# FIRE AS A BUILDING DESIGN LOAD

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# FIRE AS A BUILDING DESIGN LOAD

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*SUMMARY*

***The concept of designing buildings to resist loads is fundamental to the design and regulatory process. Fire has traditionally been addressed differently because fires are difficult to describe in the same way as other building loads. This paper proposes a way of adjusting generic design fires to the specifics of a bidding to result in a design load that is consistent with other design loads and to which safety factors can be applied. This capability is especially useful in addressing risk management and performance-based regulatory systems.***

## BACKGROUND

Structural design involves the specification in Codes of appropriate loads and the design of a building to resist those loads. Some of these loads, such as dead load, live load, and snow load, are static. Others, such as impact load, wind load, and seismic load are dynamic. But each acts on the building as a whole and (except for the dead load) is not affected by the building itself, although some are affected by the local conditions at the building site. Each has a characteristic value that in some cases is selected from a statistical distribution over time. And each leads to design characteristics that resist the applied load and to which safety factors can be applied to address uncertainties in the materials, assembly, and the loads themselves.

Fire has always been different. First, fires do not act on the entire building but rather on Individual spaces. This localized effect of the fire leads to significant differences in consequences depending on the building components and contents present in the fire's location. The fire is strongly influenced by the geometry, ventilation, and contents of the space in which it occurs. While it is possible to determine a statistical distribution of historical fire severity, this eventual severity is strongly dependent on many mitigating factors, and nearly every small fire has the potential to grow to a large state or to be stopped at any stage by any of a long list of factors.

These issues make the specification of appropriate design fires a significant problem in the context of performance-based designs under either performance codes or under the equivalency clause in prescriptive codes. The interrelationships between structural design and fire protection make it highly desirable to find a way to treat fire as yet another building design load, at least for the protection of the building itself from the fire's effects. Additionally, in a performance system it is highly desirable to be able to describe a range of design fires for which a given building design is required to perform. This is clearly demonstrated by the Design Performance Levels concept incorporated into the draft International Code Council (ICC) Performance Code for Buildings and Facilities[1] currently in the adoption process in the U.S.

## THE CONCEPT OF BUILDING LOADS

The provision of structural safety in buildings is based on the specification of loads that the building is **required** to resist'. The use of loads as a means to regulate structural safety (what structural engineers call the ***limit state design*** method) has two components. First is the definition of a load including how it acts on the building and the related engineering analysis and design methods. This includes the selection of safety factors to compensate for inherent uncertainties that are established by the engineering and design communities with the concurrence of the regulators. These are "best practice" Issues that are addressed by the professions and regulated through professional licensing. Second is the establishment of acceptable criteria as a public policy decision expressed in regulation. Because perfect safety can never be achieved, it falls on the regulators to establish how safe is safe enough for society.

The simplest of building loads are the "gravity" loads. The ***dead load*** is the weight of the building itself and the ***live ioad*** is the weight of the contents and occupants. The expected use of the building generally dictates the typical live load for which it is designed, accounting for contents and occupant loads. Special provisions are often made for specific items that may be particularly **heavy** – for example libraries or file **room** in offices or large machines in a manufacturing facility. Since the structural elements have to be ***sized*** to *carry* these loads, the dead load is computed after the other loads are determined and the size and weight of the structural elements can be determined. All of these "gravity" loads act on the building only in the vertical direction.

Uncertainty in both the specification of loads and the actual strength of materials is addressed in structural engineering by applying safety factors to both the load and to the material properties. The safety factors used are selected to be large enough to account for the estimated uncertainty and additional safety factors, like the so-called *importance factor*, may be applied for especially important or hazardous buildings.

Some loads are determined by statistical distribution of hstorical **data** in the building's location. Wind load is determined **fiom** weather **data** for the area and is (mostly) a horizontal load on the building. Most U.S. codes require a building to resist wind loads without damage representing the maximum wind expected in any 50 year period, such limit being a public **policy** decision balancing cost with public expectations. In coastal areas these design winds may include hurricane speeds, but in **areas** subject to tornados, buildings are not expected to resist a direct hit **as** a matter of public policy because such is considered impractical.

Seismic design loads have been the subject of considerable study and public policy debate. Design loads specified in the Codes are derived **fiom** the historical seismic activity in a geographic region but for significantly longer return periods than for any other natural hazard. **While** buildings are designed **to** withstand a 50 **year** wind and a 100 year flood, a common seismic requirement is to design for a 475 **year** earthquake. But again, such are public policy **decisions** that are separate and distinct from any technical issue and not within the purview of the designer, engineer, or code official.

The result is a system that is well suited to performance-based regulation. Qualitative objectives (e.g., no structural collapse) can be translated into quantitative design loads by policy makers and then applied by designers in a rational way that accounts for uncertainty. Statistically, failures are rare and generally attributable to older structures exhibiting known shortcomings that have not been addressed due to cost or to enforcement issues.

## MANAGEMENT OF RISK

The Design Performance Level method implemented in the ICC Code provides a means to assess and manage risk from multiple threats to the building, occupants, contents, and society including those from fire, by a common approach that specifies multiple levels of performance for each threat. Performance groups replace the traditional Use Groups as a means to specify the societal level of risk acceptance for each of four levels of magnitude of design event. This approach also allows regulatory review to be triggered by a potential change in risk rather than a change in use. This is more desirable because a change in use does not necessarily result in a change in risk, and changes that do not involve a different use class may result in a significant change in risk.

Figure 1 MAXIMUM LEVEL OF DAMAGE TO BE TOLERATED BASED ON PERFORMANCE GROUPS AND DESIGN EVENT MAGNITUDES

INCREASING LEVEL OF PERFORMANCE

→→→→→→→→→→→→→→→

PERFC I

MAGNITUDE OF DESIGN EVENT

INCREASING MAGNITUDE OF EVENT

| | Performance Group I | Performance Group II | Performance Group III | Performance Group IV |
|---|---|---|---|---|
| VERY LARGE (Very Rare) | SEVERE | SEVERE | HIGH | MODERATE |
| LARGE (Rare) | SEVERE | HIGH | MODERATE | MILD |
| MEDIUM (Less Frequent) | HIGH | MODERATE | MILD | MILD |
| SMALL (Frequent) | MODERATE | MILD | MILD | MILD |

The table relating performance group, magnitude (and implied frequency) of event, and maximum tolerable damage fiom the draft ICC Code is shown in figure 1. This approach to risk management deals with the performance of the building for fire and natural hazards in a consistent way by separating the design loads into continuous (dead and live loads that define the basic structural design) and occasional, peak loads associated with events that can be expected to occur at some statistical frequency. This is convenient from a regulatory viewpoint because only the latter class of loads require public policy decisions about the acceptable design thresholds. Thus it is desirable to be able to describe fire as an occasional building load in the same context as wind or seismic loads.

The risk management matrix also introduces a complication by specifying multiple levels of performance. That is, the applied loads are not simply the "worst case" loads associated with the most severe (and least frequent) events. Rather it is necessary to assess building performance for several levels of load associated with events of differing frequency. **As** was previously discussed the establishment of each of these thresholds is outside the scope of the engineering and design community because it is a public policy decision reflecting a balance between the public expectations for the built environment and the costs associated with this performance that society is willing to bear.

## DESIGN FIRES

Another approach to specifying performance levels is the description of design events for which a specific level of building performance is expected. In the National Fire Protection Association's new building code, NFPA 5000[3], 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. Thus this too would require the specification of a fire load sized to result in the desired impact on the specific building under analysis. Similar design events are described in NFPA 5000 for seismic, wind, and other loads.

## LOADS ASSOCIATED WITH EVENTS

Occasional loads (snow, wind, seismic) associated with specific events occur with some statistical fiequency and magnitude over different time scales Each load affects the building in specific ways; snow load is a static load acting uniformly over horizontal surfaces, wind load is dynamic and produces a load that varies with height in a predictable way, and seismic loads are dynamic and act as accelerations in any plane applied to the base of the building. A common characteristic of each of these is that the load associated with an event is independent of the building to which the load is applied. This is not the case with fire where the growth rate and eventual size is strongly a function of the building, its contents, and fire protection features. In theory, any small fire can become a large fire if nothing intervenes and a large fire in a small space results in a very different load than the same large fire in a large space.

## ESTIMATING THE LOAD IMPOSED BY A FIRE

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 Project4 to deal with the translation of 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 $kW/m^2$ which is insufficient to drive flame spread on most materials. Similarly, a heat flux of 3 $kW/m^2$ 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** $kW/m^2$ may ignite other objects in **the** room but is **below** flashover. **A** heat **flux** of 25 $kW/m^2$ is characteristic of flashover that would result in flames out the door and spread to the adjacent compartment.

**Table 1 - 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 Obiect | 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 fiom simple equations like the MQH Correlation5 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.

## ESTIMATING THE FIRE LOAD

The fire load that the building is required to resist is defined as **a** thermal stress (steady-state upper layer temperature) resulting from a fire within **a** building space. The energy needed to produce the target temperature is a function of the geometry, heat losses, **and** ventilation of the space and can be estimated in a number of ways. One such way is presented below.

McCaffery et *al*[4] presents their equation 10a,

$$Q = \left\{ \sqrt{g}\, c_p \rho_0 T_0^{2} \left( \frac{\Delta T}{480} \right)^2 \right\}^{1/2} \bullet \left\{ h_k A_w A_0 \sqrt{H_0} \right\}^{1/2}$$

| Upper Layer Temperature (°C) | C |
|---|---|
| 100 | 38 |
| 200 | 130 |
| 450 | 480 |
| 600 | 750 |

Using these constants the equation can be used to determine the (asymptotic) values of Q that would result in each upper layer temperature for any compartment geometry and ventilation of interest. Typically the designer would use a so-called T-squared heat release rate curve with a growth rate (slow, moderate, fast, or ultrafast) consistent with the nature of the combustible materials that would be found in the space (see figure 2).

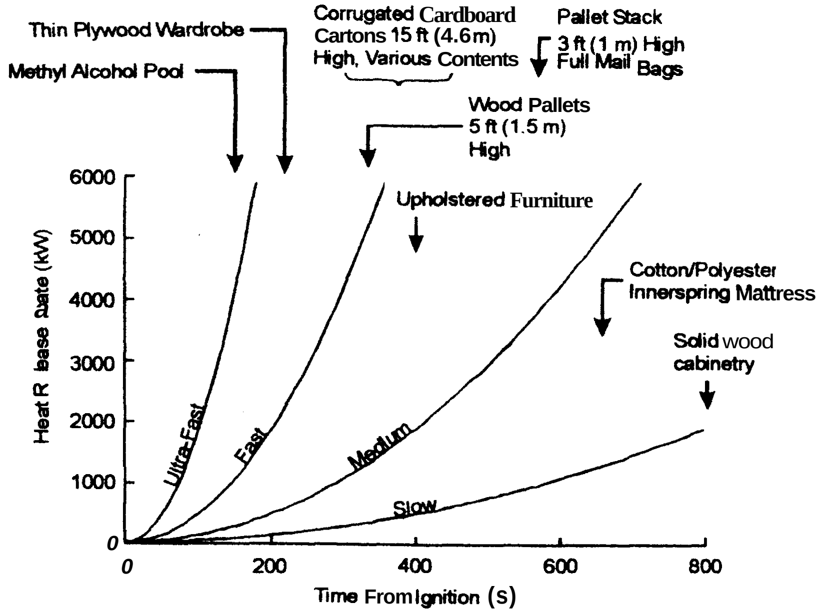
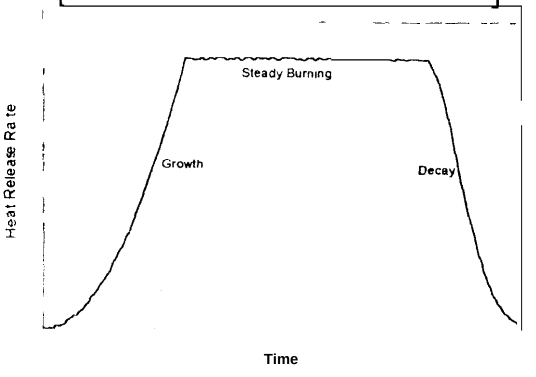


Figure 2 – T-Squared Fires with Related Materials

**Figure 3 – Generalized HRR Curve**



The value of Q associated with the desired upper layer temperature is used to determine the plateau value for the transition to steady burning The duration of the steady burning phase is based on the quantity of fuel present, continuing until 80% (the usual convention) of the fuel is consumed at which time the decay phase is assumed to be the inverse of the growth phase.

In using this equation, $h_k$ is the effective heat transfer coefficient through the ceiling/walls and is discussed at length by McCaffery[5] For long times it reduces to k $\delta$ and this simplification should be appropriate for estimating structural fire resistance For evaluating effects that may occur over short times the more detailed treatment as shown in the reference (see their Table 3) may be needed For ventilation through multiple openings the sum of the $A_0\sqrt{H_0}$ values would be used

## EXAMPLE DETERMINATION OF FIRE LOAD

Consider a compartment of origin that measures 3m x 3m with a ceiling height of 2.4m and a single opening 1.8 m high by 0.6 m wide. The walls and ceiling are 0.016 m gypsum plaster on metal lathe. We wish to determine the design fire curve for small, medium, large, and very large fire events.

The equation used to determine the steady state heat release rate is,

$$Q = C \bullet \{ h_k A_w A_0 \sqrt{H_0} \}^{1/2}$$

where:

$h_k = k/\delta = 0.03$ kW/m K
$k = 0.48 \times 10^{-3}$ kW/m C
$\delta = 0.016$m
$A_w = A_{walls} + A_{floor} + A_{ceiling} - A_{openings} = 4 \times (3 \times 2.4) + (3 \times 3) + (3 \times 3) - 1.08 = 45.72\ m^2$
$A_0 = 1.8 \times 0.6 = 1.08\ m^2$
$H_0 = 1.8$m
C = a constant derived for the upper layer temperature in the compartment of interest

Evaluating the equation for the four events gives the results shown in Table 3

**Table 3 – Fire Loads for Fire Events in a Small Office**

| Event | Upper Temp (°C) | C $\left(\frac{kW \bullet K}{m^{5/2}}\right)^{1/2}$ | Max Q (kW) |
|---|---|---|---|
| Small | 100 | 38 | 53 |
| Medium | 200 | 130 | 183 |
| Large | 450 | 480 | 676 |
| Very large | 600 | 750 | 1057 |

These results make sense in that the small event in an office-sized room at about 50 kW is the typical trash can fire that does not spread beyond the trash can unless there is direct flame contact with other combustibles. The medium event at under 200 kW might be enough to ignite a nearby object by radiation but is unlikely to spread. The large event at nearly 700 kW would be likely to spread and the very large event at more than 1 MW would flash over the space. Thomas' flashover correlation[6] applied to this room yields a minimum flashover energy of just over 900 kW.

Increasing the space to a "bull pen" office of 30 m by 30 m with four single doors would increase the maximum heat release rates for the four events to 722, 2420, 9120, and 14250 kW, respectively. Again, these appear to be reasonable for a space this large.

## ESTIMATING BUILDING IMPACT TIME

The method described above results in a design fire (heat release rate) curve that results in a level of impact on the building, contents, and occupants. While the impacts on contents and occupants are usually immediate, impacts on the building (e.g., structural) may require time for heat transfer through covering materials. Here the concept of *thermal penetration time* discussed in reference 5 can be useful This is the time needed for the heat pulse to penetrate a thermally thick compartment boundary. The equation is given as:

$$t_p = \frac{1}{\alpha}\left(\frac{\delta}{2}\right)^2$$

where:

a = thermal diffusivity k $\rho c$ (m$^2$/s)
S = thickness (m)

This thermal penetration time then represents the time delay to exposure of the covered structural element. While there would be a thermal gradient through the covering material a conservative assumption would be to neglect this. Thus, following the thermal penetration time the structural element could be assumed to be at the temperature of the exposed side.

## LIMITATIONS OF THE METHOD

Use of the upper layer temperature in the compartment of origin as the metric for the fire load should be generally appropriate but the methods of relating that temperature to a heat release rate are subject to various limitations. The method described in this paper, based on the MQH correlation, is subject to the limitations of that method.

The MQH correlation has been shown to be robust for predictions up to flashover or to ventilation controlled burning'. The database from which the correlation constants were derived includes over 100 experiments at full- and reduced scale, and for a range of fuels including gas burners, wood and plastic cribs, and furniture items. The method overpredicts temperatures as the ventilation parameter approaches zero, so it should not be used where the ventilation is only through cracks or undercuts. The method should not be used for highly conductive (e.g., metal) walls.

The method should work well for horizontal room dimensions up to 30 or more meters, but should be highly sensitive to ceiling height. As ceiling height increases the entrainment height of the plume increases, rapidly reducing the plume and upper layer temperatures. Further, the concept of the upper layer temperature as the metric for the load depends on radiation fiom the upper layer driving ignition and flame spread in the lower part of the room. A taller room will decrease the flux to the floor fiom the upper layer by the square of the height. Thus this approach should only be used for "normal" ceiling heights (about 5 m or less).

Outside of the limits suggested above it is possible to use appropriate fire models iteratively in order to estimate the heat release rate needed to produce a specific upper layer temperature or heat flux to the floor. The CFAST model' predicts both of these parameters, directly and contains the appropriate physics for use in tall spaces.

## CONCLUDING REMARKS

The concept of loads as impacts to which a building design reacts is fundamental to the design and regulation of building safety. Safety factors are applied to loads and to material properties as a method of addressing uncertainties. Regulatory officials have comfort with these methods and experience in the U.S. with the practical application of these techniques is outstanding. This paper suggests a way of addressing fire as a building load in a manner that is consistent with the way in which other loads are used in the design process.

The application of this concept in practice has been demonstrated with a simple estimation technique based on the well-accepted MQH correlation. This allows the rate of heat release for a design fire to be adjusted for the specifics of the space of origin to result in a specified impact (load). This simple method is suitable for spaces of common size and other engineering methods exist to address larger or more unusual spaces. Thus the method should be practical for use in a broad range of performance-based design and regulatory applications.

## NOMENCLATURE

a = Thermal diffisivity of **ceiling/wall** material = k/ρc ($m^2/s$)
A,= Area of opening = $W_o$ x $H_o$ ($m^2$)
Aw = Compartment surface area minus area of openings = 2(L x H + L x H + **H** x W) – $A_o$ ($m^2$)
C = a Constant derived for the upper layer temperature in the compartment of interest
$c_p$ = Specific heat of air ($c_p$ = 1.0 **kJ** $\mathbf{kg^{-1}\ K^{-1}}$)
g = gravitational constant (9.8 $m/s^2$)
$h_k$ = effective heat transfer coefficient = k/δ (kW/m K)
k = Thermal conductivity of walls/ceilings (kW/m C)
δ = thickness of walls/ceilings (m)
$\rho_0$ = Ambient gas density, 1.2 $\mathbf{kg/m^3}$)
T, = Ambient temperature (22 **°C** or 295 **°K)**
T = Temperature ( °C or °K)

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