:		
(73/100)	12	15
(100/130)	12	15
(115/145)	12	14.5
Kerosene	10 (150°C)	13 (150°C)
JP-1 fuel	10.5 (150°C)	14 (150°C)
JP-3 fuel	12	14.5
JP-4 fuel	11.5	14.5
Natural Gas		
(Pittsburgh)	12	14.5
n-Butyl chloride	14	–
	12 (100°C)	–
Methylene chloride	19 (30°C)	–
	17 (100°C)	–
Ethylene dichloride	13	–
	11.5 (100°C)	–
1,1,1-Trichloroethane	14	–
Trichloroethylene	9 (100°C)	–
Acetone	11.5	14
n-Butanol	–	16.5 (150°C)
Carbon disulfide	5	7.5
Carbon monoxide	5.5	5.5

Gas or Vapor	Limiting Oxidant Concentration N_2/Air (volume % O_2 above which deflagration can take place)	Limiting Oxidant Concentration CO_2/Air (volume % O_2 above which deflagration can take place)
Ethanol	10.5	13
2-Ethyl butanol	9.5 (150°C)	–
Ethyl ether	10.5	13
Hydrogen	5	5.2
Hydrogen sulfide	7.5	11.5
Isobutyl formate	12.5	15
Methanol	10	12
Methyl acetate	11	13.5
Methyl ether	10.5	13
Methyl formate	10	12.5
Methyl ethyl ketone	11	13.5

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.12 Pool Burning: Thermochemical and Empirical Constants for a Number of Common Organic Fuels

Material	Density ($kg \bullet m^{-3}$)	Δh_g ($kJ \bullet kg^{-1}$)	Δh_c ($MJ \bullet kg^{-1}$)	$\dot{m}''_\infty$ ($kg \bullet m^{-2} \bullet s^{-1}$)	$k\beta$ (m^{-1})
Cryogenics					
Liquid H_2	70	442	120.0	0.017 (±0.001)	6.1 (±0.4)
LNG (most CH_4)	415	619	50.0	0.078 (±0.018)	1.1 (±0.8)
LPG (mostly C_3H_8)	585	426	46.0	0.099 (±0.009)	1.4 (±0.5)
Alcohols					
Methanol (CH_3OH)	796	1,195	20.0	*	*
Ethanol (C_2H_5OH)	794	891	26.8	*	*
Simple Organic Fuels					
Butane (C_4H_{10})	573	362	45.7	0.078 (±0.003)	2.7 (±0.3)
Benzene (C_6H_6)	874	484	40.1	0.085 (±0.002)	2.7 (±0.3)
Hexane (C_6H_{14})	650	433	44.7	0.074 (±0.005)	1.9 (±0.4)
Heptane (C_7H_{16})	675	448	44.6	0.101 (±0.009)	1.1 (±0.3)
Xylenes (C_8H_{10})	870	543	40.8	0.090 (±0.007)	1.4 (±0.3)
Acetone (C_3H_6O)	791	668	25.8	0.041 (±0.003)	1.9 (±0.3)
Dioxane ($C_4H_8O_2$)	1,035	552	26.2	0.018	5.4
Diethyl ether ($C_4H_{10}O$)	714	382	34.2	0.085 (±0.018)	0.7 (±0.3)
Petroleum Products					
Benzine	740	–	44.7	0.048 (±0.002)	3.6 (±0.4)
Gasoline	740	330	43.7	0.055 (±0.002)	2.1 (±0.3)
Kerosene	820	670	43.2	0.039 (±0.003)	3.5 (±0.8)
JP-4	760	–	43.5	0.051 (±0.002)	3.6 (±0.1)
JP-5	810	700	43.0	0.054 (±0.002)	1.6 (±0.3)
Transformer oil, hydrocarbon	760	–	46.4	0.039	0.7
Fuel oil, heavy	940–1,000	–	39.7	0.035 (±0.003)	1.7 (±0.6)

Material	Density (kg•m^{-3})	Δh_g (kJ•kg^{-1})	Δh_c (MJ•kg^{-1})	$\dot{m}''_\infty$ (kg•m^{-2}•s^{-1})	$k\beta$ (m^{-1})
Crude oil	830–880	–	42.5–42.7	0.060	0.62
Solids					
Polymethylmethacrylate	1,184	1,611	24.9	0.020 (±0.002)	3.3 (±0.8)
Polyoxymethylene $(CH_2O)_n$	1,425	2,430	15.7		
Polypropylene $(C_3H_6)_n$	905	2,030	43.2		
Polystyrene $(C_8H_8)_n$	1,050	1,720	39.7		

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.

11.13 Effective Opposed-Flow Flame Spread Properties

Material	T_{ig} (°C)	$k\rho c$ (kW^2•s/m^4•K^2)	Φ (kW^2/m^3)	$T_{s,min}$ (°C)	$\Phi/k\rho c$ (mK^2/s)
PMMA polycast (1.59 mm)	278	0.73	5.4	120	8
Polyurethane (S353M)	280	–	–	105	82
Hardboard (6.35 mm)	298	1.87	4.5	170	2
Carpet (acrylic)	300	0.42	9.9	165	24
Fiberboard, low density (S119M)	330	–	–	90	42
Fiber insulation board	355	0.46	2.2	210	5
Hardboard (3.175 mm)	365	0.88	10.9	40	12
Hardboard (S159M)	372	–	–	80	18
PMMA type g (1.27 cm)	378	1.02	14.4	90	14
Asphalt shingle	378	0.70	5.3	140	8
Douglas fir particle board (1.27 cm)	382	0.94	12.7	210	14
Wood panel (S178M)	385	–	–	155	43
Plywood, plain (1.27 cm)	390	0.54	12.9	120	24
Chipboard (S118M)	390	–	–	180	11
Plywood, plain (0.635 cm)	390	0.46	7.4	170	16
Foam, flexible (2.54 cm)	390	0.32	11.7	120	37
GRP (2.24 mm)	390	0.32	9.9	80	31
Mineral wool, textile paper (S160M)	400	–	–	105	34
Hardboard (gloss paint) (3.4 mm)	400	1.22	3.5	320	3
Hardboard (nitrocellulose paint)	400	0.79	9.8	180	12
GRP (1.14 mm)	400	0.72	4.2	365	6
Particle board (1.27 cm stock)	412	0.93	4.2	275	5
Gypsum board, wallpaper (S142M)	412	0.57	0.79	240	1
Carpet (nylon/wool blend)	412	0.68	11.1	265	16
Carpet #2 (wool, untreated)	435	0.25	7.3	335	30
Foam, rigid (2.54 cm)	435	0.03	4.0	215	141
Polyisocyanurate (5.08 cm)	445	0.02	4.9	275	201
Fiberglass shingle	445	0.50	9.0	415	18
Carpet #2 (wool, treated)	455	0.24	0.8	365	4
Carpet #1 (wool, stock)	465	0.11	1.8	450	17

Material	T_{ig} (°C)	$k\rho c$ ($kW^2 \bullet s/m^4 \bullet K^2$)	Φ (kW^2/m^3)	$T_{s,min}$ (°C)	$\Phi/k\rho c$ (mK^2/s)
Aircraft panel epoxy Fiberite	505	0.24	*	505	*
Gypsum board, FR (1.27 cm)	510	0.40	9.2	300	23
Polycarbonate (1.52 mm)	528	1.16	14.7	455	13
Gypsum board (common) (1.27 mm)	565	0.45	14.4	425	32
Plywood, FR (1.27 cm)	620	0.76	*	620	*
Polystyrene (5.08 cm)	630	0.38	*	630	*

Note: Values are only significant to two places.
* Flame spread was not measurable.

Source: SFPE *Handbook of Fire Protection Engineering*, fifth edition, with permission from SFPE.