

Determining Design Fires for Design-level and Extreme Events

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Background

Proper fire safety design requires the appropriate selection of design fires against which the performance of the building is evaluated. The selection of the design fire(s) directly impacts all aspects of fire safety performance, including the structural fire resistance, compartmentation against fire spread, egress systems, manual or automatic detection systems, suppression systems, and smoke control. In a prescriptive regulatory environment design fires were implied in the required fire resistance ratings and active system requirements, as a function of use group. As performance based regulations evolved the need to assess performance against actual conditions of use became clear. The attacks on the World Trade Center of September 11, 2001 resulted in regulatory interest in understanding the potential consequences of extreme events in addition to performance against design level events.

These regulatory needs have led to a number of efforts to develop consensus on design fires, characteristic fuel loads¹, and engineering methods to assess performance against a range of end use conditions up to extreme events. This paper will discuss ongoing activities, suggest some reasonable approaches, and hopefully serve as a roadmap for coordinating many of these activities under the auspices of CIB W14.

Design Level and Extreme Events

Design level (fire) events are those fires that are expected to occur over the life of a building for which the building is expected to meet its design safety objectives. These are often the most common fires that have occurred in such buildings, but historical experience may not be predictive of future incidents. A better approach is to determine the fires that are reasonably expected and which represent the maximum threats that should be mitigated. These could be identified through a fire hazard analysis.

Extreme events are any incidents that exceed the design level event and so are beyond that for which the building is expected to meet its design objectives. The concept is not new; it has long been a matter of public policy that, although some coastal areas design against hurricane winds well in excess of 100 mph, tornados are considered extreme events against which buildings are not expected to perform. Building regulators need to understand the potential consequences of extreme events to determine if society will

¹ This paper will discuss fuel loads and fire loads. While sometimes used interchangeably, this paper will use fuel load for mass density (kg/m^2) of combustibles and fire load as energy density (MJ/m^2) of combustibles within a space. By convention these are related by the heat of combustion of wood (18 MJ/kg).

accept these given the likelihood of the event. Such risk informed regulation is common in the nuclear power industry.

For both design fires and extreme events involving fire it is reasonable to start with an estimate of the quantity of combustibles present in the space that represent the energy content available, given an ignition. Generally this includes only items brought into the building and not combustible building materials in the same way that structural engineers design for “live loads” as the gravity load represented by contents as opposed to the “dead load” of the building itself.

Fuel (Fire) Load Surveys

Fuel loads have historically been established by surveys of typical buildings in various use categories defined by the Codes. Live loads used in structural design were established in the identical manner.

While the relationship between fuel load and fire severity was established by Ingberg in 1928 (see discussion in the next section) his first detailed fire load survey data was not published until 1942 in BMS 92. The collection of these data began in the late 1920's under the auspices of a consortium of Federal agencies known as the Central Housing Committee on Research, Design, and Construction. Ingberg continued to conduct fuel load surveys and published a second set of data in BMS 149 (1957).

When fuel loads were in vogue for determining fire severity there were several survey programs conducted to establish data for representative use categories. The National Bureau of Standards (now NIST) published fuel load surveys of residential buildings [Issen 1980], and office buildings [Culver 1976 and Bryson 1968]. A fire load survey of office buildings was also recently carried out in Finland [Korpela 2000]. A very detailed study was carried out in Switzerland in 1967-69 for the Swiss Fire Prevention Association for Industry and Trade [England 2000]. Here a minimum of 10 samples (normally more than 20) were analyzed for about 250 occupancy types. Because of its broad scope these Swiss data are often cited in modern fire engineering guideline documents.

There is one, modern exercise to gather fuel load data. A PhD student at Carleton University in Ottawa is visiting various shops (mercantile and both sit-down and fast food restaurants) to weigh contents [Hadjisophocleous 2004]. In an extension of the traditional survey, they are estimating the fraction of cellulosic, plastic, and food to provide some better estimates of combustion chemistry.

Surveys conducted in the US report the data as fuel loads and those from Europe report fire loads, but since these are related by the heat of combustion of wood they are directly comparable. Table 1 presents data from the International Fire Engineering Guidelines (IFEG 2005), BMS 92 and 149, and the Swiss studies in both fuel load and fire load by occupancy for comparison. Given that the data were collected over nearly half a century the numbers are reasonably consistent.

It should also be pointed out that fire engineering guideline documents including the IFEG caution that mean values should not be used for design since half the buildings would be expected to exceed this value. Thus they all recommend use of the 90% or 95% fractile values which are reported in most of the surveys. These values are included in Table 1.

Table 1 – Comparison of fuel (fire) load data

	IFEG Fuel Load Table (from CIB 1983)				BMS 92 (1942) & BMS 149 (1957)			Swiss data (1969)	
	Mean	95% Fractile			use Max for upper fractile			90% fractile (mean x 1.65)	
Occupancy	MJ/m ²	MJ/m ²	kg/m ²	lb/ft ²	Max (MJ/m ²)	Mean (lb/ft ²)	Max (lb/ft ²)	(MJ/m ²)	(lb/ft ²)
Dwelling	780	970	54	12	1145	8.8	14	495	6
Hospital	230	520	29	6	425	2.8	5.2	495	6
Hospital storage	2000	4400	244	54	1800	21	22	1320	16
Hotel room	310	510	28	6	1227	10.4	15	495	6
Office	420	760	42	9	1366	10.9	16.7	1320	16
Shop	600	1300	72	16	1064	9.6	13	660	8
Manufact.	300	720	40	9	1096	11	13.4	660	8
Storage	1180	2690	149	33	1497	16	18.3	825	10
Library	1500	2750	153	34	2888	18.8	35.3	3300	40
School	285	450	25	6	916	9.4	11.2	495	6

Another important point about these survey data is that spaces containing libraries in schools or legal offices have fuel loads more like libraries than like offices, and spaces used as storage rooms in hospitals or manufacturing have fuel loads more like storage occupancies.

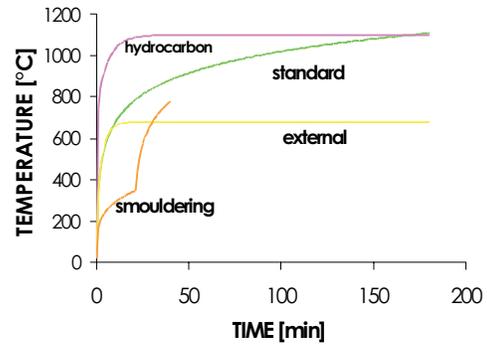
Table 2 Fire Severity for Various Fuel Loads

Fuel Load (lb/ft ²)	Fire Severity (hours)
5	½
10	1
15	1 ½
20	2
30	3
40	4 ½
50	7
60	8
70	9

Fire Severity and Fire Load

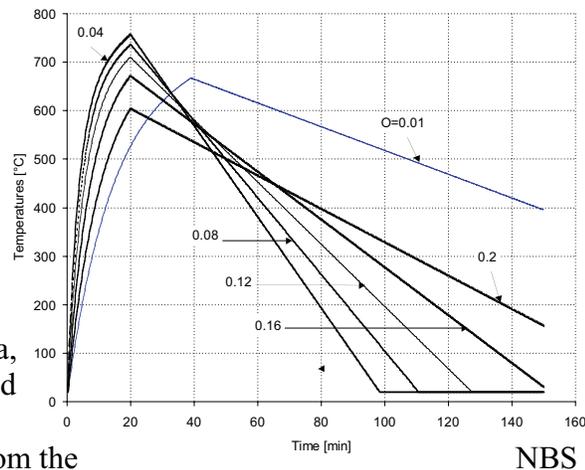
The first design fire applied in regulation was the standard time-temperature curve from ASTM E119, first published in 1918. Contrary to popular belief the curve originated in 1917 as the recommendation of a committee [Babrauskas 1976] and was verified experimentally by the Federal Triangle burns [Ingberg 1928] in the 1920's. These tests used stacks of wood pallets to represent the fuel load of typical office occupancies of the

time. Since offices of the day were filled with wooden furniture and paper, this was not much of a stretch. This led to the empirical relationship between fuel load, fire duration, and resistance in units of time still used today.



Ingberg's key finding was the correlation between fuel load and fire duration shown in Table 2. The duration of the fire was referred to as the fire severity (in hours) and represented the time needed to consume most of the fuel in the compartment, assuming no attempt to extinguish the fire. At that time the effects of ventilation, the form of the fuel (which affects the rate of burning) and heat losses to boundaries were not recognized. Ingberg's concept was that under this worst case condition (no suppression), all the combustibles in the compartment should be consumed without causing failure of any structural member passing through that compartment (burnout without local or global collapse).

Based on this idea, a system of required fire resistance ratings related to building characteristics was proposed by NBS (now NIST) in the landmark BMS 92 (1942). This document first proposed the modern system of construction classification, including Type I (Fireproof), Type II (Incombustible), Type III (Exterior Protected), and Type IV (Wood), each being subdivided into several sub classifications based on building height and uncomparted area, and on building use. All of this was related to accepted practice at the time in six U.S. cities, and fuel load data were provided from the fuel load surveys conducted in residences, offices, schools, hospitals, and warehouses.



Not much happened to these fundamental concepts until the development of the Eurocodes when the EU Construction Products Directive called for the "robust solution" needed for performance based regulation. Clearly the ASTM E119/ISO 834 approach did not provide the data needed to assess performance in end use conditions. After many years of work the Europeans developed a set of time temperature curves to be used in furnace testing (figure 1) and *parametric fires* (figure 2) to be used as design fires in compartment fire models [Eurocode 1 1994].

Total Energy vs. Rate of Energy Release

The traditional method of establishing design levels is from experience. Expected performance in fire is based on the typical fires that have occurred with special emphasis on specific fire incidents of note. Early work on fire severity [Ingberg 1928] led to the correlations between fuel load and fire time shown in Table 2. It was generally held that the standard time-temperature curve represented a limiting condition for a ventilation controlled fire with typical fuel loads and ventilation characteristic of most buildings. Ingberg's objective was for the building to withstand the total burnout of any compartment without resulting in partial or total collapse by failure of structural members passing through that compartment.

The critical role of ventilation was recognized by individuals like Phillip Thomas and Margaret Law, who suggested that the fire load per unit window area might make a better design parameter [Thomas et al, 1967²]. Law, like Ingberg wrote of designing spaces so that they could suffer complete burnout without local or global collapse. She [Law 1971] and Thomas further refined the approach to account for the effects of compartment ventilation and heat loss to boundaries by adding terms for each to the fire severity equation as shown below. A few years later Gross suggested the Thomas enhancement to account for heat losses and ventilation [Gross 1977]. The so-called *effective fire resistance* is defined as:

$$T_f = KL/A_f \times A_f/(A_w A_t)^{1/2} \text{ (min)}$$

Where: T_f is the effective fire resistance (min)
K is approx 1.3 (range 0.7 to 1.5) (m^2/kg)
L is the fire load (kg)
 A_f is the floor area (m^2)
 A_w is the ventilation area (m^2)
 A_t is the area of compartment surfaces
to which heat is lost (excluding the
ventilation area) (m^2)

Things started to get more complicated with the introduction of synthetic materials into common use. Most plastics have twice the heat of combustion and burn with a higher radiative fraction that accelerates fire development. The development of heat release rate measurements provided the ability to measure energy as an extensible property that explained what was happening. The shortcomings of fuel load became apparent; that the rate at which energy is released can vary greatly for the same fuel load depending on the fuel characteristics (a solid block of wood will burn very differently from a wood crib or a pile of sawdust, each of which may represent the same fuel load).

Heskestad and Delichatsios [Heskestad 1978] saw that the growth phase of flaming fires generally followed a polynomial curve with most fuels reasonably described by the so-called t-squared (or αt^2) form. First applied in the design of detection systems, the

² It is interesting to note that in this paper Thomas observes, "one can, in principle, write a heat balance equation from which the temperature-time variation [in the compartment] could be evaluated if one knew the rate of heat release as a function of time." In this statement Thomas predicted the modern fire model.

description of design fires as t-squared fires soon caught on. For the first time it was possible to select design fires based on the potential energy release of the fuel found in actual use rather than for fuel types and concentrations “typical” of the use group. Designing for the potential fire permits fuel control to be a viable design alternative but raises the issue that future uses of the space would be bound by the fuel limits incorporated into the design – a longstanding problem with storage occupancies where changes in the stored commodity can sometimes overwhelm the installed protection.

Estimating Design Fires

In a performance analysis, fire duration is not sufficient since it is the early stages of the fire that most affect the objectives of life safety for the occupants and minimizing property damage for the owner. The structural engineers want to define fire as a building load (like the others with which they deal) so that they can design the structure to resist that load. The problem is that fire is not a load. It starts out affecting one compartment (like a concentrated load) but can spread to eventually affect the entire building. Further, fires are strongly affected by the building itself, especially ventilation, but also heat losses and the existence of active and passive fire protection features.

In fact, fire is a stochastic event that is highly dependent on the conditional probabilities of mitigating factors, planned and unplanned. Simply examine any major fire incident and you will see that the event was driven by a series of multiple things going wrong. The fact that there are many places in the path for a growing fire to be stopped is the reason that major fires are rare events. This observation led to the specification of generic design fire scenarios in the performance option of the NFPA Building Construction and Safety Code (NFPA 5000).

In the National Fire Protection Association’s new building code, NFPA 5000 [NFPA 2003], design events, including design fires are described in generic terms. For example, “... an ultrafast-developing fire, in the primary means of egress, with interior doors open at the start of the fire.” would need to be translated into an appropriate heat release rate and species production rate(s) accounting for the specifics of the building geometry, ventilation, and typical fuel characteristics. Similar design events are described in NFPA 5000 for seismic, wind, and other loads.

Fire as a Building Design Load [Bukowski 2001]

The key to describing design fires as a building design load may be in terms of its impact on the building while accounting for the impact of the building space on the fire. One possible approach was developed as part of the National Fire Risk Assessment Research Project [Clarke 1990] to deal with the translation of National Fire Incident Reporting System (NFIRS) extent of flame spread categories into design fires (heat release rates) for specific prototypical buildings. The approach was to define a fire that was confined to the object of origin as one whose heat release rate was sufficient to result in a steady state upper layer temperature of 100 °C. This upper layer temperature would result in a radiant flux to other combustibles in the room of about 1 kW/m² which is insufficient to drive flame spread on most materials. Similarly, a heat flux of 3 kW/m² would typically drive flame spread only near the object of origin where the flux from the flame provides

additional drive for flame spread. A heat flux of 15 kW/m² may ignite other objects in the room but is below flashover. A heat flux of 25 kW/m² is characteristic of flashover that would result in flames out the door and spread to the adjacent compartment.

Table 3 - Maximum upper layer conditions associated with extent of flame spread classes

Extent of Flame Spread Class	Radiant Flux from the Upper Layer (kW/m ²)	Maximum Upper Layer Temperature (°C)
Confined to Object	1	100
Confined to Area	3	200
Confined to Room	15	450
Beyond Room	25	600

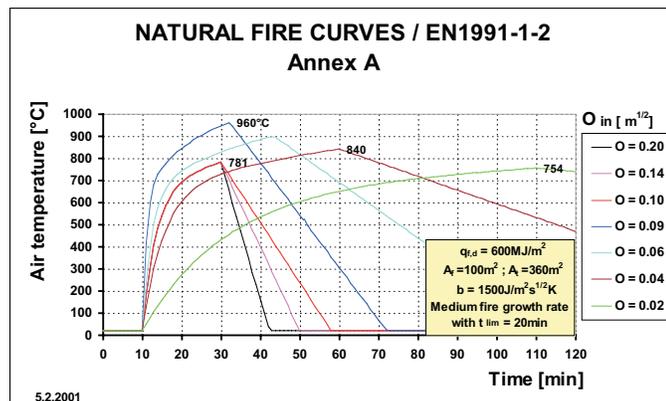
With these definitions, the maximum (steady state) upper layer temperature can be related to a heat release rate for a specific room geometry, bounding materials and ventilation conditions by any one of several calculations ranging from simple equations like the MQH Correlation [McCaffery 1981] to compartment fire models. The process is not unlike the determination of dead load where the weight of building elements is determined after a preliminary structural design has identified the size of element needed to support the other loads.

This approach allows the fire to be defined in terms of its impact on the space of origin, in the manner of a load to which the building can react. The association to the NFIRS extent of flame spread class establishes the statistical distribution frequency or return frequency analogous to natural hazards and allows the specification of fire loads for varying frequencies of events. The primary limitation of this approach is that, where the extent of flame spread is less than the room, the incident data does not indicate if this was due to limited fuel, the operation of an automatic suppression system, or random discovery by a person who initiated manual suppression. But in the end it should not matter how the fire load was limited but only that it was.

Natural Fires

In 2001 a report [CEC 2001] was published in Europe on what was termed the Natural Fire Safety Project with the objective to “establish a more realistic and more credible approach to analysis of structural safety in case of fire that takes account of active fire fighting measures and real fire characteristics.” This is a risk based system (accounting for probability of ignition and success of active measures) that accounts for building characteristics, fire scenario, fire load, pyrolysis rate, compartment, and ventilation. The result is a design fire (heating curve) as a function of the fire load, and the time to structural failure due to fire (which may be infinite) that can be compared to evacuation time and the consequences of the failure.

This process is thorough and well conceived, with linkages to the Eurocodes' parametric fires (see Figure 3). They utilize zone models to calculate fire development, transferring the fire environment to structural models that assess the stability of the structure. Recent advances that automate this linkage [NIST 2005] should make the process easier, although there is a computational burden to the more sophisticated models employed.



Extreme Events

In the modern world of terrorist threats building regulators in many countries have incorporated risk-informed regulation for extreme events into their duties. Extreme events are those that exceed normal design levels established as a matter of public policy. Consequences of extreme events may exceed normally accepted public safety objectives but consequences should be commensurate with the likelihood of the event.

Designing for extreme events follows the same process as for design level events except that the events themselves represent credible threats suggested by the intelligence community. In addition to conventional bombs these often include chemical, biological, and radiological threats for which buildings need to provide some level of protection.

Suggested approaches for Regulation

Since the fuel (fire) load density represents the quantity of combustibles expected to be present in the space, this is a reasonable basis for design level fires. Using the 95% fractile provides necessary conservatism. Incident statistics can be used to determine expected scenarios and ignition sources for the normal use of the building. Thus the Natural Fires approach [CEC 2001] or the similar "fire as a building design load" approach [Bukowski 2001] should provide similar results. Since most significant fires burn at the ventilation limit for most of their course, the specified fuel load burning at this limit will provide the design fire intensity, with excess fuel burning in door vents and out windows. Modern fire models make the link from fuel (fire) load density to a time-temperature exposure in any compartment.

Several scenarios should be examined for any building use. The National Fire Protection Association (US) developed a general set of fire scenario descriptors which are included in the performance-based design chapter of their Building Construction and Safety Code (NFPA 5000) and Life Safety Code (NFPA 101). Another approach is to run numerous fire hazard scenarios using zone models to identify risk significant scenarios for more detailed analysis with *cf*d models. Sensitivity to variations in specified input parameters should follow, again using the zone models. [Bukowski 2004, Notarianni 2000]

Note that in a number of occupancies, fires involving “unusual” fuel loads associated with tenant modifications, general construction or renovation, or maintenance and repair, while rare, can result in significant losses. Since building codes normally regulate initial construction, renovation, and demolition, such fire scenarios would be considered design events and not extreme events.

Extreme events are rare but of interest because they may result in high consequences. In most cases an extreme event begins with some unusual initiating event (e.g., airplane crash, terrorist attack, explosion, natural disaster) which in some way leads to:

- The presence of additional fuel which acts as a large area ignitor or high fuel load,
- The availability of significantly higher ventilation that supports unusually high burning rates, or
- Other things going wrong, such as protection features failing to operate as intended, or
- Structural damage resulting from the initiating event.

All of these were observed in the September 11, 2001 attacks in New York. The aircraft deposited fuel into WTC 1 and 2 which acted as a large ignition source for the building contents, they made large holes in the building envelope which supported burning rates an order of magnitude higher than the normal building ventilation, and they severed the sprinkler system risers and destroyed two of three stairways in one building and all three in the other [NIST 2005a].

Deciding scenarios for extreme events is more problematic since they will generally involve events that have not yet occurred. For buildings located near airports the aircraft crash might be appropriate. Today, vulnerability to explosives is assessed in terms of the limiting size of device that could evade the security plan for the building.

Concluding Remarks

Both prescriptive and performance based regulation will benefit from a more explicit treatment of design fire events as this will permit a more holistic treatment of the building performance. The use of fuel (fire) load remains reasonable as this represents the total potential energy that can be released within the building once ignited. However modern understanding of fire dynamics underscores the need to account for the rate of heat release and the influence of ventilation and heat losses on this rate. These effects can be included simply, as in the algebraic equation suggested by Thomas and Law, or by the application of modern fire models within the construct of the Natural Fires or building load approaches discussed herein. It is also possible to conduct extreme events analysis in a way that meets the growing need for risk informed regulation.

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