

Facts for Steel Buildings

number **1**

Fire

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**In memory of
Richard G. Gewain
1929–2003**

A renowned fire protection engineer and building code expert, Richard G. Gewain died on February 13, 2003 after complications from heart surgery. This document was one of the last engineering projects that Dick was working on prior to his death, and it is dedicated to his memory.

Since 1986, Dick was a Senior Engineer with the consulting firm of Hughes Associates, Inc. in Baltimore, MD. He specialized in developing and reviewing active and passive fire protection systems, as well as performance-based engineering to predict realistic fire exposures and the fire resistance criteria. His consulting work encompassed design work in a multitude of fire exposure applications and assessments of fire-damaged buildings. More recently, Dick was also a member of the FEMA/ASCE-SEI World Trade Center Building Performance Study Team.

From 1965-1986, Dick was the Chief Fire Protection Engineer for the American Iron and Steel Institute (AISI) in Washington, DC. During those years, he directed a multi-million dollar industry research program, developed and published design aids and computer software, and published engineering procedures for the fire design of steel buildings. His leadership role in advancing steel fire design for the good of the general public and industry is well known.

Throughout his illustrious career, Dick authored numerous technical papers and gave many presentations. As befitting someone of his stature, he was an active member of many professional organizations, societies, and committees, including the AISC Fire Safety Engineering Committee, National Fire Protection Association (NFPA), ASTM E5, Society of Fire Protection Engineers (SFPE), and ACI.

Dick was liked and respected for his vast knowledge and experience in fire protection engineering. His many life-long contributions to the profession and practice of fire protection engineering are hereby acknowledged with great appreciation. His life's work provides a significant basis for the future work to be continued by his many colleagues.

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INTRODUCTION

Steel-framed structures in high-rise office buildings have historically survived fire exposures extremely well. Two examples of severe fires are the 1988 First Interstate Bank fire in Los Angeles and the 1991 One Meridian Plaza fire in Philadelphia; the details of these and other significant building fires are given in Section 7.2. In fact, there has been no recorded structural failure of a protected high-rise steel frame building solely due to fire.

FEMA 403 (FEMA, 2002) documents the performance of the World Trade Center (WTC) towers and surrounding structures in the malicious terrorist attacks of September 11, 2001, and forms the basis for the continuing work of the National Institute of Standards and Technology (NIST). It is important to distinguish "normal" building fires from this extraordinary WTC experience, which involved the combination of severe structural damage, destruction of fire protection, suppression and egress systems, and simultaneous severe fires on several floors. The September 11 tragedy and the breadth of commonly asked questions about building fires, fire safety, and fire resistance have provided the main impetus to this compilation of available information. It is intended to serve as an objective general reference and introductory primer, in a convenient question and answer format, for the benefit of engineers, architects, building code officials, owners, developers, construction managers, general contractors and the general public and others with interest in the subject. More detailed information, data, analysis or design criteria are available in the cited references. This compilation is organized as follows:

- Section 1.** General Fire Science
 - Section 2.** Fire Resistance of Steel Systems
 - Section 3.** U.S. Building Code Criteria and Use of Prescriptive Fire Resistance Ratings
 - Section 4.** The ASTM E119 Standard Fire Test
 - Section 5.** Application of ASTM E119 Fire Ratings
 - Section 6.** Strength and Reparability of Steel After a Fire
 - Section 7.** Past Building Fire Incidents and Casualties
 - Section 8.** Special Steel Fire Resistance Issues and Future Needs
- References**

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Section 1

GENERAL FIRE SCIENCE

1.1 What are the goals of fire design provisions and building code requirements?

The primary goal of fire protection in buildings is to preserve life safety. A secondary goal is to protect property and safeguard the environment. These goals are achieved by:

- Providing safe means of escape, or safe refuge, for the occupants in the event of a fire.
- Designing the building to limit the progress and spread of fire and smoke, and to minimize structural damage.

Smoke is by far the greatest direct cause of casualties and injuries during fires—approximately 75 percent of fire victims die from smoke inhalation (Gann, et al, 1994). These deaths can occur in areas remote from the fire itself due to smoke propagation throughout the building, which thereby contaminates other floors and rooms, as well as potential escape routes, such as stairwells and hallways.

Building codes include requirements for smoke barriers. The International Building Code (ICC, 2003), hereafter referred to as the IBC, defines a smoke barrier as “a continuous membrane, either vertical or horizontal, such as a wall, floor, or ceiling assembly, that is designed and constructed to restrict the movement of smoke.” Likewise, the National Fire Protection Association Building Code (NFPA, 2003), hereafter referred to as NFPA 5000, defines a smoke barrier as “a continuous membrane, or a membrane with discontinuities created by protected openings, where such membrane is designed and constructed to restrict the movement of smoke.” However, these general definitions do not provide a specific or quantitative measure, or standard, by which a smoke barrier can be rated.

1.2 What fire protection systems are commonly used in buildings?

Building fire protection systems include active components (see 1.3) and passive components (see 1.4). Building codes such as the IBC and NFPA 500 mandate the minimum fire protection requirements for buildings in the form of active and/or passive protection. In some specific cases, either active or passive systems are permitted to be used alone. In other cases, both active and passive systems are required. Building codes thereby provide a balanced approach, relying on one system or both as appropriate to ensure safety for the associated occupancies and exposures.

1.3 What are some examples of active fire protection systems?

Active fire protection systems are those that utilize automatic devices or human action to initiate countermeasures, such as to suppress the fire and/or alert occupants to the emergency for the purposes of building evacuation. Examples of active fire protection systems include:

- Automatic sprinkler systems.
- Smoke and fire detector and alarm systems.
- Water supply systems, hose cabinets, fire extinguishers.
- Systems and personnel involved in fire department response.

1.4 What are some examples of passive fire protection systems?

Passive fire protection systems are those that function without external activation. Examples of passive fire protection systems include:

- Building code limitations for the combustion characteristics of construction materials, finishes, internal furnishings and contents.
- Compartmentalized design, which includes horizontal and vertical fire and smoke barriers, fire doors and windows, fire stops, and fire dampers.
- Structural fire protection materials that prevent or delay the temperature rise in structural elements. For structural steel framing, these materials usually are spray-applied fire resistive materials (SFRM), gypsum board enclosures, or intumescent coatings.

1.5 How effective and reliable are automatic sprinkler systems?

Sprinkler systems have proven to be exceptionally effective and reliable when properly designed, installed and maintained. Their effectiveness in improving life safety is particularly noteworthy.

Strict regulations are in place in the U.S. for sprinkler system design, installation, inspection, testing and maintenance. The historical record of sprinkler system performance during conventional fires, the National Fire Protection

Association (NFPA) report states (Rohr, 2001), are summed up best as follows:

“Sprinklers typically reduce chances of dying in a fire and the average property loss by one-half to two-thirds in any kind of property where they are used.”

“NFPA has no record of a fire killing more than two people in a completely sprinklered public assembly, educational, institutional or residential building where the system was working properly.”

See 7.5 for further information.

1.6 What are the fundamental stages of a fire?

There are 4 fundamental stages in a natural fire. These stages are schematically illustrated in Figure. 1.1.

The first stage is the incipient ignition phase, wherein heating of the potential fuel source(s) takes place. The second stage is the growth stage, which involves ignition with visible flaming combustion. As the fire grows and reaches sufficiently high temperatures—about 1,100 °F (600 °C)—it may become fully developed within the compartment and reach the so-called “flashover” condition (see 1.7), which generally marks the beginning of the third stage called the burning period. The temperatures and heat flux are so great within the fire compartment that all exposed surfaces are burning and the available ventilation will govern the rate of heat release. This most severe stage of the fire causes has the greatest effects on the building elements. Eventually, the fuel for the fire in the given compartment becomes exhausted, and the fire will start to die out during the fourth stage called the decay period. The decay phase is generally begins when about 70 percent of the combustible materials in the compartment have burned.

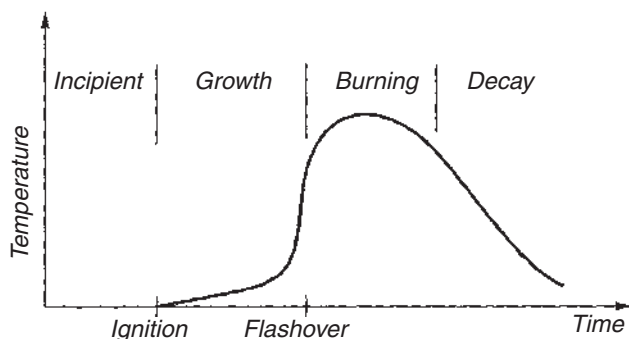


Fig. 1.1. Stages of Fire Development (Buchanan, 2001)

It can thus be seen that a fire in a specific compartment eventually self extinguishes. However, its spread to other compartments must be prevented or the fire can continue migrating both vertically and horizontally, repeating the entire cycle of fire ignition, growth, burning, and decay periods.

It is also obvious from the curve in Figure 1.1 that the most effective means for providing fire safety is either prevention of fire ignition altogether, or extinguishment of the fire during the early growth stage. Once a fire reaches the dangerous burning period, evacuation and fire department response become even more necessary. Adequate preparedness and awareness by the building management, its occupants, and the local fire departments for response to fire emergencies are imperative in order to minimize the consequences of fires.

1.7 What is “flashover”?

“Flashover” is the abrupt transition from relatively light burning of a small number of combustibles in the room, or a small portion of the room, to full-room involvement in fire. Room fire flashover is in essence a state in which all of the combustible contents of the room experience a nearly simultaneous ignition, with very visible flaming throughout. Fortunately, most fires never reach flashover, either because they are successfully detected and extinguished, or because the necessary ambient conditions within the compartment are lacking. Some fires self extinguish due to insufficient air supply (ventilation), or due to inadequate presence of combustibles to continue the fire. Historical data indicates that flashover will not occur in premises with properly designed, installed and functional automatic sprinkler systems.

Whether or not flashover occurs during an uncontrolled fire, and the time required to reach the flashover stage, depends on many factors, including:

- The amount and properties of combustible contents.
- The volume of the compartment.
- Ventilation conditions

In larger compartments, if flashover occurs at all, the time to reach this condition will be longer. In well-ventilated larger premises, such as open-deck parking structures, large hotel atriums, and sprawling warehouses and retail stores, “flashover” probably cannot occur.

1.8 How does a natural fire differ from a standard fire used in laboratory tests to obtain fire ratings for structural assemblies?

ASTM E119 *Standard Test Method for Fire Tests of Building Construction and Materials* provides the basis for the

test fire used in establishing fire ratings of structural building elements in the US. UL 263 *Fire Tests of Building Construction and Materials* and NFPA 251 *Standard Methods of Fire Endurance of Building Construction and Materials* are similar documents. The controlled ASTM E119 standard fire is fast starting, hot, and rising with an equivalent burning temperature of 1,000 °F (538 °C) after only 5 minutes. Internationally, the ISO 834 standard fire has similar characteristics. See Sections 2 and 4 for further information on ASTM E119.

A natural fire, when uncontrolled, has distinct stages of growth, burning, and most notably, decay (see 1.6). In contrast, the ASTM E119 standard fire has no decay branch, but specifies ever-increasing furnace compartment temperatures with time that can reach 2,300 °F (1,260 °C) at 8 hours, if testing were to reach this duration. Normally, ASTM E119 fire tests are not conducted for more than 3 to 4 hours.

The ASTM E119 standard fire thus represents the most intense burning stage of a real fire, but with inexhaustible and increasing fuel supply provided by the furnace. A natural fire eventually consumes its combustibles in a time that is dependent upon the initial quantity and type of fire load (combustibles, see 1.11) and ventilation present in the compartment. Hence, the actual fire load and ventilation present in the room will determine the nature, intensity, and duration of a real fire. Uncontrolled, well-ventilated fires burn faster and reach higher temperatures than poorly ventilated fires, but they have a shorter duration for the same fuel. This is illustrated in Figure 1.2, in which F_v is a ventilation factor.

In Figure 1.3, the ASTM E119 standard time-temperature curve is superimposed on representative real fire curves under burning conditions for various fuel loads and a constant ventilation factor. The maximum fire temperature, its

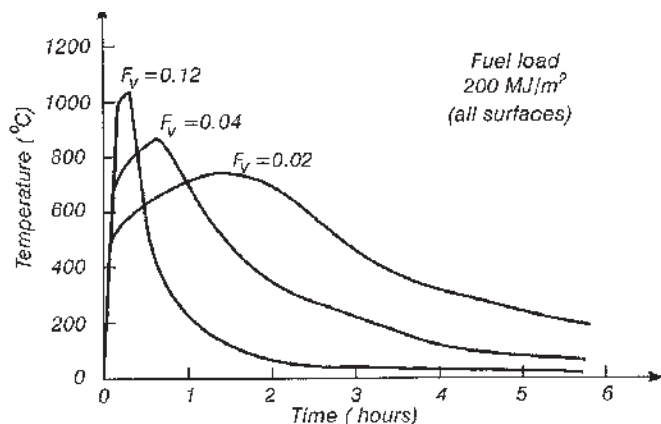


Fig. 1.2. Real Time-Temperature Curves for Different Ventilation Factors F_v with a Constant Fuel Load (Buchanan, 2001)

decay phase, and fire time duration are significantly affected by the fuel content, and are quite different from the standard time-temperature curve. As expected, higher fuel loads cause longer and hotter fires under uncontrolled conditions. The standard fire time-temperature curve between 1 to 4 hours provides a reasonably good estimate of the maximum room temperature that will be encountered in a real conventional fire in many cases. However, in real uncontrolled fires, these high temperatures most likely occur over only a relatively short time interval.

For faster-starting and hotter fires, such as those that occur from petrochemicals or other hazardous materials, a standard fire exposure more severe than that given in ASTM E119 may be more appropriate. ASTM E1529 (UL 1709) *Standard Test Method for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies* defines such a standard fire exposure that reaches and remains at about 2,000 °F (1,100 °C) after 5 minutes.

Mathematical representations of the ASTM E119 standard fire time-temperature curves and a variety of real fire time-temperature curves can be made for analytical purposes. Various such formulations can be found in the literature listed in Section 8.2.

1.9 At what temperature and for how long does a normal fire burn?

The maximum temperature and duration of a fire in a building compartment depends on several variables, including

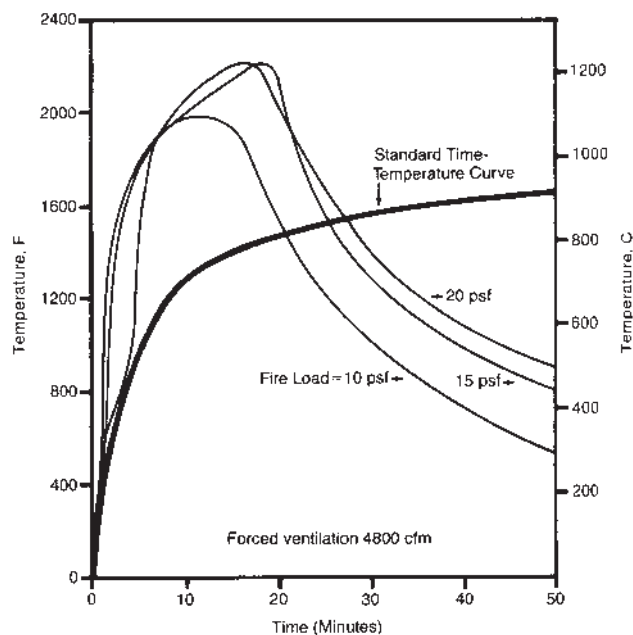


Fig. 1.3. ASTM E119 Standard Fire and Real Fire Time-Temperature Curves (AIS, 1981)

Table 1.1 Relationships Between Fire Load (Wood Equivalent) and Standard Fire Endurance Time (Ingberg, 1928) (AISI, 1981)

Average Fire Load, psf	Average Fire Load, kg/m ²	Equivalent Fire Endurance (hours)
5	24.4	½
7 ½	36.6	¾
10	48.8	1
15	73.2	1 ½
20	97.6	2
30	146.5	3
40	195.3	4 ½
50	244.1	6
60	292.9	7 ½

the amount and configuration of available combustibles, ventilation conditions, properties of the compartment enclosure, and weather conditions. In a typical fire, such as in an office, residential or retail occupancy, the maximum temperature of a fully developed fire will likely not exceed 1,500 °F (815 °C), though it could range up to a peak of 2,000 °F (1,093 °C) under more severe conditions. The maximum temperature will typically last for only 10 to 20 minutes during the peak of its burning period within the compartment. Consequently, the average real gas temperature within the fire compartment will not reach its maximum level (see Figure 1.3) over the fire duration for any exposure.

1.10 Given these differences between real and standard fires, why are the common fire ratings based on the standard fire?

There are unavoidable variations and uncertainties in real building fires. No two real fires will have the same time-temperature curve. A standard fire test and associated time-temperature curve, such as that prescribed in ASTM E119, is used to provide a simple and constant comparative baseline for the relative assessment of fire endurance times for different structural members and assemblies.

No standard fire is a predictor of actual fire resistance times during a real fire, though the early work by Ingberg (1928) showed an approximate correlation between the fire severity of a standard fire with a real fire by comparing and equilibrating the areas under the respective time-temperature curves. Note that the shape of the building compartment, the type of combustible materials, their rate of heat release and the ventilation conditions are not explicitly considered in this approximate correlation. Under these assumptions and with noncombustible construction, Ingberg developed the equivalent fire severity hypothesis, which relates the average fire loads on a wood equivalent basis (see 1.11) in a given compartment area to a fire endurance time in a standard fire. These relationships are illustrated in Table 1.1.

Given a wood-equivalent fire load of 10 pounds per square foot (psf) in a room with a 1-hour fire-resistive construction rating, it should be able to survive a complete fire burnout of the room without structural collapse and prevent fire propagation beyond the room of fire origin. Such general equivalencies still form the underlying rationale behind the use of standard fire resistance ratings in today's building codes. Despite the inherent assumptions and limitations compared to actual conditions, the use of a standard fire continues to offer the best approach for assessment of the comparative fire resistance of structural assemblies.

1.11 What is a fire load and what is the range of typical fire loads in buildings?

The fire load is the amount of combustible material in the compartment. Traditionally, this has been expressed in terms of the wood-equivalent weight of combustible building contents per unit building floor area (that is, in pounds per square foot or psf). The actual weight of combustible contents is adjusted to the so-called wood-equivalent weight based on the estimated potential heat of contents normalized to the potential heat of wood. Alternatively, the more modern representation of fire load is in terms of the potential heat of building contents per unit building floor area, e.g. Btu/ft² (or MJ/m² in metric units).

The available fuel load is determined by the room size and the nature, amount and arrangement of its combustible contents. Fire loads should normally account for all combustible building contents, including furnishings, equipment, and combustible construction components. In reality, the majority of the fire load in a building results from additional furnishing and contents being introduced after the construction is completed, which is sometimes not adequately considered in evaluating the risk to fire safety.

The combustibles can be characterized by several properties. Primarily its potential heat, net calorific value, or heat

of combustion is used. These are expressed in terms of heat energy per unit of weight (or mass), e.g. Btu/lb (or MJ/kg in metric units). Wood is often used as an ordinary combustible benchmark, having approximately 7,000 to 8,000 Btu/lb (16 to 18 MJ/kg). Plastics contain more heat of combustion: 10,000 to 17,000 Btu/lb (24 to 40 MJ/kg). Liquid petroleum products range within 12,000 to 20,000 Btu/lb (27 to 46 MJ/kg). Multiplication of this property by the expected combustible weight (mass) distribution in the space gives the total potential heat energy that could be released during a fire event.

A conventional office building fire involving combustibles such as wood and plastics with potential heat energy of 7,000 to 17,000 Btu/lb (16 to 40 MJ/kg) and a typical fire load density for an office space of 6 psf (30 kg/m²), would create a total potential heat energy of 42,000 to 102,000 Btu/ft² (about 480 to 1,200 MJ/m²) per unit floor area. A storage room, or a library, might double this fire load. Fire engineering textbooks and handbooks (SFPE, 2002) contain much more specific information and burning properties on these and other combustible materials.

1.12 How fast does a conventional fire spread?

If ignition can be prevented or the fire detected and suppressed during its growth or early burning stage, it can be effectively contained within a matter of minutes and will not spread further. For this reason, fire prevention and early suppression are the best solutions to fire safety.

Automatic sprinklers have been found to be very effective for putting out most fires before they can reach flashover, or before they grow to an uncontrolled state during the burning phase. If a fire does progress to flashover or an otherwise uncontrollable burning stage, the rate at which it spreads and grows in a building depends on many other factors that are site and time specific to the particular event. These include:

- Combustion properties of the construction materials and building contents.
- Ventilation conditions.
- Room geometry and configuration.
- Timeliness of detection.
- Effectiveness of fire suppression response by the occupants and/or the local fire department.
- Availability and effectiveness of automatic fire suppression systems.
- Availability and effectiveness of fire barriers.

As witnessed in several past building fires, if fire ignition and growth is not prevented or suppressed within the compartment of fire origin, it can spread quickly to multiple rooms and floors. Any unusual circumstances that would facilitate fire initiation and propagation, such as arson, terrorist acts, illegal presence of fuels and combustibles, clearly accelerate and increase the fire dangers compared to those expected in an accidental conventional fire.

1.13 How does the heat transfer from the fire to the surrounding structure occur?

Ultimately, it is not just the room fire temperature that controls structural response, but the heat input and corresponding temperature rise that occurs in the structural material. In general, heat transfer can occur in 3 ways: conduction, convection, and radiation.

Conduction is heat transfer through solid materials, and involves the material properties of density, specific heat, and thermal conductivity. Convection is heat transfer through fluids, either gases or liquids, which is a linear function of the gas temperatures. Radiation is the transfer of heat energy by electromagnetic waves, which depends on the gas temperature raised to the fourth power.

For protected structural steel, the temperature increase due to fire results primarily from radiation to the fire protection material and conduction through the protection, with inclusion of the appropriate insulating properties and thickness of the material. Therefore, the temperatures in protected steel will be continually less than those of the fire during the heating phase. How much less depends on the thickness and nature of the insulating material, as well as the size and weight of the steel member itself. Of equal importance are the thermo-physical properties of the steel fire protection material, such as cohesion and adhesion during the fire event.

For unprotected (bare) steel, temperatures are affected both by convection and radiation. The pertinent heat transfer equations, thermal parameters and properties are available in the literature (SFPE, 2002). In this case, the temperatures of the bare steel will eventually reach the same levels as that of the fire compartment. The unprotected steel temperatures are a function of the nature of the fire exposure and the weight and heated perimeter of the steel shape. Hence, the time for the steel to reach temperature equilibrium with its surroundings will depend on these conditions. Once steel temperature equivalence with the fire is reached, it will be essentially maintained for the duration of the fire. If the primary heating of the steel is due to its direct exposure to flame impingement, or line-of-sight radiant heat, shielding of the steel is one effective way to reduce its temperature increase.

1.14 What are “thermal mass” and “thermal inertia”?

“Thermal mass” is sometimes used to refer to effective specific heat or heat capacity. Effective specific heat, usually expressed in Btu/[lb °F] (or J/[kg °C] in metric units), is the amount of energy, per unit mass or weight of material, required to raise the temperature of the material by one temperature unit. Similarly, effective heat capacity, which is sometimes called volume-specific heat, expressed in Btu/[ft³ °F] (or J/[m³ °C] in metric units) is the amount of energy, per unit volume of material, required to raise the temperature of the material by one temperature unit. This derived property is simply the product of the material specific heat and its density.

Another derived property is the “thermal inertia”, which is the product of the material thermal conductivity, density, and specific heat, with dimensional units of Btu²/[ft⁴ °F²h] (or W²s/[m⁴ °C²] in metric units). Materials with a high thermal inertia are more desirable, since they will not ignite or heat up quickly.

For most construction materials, specific heat, heat capacity and thermal conductivity values are all temperature dependent, as is the derived property of thermal inertia. These thermal property values change significantly in the temperature range associated with building fires, which is 100 to 2,000 °F (40 to 1,100 °C), because most materials undergo physiochemical changes at elevated temperatures. The thermal properties are also sensitive to the testing method used and the rate of temperature rise. Therefore, it is common to find different values of material properties for the same material in different literature sources.

1.15 What is a “heat sink”?

A “heat sink” is anything that can absorb large amounts of heat through physical and/or chemical processes. Usually, materials containing large amounts of chemically combined water in their structure, such as gypsum or concrete, absorb significant amounts of heat due to the energy consumed in the water evaporation process. Materials with high thermal conductivity and high effective heat capacity will also act as heat sinks.

1.16 Where can one find the thermal conductivity or thermal resistance values of the building and fire protection materials?

Information on the thermo-mechanical properties at elevated temperatures of the common construction materials (steel, concrete, masonry, and wood) and fire protection materials (spray-applied coatings, gypsum board, etc.) is scattered. For some materials, it is not available at all. One good general source for the thermo-mechanical properties of various types of building materials and combustibles is SFPE (2002). Some further information on the properties of steel at elevated temperatures is given in Section 2.

Section 2

FIRE RESISTANCE OF STEEL SYSTEMS

2.1 What does the term “fire resistant” mean?

Fire resistance is the duration during which a structural assembly or element exhibits adequate structural integrity, stability and temperature transmission, usually as specified by a given standard test method. Thus, a structural assembly or element with a fire resistance rating is one that has been tested or evaluated to determine its resistance to a standard fire, such as that in ASTM E119. This fire rating is usually expressed as a number of hours and describes the ability of the assembly or element to withstand fire in a relative sense compared with other assemblies or elements. There are testing protocols for the evaluation of the performance of beams, columns, walls, floors, and roofs, and these elements commonly are determined to have fire resistance ratings from 1 to 4 hours. A prototype of an actual construction assembly is tested using these protocols, prescribed limiting temperatures, and other criteria to determine the hourly rating, i.e. the fire resistance. For further information, see Section 2.6.

2.2 What does the term “fire protected” mean?

Fire protection, in a general sense, refers to everything associated with providing fire safety, including sprinklers, egress, separations, fire detectors and alarms, and fire resistance. With regard to steel and other building materials, fire protection also refers more narrowly to the insulative materials applied to the structural members. For further information, see Section 1.2.

2.3 Do the terms “fire-resistant” and “fire-protected” mean “fireproof”?

No, the term “fireproof” is commonly used, but an unfortunate colloquial misnomer - no building material is actually fireproof. All construction materials suffer degradation of their properties and damage at elevated temperatures. Materials that are designed to have some substantial level of fire resistance often improperly use the term “fireproof” to describe their end objective, or the process by which that measure is accomplished. Indeed the misnomer extends to the use of the term “fireproofing” to describe the spray-applied fire-resistive materials that get applied to steel. This more technically correct but seldom used term can be abbreviated SFRM.

2.4 How is a fire resistance rating developed?

ASTM E119 has been the basic and traditional standard for fire-resistance testing in the US since 1918. UL 263 and NFPA 251 are similar, as is the international standard ISO 834. ASTM E119 is applicable to individual beams, columns, floors, walls, and other building elements of any material. Each assembly or element is subjected to a standard fire with a time-temperature curve as shown previously in Figure 1.3. In applications involving hydrocarbon pool fires, ASTM E1529 or its equivalent UL 1709 is used.

These documents establish the specific testing requirements and acceptance criteria used to establish fire resistance ratings. They define the laboratory equipment needed to accommodate the minimum required specimen sizes within a controlled furnace chamber, the instrumentation needed to measure temperatures in the furnace and the test specimen, and the means to apply superimposed loading to the specimen, as needed. There are several experimental facilities in the US that conduct standard fire resistance tests, including Underwriters Laboratories, Inc. (UL), FM Global, Southwest Research Institute, and Omega Point Laboratories. The fire resistance ratings produced by these and similar facilities are commonly accepted by US building code authorities based upon their publication in the literature, such as the UL Fire Resistance Directory.

The maximum fire test frame will vary in size among the individual laboratory facilities. Consequently, the fire specimen dimensions are quite limited relative to actual construction. For example, UL has the capability to test up to a 14 ft by 17 ft specimens for beams, floor assemblies, and roof assemblies, up to a 10 ft by 10 ft specimens for walls, and up to 9 ft high specimens for columns. Thus, the typical fire test is made of an isolated or smaller-scale prototype assembly or element, not necessarily full-scale replications of actual construction. ASTM E119 is therefore strictly a comparative standardized test of selected structural and product features.

Usually, the fire test duration closely matches the desired fire rating (e.g., 1, 2, 3 or 4 hours). ASTM E119 prescribes ever-increasing temperatures with time duration; 1,700 °F (927 °C) at 1 hour increasing to 2,000 °F (1,093 °C) at 4 hours. This standard fire exposure attempts to represent a fully developed fire exposure with an implied endless fuel supply and adequate ventilation for intense fire continuation in a given location. In contrast, a real fire reaches a decay period (see Section 1.6) and eventual burnout. Approximate time equivalencies can be established between the standard

and natural fire exposures for some conditions. The resulting fire-resistance rating is expressed as the interval of hours that the assembly or element was able to withstand exposure to the standard fire before a limiting criterion was reached. Examples of the limiting criteria include:

- The assembly or element can no longer support the applied load.
- Excessive temperature rise in steel specimens tested without load.
- Excessive temperature rise on the unexposed surface of floor, roof or wall specimens.
- Passage of gases (through floor, roof or wall specimens) hot enough to ignite cotton waste pads applied to the unexposed surface.

The ASTM E119 standard thereby:

- Evaluates the relative heat transmission and structural integrity characteristics of specimens under the standard fire exposure.
- For specimens tested without load, establishes critical temperature limits, which are conservative estimates based on the maximum allowed reduction in the strength of structural members at elevated temperatures.
- Explicitly assesses the adequacy of a properly applied fire protection material or system, including the preclusion of vulnerabilities to deterioration, delaminating and detachment from the steel specimen.

See also Section 4.

2.5 What are the assumptions of ASTM E119 fire resistance ratings?

There are several assumptions that form the basis of ASTM E119 fire resistance ratings:

- The basis of the rating uses a standard time-temperature curve that differs from the time-temperature curve for a real uncontrolled fire, as described in Section 1.8.
- The standard fire assumes a uniform temperature distribution through the entire fire compartment. In actual fires, the temperature distribution is not really uniform.
- Hot gas pressures in real fire compartments could be different from test furnace pressure.
- The loading intensity and pattern applied to the specimen during the test are not intended to account for the actual loading conditions in a real building during a real fire.

- The loading intensity in the test is based upon the maximum calculated strength, whereas members are not likely to be supporting their full design load in a real fire.
- The test and real applications will differ in specimen boundary conditions, assembly and component size.
- ASTM E119 does not address smoke generation and propagation effects or their effects on life safety, though other standards do specifically address combustibility and smoke.
- Published fire resistance ratings are given in terms of whole hours of time during which the specimen met the acceptance criteria, not necessarily the full recorded fire endurance times. That is, two rated assemblies, one with an actual fire endurance of 121 minutes and another with 179 minutes qualify for the same 2-hour rating.
- Aside from the basic experimental outputs needed to determine the ASTM E119 rating, other potentially useful test results are not normally collected, such as the thermo-physical property variations at high temperatures of the construction and fire protection materials.

Regardless of the aforementioned assumptions and limitations, ASTM E119 has historically served as a useful and conservative benchmark measure of the relative fire resistance of different building elements and materials.

2.6 Are structural steel frames and members fire resistant? What is the nature of high temperature effects on steel and other building materials?

Yes, steel is fire resistant. Steel is a durable noncombustible material with many excellent structural properties. The mechanical properties of steel deteriorate under elevated temperatures are described in Section 2.7. Consequently, steel must be properly designed and constructed using an appropriate system or assembly. Modern building codes contain prescriptive criteria for determining when and what requirements apply for the various types of construction, heights, areas, and occupancies. Under limited conditions, unprotected steel is permitted for certain types of hazard, occupancy, heights, and areas, such as some low-rise buildings, sports stadia and open-deck parking garages. When required, steel members can be insulated from fire effects through various means, including spray-applied fire-resistive materials, intumescent coatings, gypsum-board enclosure, and concrete encasement or filling.

Prolonged heating will adversely affect all building materials, with visible damage and distortions always occurring under prolonged elevated temperatures. Deflections of structural members during long and hot fires can reach many inches, or several feet, which is an order of magnitude

greater than the small elastic deflections that are normally contemplated in structural design. Local buckling and twisting can also be experienced under high temperatures. Concrete spalls when exposed to elevated temperature, thereby exposing its reinforcing steel to the direct effects of the fire. Concrete strength is also degraded at elevated temperatures.

2.7 How much does the steel strength and stiffness degrade at higher temperatures? Will steel melt in a fire?

At higher temperatures, both the yield strength and tensile strength of steel decrease, as does the modulus of elasticity. Curves showing the strength and stiffness reductions in steel with increasing temperature can be found in ASCE (1992), SFPE (2002) and other references given in Section 8.2. In general, steel retains strength and stiffness approximately equal to 50 percent of its strength and stiffness at ambient conditions at a temperature of 1,100 °F (593 °C). This is comparable to the strength and stiffness reductions for ordinary concrete. At 1,300 °F (704 °C), steel retains about 20 percent strength and stiffness. A near-total depletion of strength occurs at approximately 2,200 °F (1,204 °C).

Usually, it is convenient to represent the variation of yield strength as a function of temperature and as a fraction relative to the steel strength at ambient temperature, as shown in Figure 2.1 (ECCS, 2001). The same steel strength curves and values apply to both uniaxial tension and compression. Similarly, the variation of modulus of elasticity is shown in Figure 2.2.

Note that the values in Figure 2.1 were developed from small test material coupons, which were uniformly heated throughout the full cross section of the coupon. The tem-

peratures shown are those in the steel specimen and are not necessarily identical to the fire temperature (see Section 1.13). There are also many common cases in which this uniform heating of the steel member will not occur during a fire.

For example, in a composite floor the protected steel beam will be hottest at the bottom flange, which is closest to the fire, and coolest at its top flange, which is in contact with the concrete and floor deck. For this fire exposure, while the beam bottom flange may have reached sufficiently high temperatures to lose much of its strength and stiffness, the upper portions of the beam may be well below the critical temperatures for steel. In such cases, the top flange can be as much as 750 °F (400 °C) cooler than the bottom flange in a 2-hour ASTM E119 test.

These temperature reductions are temporary as long as the steel temperatures do not exceed about 1,300 °F (700 °C) for more than about 20 minutes. Such fire-damaged steel, though likely deformed, will regain its pre-fire properties at ambient conditions. However, higher temperatures and longer exposures will likely result in annealing and a reduction in yield strength. Caution should also be exercised in extrapolating these properties of the commonly used structural steels to heat-treated steels, cables and similar products with yield strengths in excess of 70 ksi (500 MPa); these products will likely require evaluation to determine the effects of high-temperature exposure.

It can be said with confidence that structural steel does not melt in building fires, although such possibility is theoretically possible for certain conditions (comparable to melting furnace conditions). Building fires simply do not generate steel melting temperatures that are around 2,700 °F (1,500 °C).

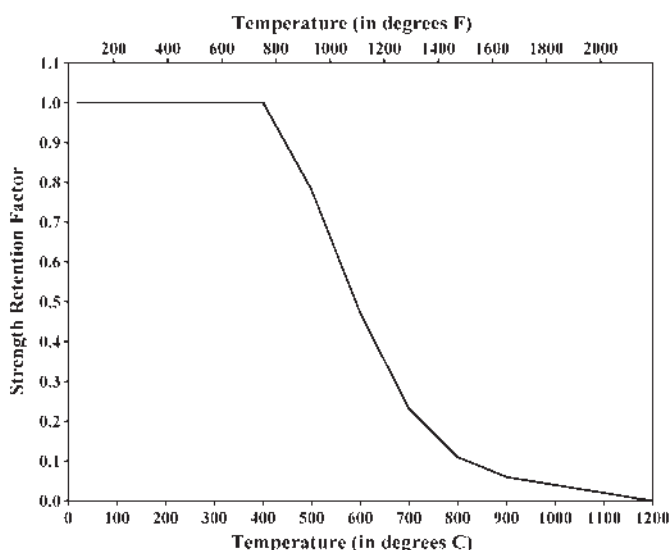


Fig. 2.1. Yield Strength Retention Factors for Structural Steel at Elevated Temperatures

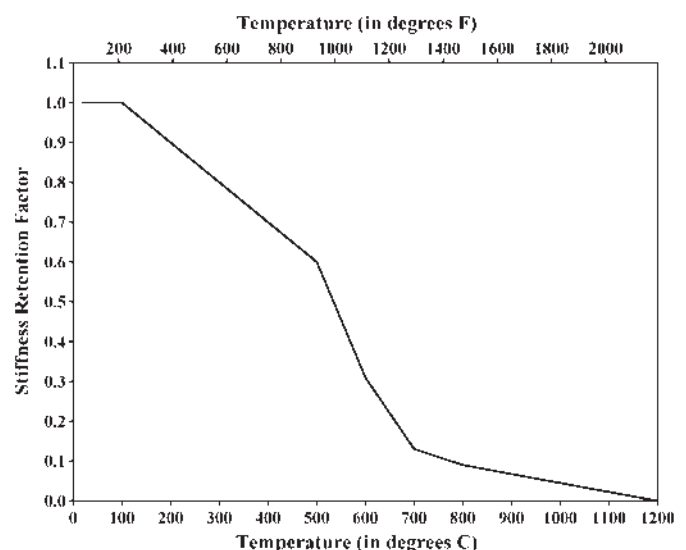


Fig. 2.2. Modulus of Elasticity Retention Factors for Structural Steel at Elevated Temperatures

2.8 Does the grade of steel used affect its response to a fire?

Common structural steel grades in the US generally exhibit similar deterioration of mechanical and thermal properties at elevated temperatures. The empirical scatter in these steel property variations is relatively minor compared to other uncertainties in fire design. Thus, the curves presented in Section 2.7 are adequate for all grades of steel.

Recently, there has been a strong effort to introduce a “fire resistant” steel grade developed in Japan. This steel has improved strength retention ratios at elevated temperatures, though similar variations in modulus of elasticity. This steel has not been widely used in the US.

2.9 How do fire protection materials function to protect steel in a fire?

Steel fire protection is achieved through one or more of the following thermodynamic mechanisms:

- Low thermal conductivity.
- High effective heat capacity.
- Heat-absorbing chemical reaction, such as endothermic decomposition or pyrolysis.
- Heat-absorbing physical reaction, such as transpiration, evaporation, sublimation, or ablation.
- Intumescence, which is the formation of a thick foam char upon heating.
- Radiation or reflection.

The common steel fire protection materials that provide one or more of these mechanisms function generally in one of three ways:

- Purely insulating—these are spray-applied fire resistive materials, such as mineral fiber and expanded aggregate coatings, such as vermiculite and perlite. UL has recently started referring to all the spray-applied fire protection coatings generically as “spray-applied fire resistive materials” (SFRM), unless they are of the mastic or intumescent type. As a result, it may now be difficult to immediately distinguish between the light and medium density, fibrous material mixed with water at the application nozzle and the cementitious materials mixed in a hopper and transported wet to the application nozzle.
- Energy absorbing—these are most commonly gypsum-based or concrete-based products, each of which release water of crystallization when exposed to high temperatures. The fire endurance time of concrete is increased by approximately 3 percent for each percent of entrapped

water (ASCE, 1992). Although gypsum is superior in this regard, concrete is a more durable material. Magnesium oxychloride cements are also in this category and contain up to 2.5 times the amount of water as gypsum.

- Intumescent—applied as paint, these coating systems expand upon exposure to high temperatures, forming an insulating layer. They are traditionally more expensive but provide many benefits, including lighter weight per surface area protected, durability, aesthetic acceptance for exposed steel, and good adhesion. They are available as both water-based and solvent-based products. These products must have adequate room to expand when exposed to the fire.

Fire protection materials could be classified as organic or inorganic depending on chemistry of their major components. Therefore, SFRM are often referred to as inorganic systems, while intumescent coatings are often referred to organic systems.

2.10 What is the composition of spray-applied fire-resistive materials (SFRM)?

Most SFRM either utilize mineral fiber or cementitious materials to insulate steel from the heat of a fire. Mineral fiber and vermiculite acoustical plaster on metal lath are two of the frequently used SFRM for on steel columns, beams and joists. These popular commercial products have proprietary formulations and, therefore, it is imperative to closely follow the manufacturer's recommendations for mixing and application.

The mineral fiber mixture combines the fibers, mineral binders, air and water. It is a limited combustible material and a poor conductor of heat. Mineral fiber fire protection material is spray-applied with specifically designed equipment which feeds the dry mixture of mineral fibers and various binding agents to a spray nozzle, where water is added to the mixture as it is sprayed on the surface to be protected. In the final cured form, the mineral fiber coating is usually lightweight, essentially non-combustible, chemically inert and a poor conductor of heat.

Cementitious SFRM are composed of a binder material mixed with aggregates. Various additives and foaming agents are also often mixed in. The common binders are calcined gypsum and Portland cement. Some formulations use magnesium oxychloride, magnesium oxysulfate, calcium aluminate, calcium phosphate, or ammonium sulfate. The common aggregates are vermiculite and perlite. Some manufacturers have substituted polystyrene beads for the vermiculite aggregate. The frequently used vermiculite acoustical plaster is a cementitious product composed of gypsum binder and perlite or vermiculite lightweight aggregates.

All SFRM products are required to be, and have been, free of asbestos since the early 1970s.

2.11 What are some common fire protection products and trade names?

Low-density inorganic systems, such as the mineral fiber Blaze-Shield II and the cementitious Monokote MK-6 SFRM products, have densities on the order of 15 lbs/ft³ (240 kg/m³) and are highly efficient and lightweight. They can be easily removed from the steel, such as by trades to mount hangers, clamps, electrical boxes, steel conduit, ductwork, and similar attachments. This ease of removal is also a concern if used in a location where activities might accidentally damage the coating. Low density products are also generally not intended for outdoor weather conditions.

Medium-density inorganic systems, such as Duraspray and Pyrocrete-LD, have densities ranging from 20 to 27 lbs/ft³ (320 to 430 kg/m³). Both of these products contain magnesium oxychloride (see Section 2.9). Medium-density inorganic systems have excellent fire resistance and serviceability.

There are also high-density inorganic systems:

- Ordinary concrete, which has a density of 100 lbs/ft³ (1600 kg/m³) for lightweight concrete and 150 lbs/ft³ (2400 kg/m³) for normal-weight concrete, is more durable, but adds weight and cost and is harder to modify in renovation work.
- Pyrok HD, Carbolite Type 40, Fendolite MII, Z-146, Albi-crete, Pyrocrete and Mandoseal products, which have densities ranging from 40 to 80 lbs/ft³ (640 to 1280 kg/m³), each contain some component that enhances its fire protective performance. For example, Carbolite products generally contain magnesium oxychloride (see Section 2.9), while Mandoseal is a vermiculite-based cementitious system.

Organic systems, also known as intumescent and mastic systems, such as Nullifire, Firefilm, Albi Clad, Sprayfilm, Thermo-Lag, and many others, are esthetically appealing and relatively thin coating systems. These products function by means of a complex series of reactions involving intumescence, sublimation, ablation, and/or heat-absorbing chemical and physical reactions. Some of these organic systems require reinforcement at the flange tips to maintain the expanded insulation in-place under fire exposure.

The suitability of a fire protection product for any specific application depends on several factors including the required fire resistance rating, expected service conditions (exposure to weathering effects, vibration, accidental impact, etc), compatibility with corrosion protection requirements (if any), esthetics and economy considerations. The manufacturers' specifications should be closely

consulted for the range and limits of their product applications.

2.12 Besides SFRM and intumescent products, what other materials/methods can be used to protect steel from fires?

The alternatives to SFRM and intumescent products include the following:

- Concrete or masonry encasement, today more of a historic approach to steel fire protection, is sometimes used when construction details involve the placement of concrete or the construction of masonry elements.
- Filling tubular steel structures columns with concrete.
- Metal lath and plaster.
- Rated suspended ceilings (for floor-ceiling and roof-ceiling assemblies).
- Enclosure in gypsum board products, mineral board products, or ceramic wool wraps.
- Reflective shielding with steel sheets.

Some more exotic fire protection methods involve remotely located exterior columns, rain screens, and water-filled tubular structures. See Section 8.7.

2.13 If fire protection is damaged, what are the consequences?

The consequences of damage to fire protection vary with the amount of damage and the nature and severity of the fire. At the extreme, both the WTC towers and the Pentagon demonstrated that extensive structural damage and widespread destruction of fire protection (spray-applied materials on structural steel in the WTC towers; concrete cover on reinforcing steel in the Pentagon) can combine for catastrophe. Localized damage due to improper application, careless renovation, or inadequate long-term maintenance is not the same.

Normally, localized damage results in higher temperatures in a segment of a structural member but does not lead to overall member failure. This has been observed in many tests performed to the requirements in ASTM E119. Likewise, the 1996 large-scale Cardington fire tests in an eight-story steel framed building demonstrated excellent performance with totally unprotected interior floor systems with bare steel beams and deck (Newman et al, 2000 and Bailey, 2001).

Even if a member were to fail, the failure of a single beam or column in a fire is highly unlikely to lead to the progressive collapse of the entire building because of the

redundancies and reserve strength inherent in the typical steel building. Most structural steel framing is governed by serviceability design criteria that result in considerable reserve strength. Alternate load paths, contribution of non-structural components, and catenary action will all usually contribute to the stability of the entire structure in the event of localized damage or overload conditions.

2.14 Can spray-applied fire protection materials (SFRM) be applied to painted or galvanized steel?

Most SFRM is configured to adhere to bare steel, galvanized steel and painted steel. There are dimensional limits in many cases, so it is recommended that the SFRM manufacturer be consulted. The manufacturer can make recommendations for galvanized surfaces and usually maintains a list of primers and paints that have been tested in accordance with ASTM E736 *Standard Test Method for Cohesion/Adhesion of Sprayed Fire Resistive Materials Applied to Structural Members*. Such tests must indicate a minimum average bond strength of 80 percent and a minimum individual bond strength of 50 percent, compared to the bond strength of the same fire resistive material when applied to bare steel. If bond strength does not meet these requirements, a mechanical bond is normally obtained by wrapping the structural member with expanded metal lath weighing at least 1.7 lbs/yd² (0.92 kg/m²).

It should be noted that Section M3.1 of the AISC Specification has long stated that shop painting of steel for buildings is not required, unless specified in the contract documents. The corresponding Commentary elucidates further on this:

“The surface condition of steel framing disclosed by the demolition of long-standing buildings has been found to be unchanged from the time of its erection, except at isolated spots where leakage may have occurred. Even in the presence of leakage, the shop coat is of minor influence.”

Thus, when acceptable, it is usually better not to prime or paint steel, both to save the unnecessary costs and to eliminate the concern for SFRM adhesion. When left unpainted, the steel surface should be clean and free of oil, dirt, and loose mill scale. See also Section 2.17.

2.15 What standards have relevance to the structural fire resistance of buildings?

ASTM E119 is the most prominent and oldest standard, which specifies test procedures to establish fire resistance ratings for assemblies and elements in buildings. ASTM E1529 is similar but intended for fire testing in exposures subject to a hydrocarbon pool fire, such as in petrochemical

refineries and similar applications. Many other relevant ASTM standards also exist:

- ASTM E84 “Standard Test Method for Surface Burning Characteristics of Building Materials”
- ASTM E136 “Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750 °C”
- ASTM E605 “Standard Test Methods for Thickness and Density of Sprayed Fire-Resistive Material Applied to Structural Members”
- ASTM E736 “Standard Test Method for Cohesion/Adhesion of Sprayed Fire-Resistive Materials Applied to Structural Members”
- ASTM E759 “Standard Test Method for Effect of Deflection on Sprayed Fire-Resistive Material Applied to Structural Members”
- ASTM E760 “Standard Test Method for Effect of Impact on Bonding of Sprayed Fire-Resistive Material Applied to Structural Members”
- ASTM E761 “Standard Test Method for Compressive Strength of Sprayed Fire-Resistive Material Applied to Structural Members”
- ASTM E859 “Standard Test Method for Air Erosion of Sprayed Fire-Resistive Materials Applied to Structural Members”
- ASTM E937 “Standard Test Method for Corrosion of Steel by Sprayed Fire-Resistive Material Applied to Structural Members”
- NFPA 259 “Test Method for Potential Heat of Building Materials”
- ASCE/SFPE 29-99 “Standard Calculation Methods for Structural Fire Protection”

2.16 How do intumescent coating systems work?

An intumescent coating, has a pre-fire appearance of a thick film of paint. When exposed to a fire, it chars, foams, and expands significantly in thickness. To retain this insulating layer, reinforcing is sometimes required at sharp corners, such as the flange tips of a wide-flange shape.

The intumescent mechanism involves the interaction of four types of compounds: a carbon source, an intumescent, a blowing agent, and a resin. The compounds of intumescent systems can generally be placed into four categories