PREDICTING THE FIRE PERFORMANCE OF BUILDINGS: ESTABLISHING APPROPRIATE CALCULATION METHODS FOR REGULATORY APPLICATIONS

by

Richard W. Bukowski
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

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PREDICTING THE FIRE PERFORMANCE OF BUILDINGS:
Establishing appropriate calculation methods for regulatory applications

Richard W. Bukowski, P.E.
Senior Research Engineer
NIST, Building and Fire Research Laboratory
Gaithersburg, MD 20899 USA

Abstract

A recently organized effort in the International Council for Building Research, Working Commission 14 (CIB W14), on Engineering Evaluation of Building Fire Safety is examining the various quantitative methods being developed to underpin performance-based codes or for determining equivalency with the implied performance of existing prescriptive codes. These methods share many common features and all recognize the range of fire models and calculational methods that the fire safety engineering profession have begun to embrace as their technical foundation.

The broad range of assumptions inherent in the available methods as well as the data required to utilize them raises some interesting questions about their appropriateness in applications to code-regulated situations. Many fire-related computations have inherent uncertainty because of lack of understanding of the physics. Thus, one can ask, where a code defines a minimum level of performance, how far must the fire safety engineer go to minimize uncertainty in a calculation intended to verify compliance? The variability of fire means that there are no unique answers against which to define accuracy; and fire experiments involve measurement uncertainties as well as approximations used to reduce the data which often have similar form to the calculations we wish to verify.

These methods all focus on managing fire risk, and their successful application depends on assessing the acceptable level of risk implied by the current codes. Some argue that the lack of a public outcry over fire losses is not a tacit acceptance of those losses by society. Thus, how can acceptable levels of risk be determined when regulatory authorities and legislators are uncomfortable with the notion that there is no zero risk so some fatalities are inevitable?

This paper explores these questions from the perspective of the fire scientist, the practicing engineer, and the regulatory official. The fire scientist needs to be explicit about the impact of assumptions on the applicability of the results. The engineer needs to utilize methods and assumptions which are justified by the application and to assess the sensitivity and uncertainty implications. The regulatory officials are insisting on appropriate and properly documented methods. There is a need for models and calculations incorporated into codes of practice, handbooks, or the codes themselves to be reviewed, verified, documented, and approved for use in specific manners and by qualified persons. There are international efforts to define levels of risk acceptable to society in specific occupancies. Until these points are addressed, the transition to performance-based codes cannot be made with confidence.

Introduction

The use of fire models and other predictive methods is becoming a common means of supporting the design and arrangement of fire protection features to code officials. In the U.S., typically this is done under existing provisions in the codes for "equivalency" to the prescriptive requirements therein. In many countries, more formalized systems of

performance evaluation are under development which are envisioned to provide the means to establish compliance with performance-based codes [1].

The use of performance-based evaluation methods is most prevalent with respect to unique buildings or large projects where variation from normal practice is most common. The result is that the code official, faced with the application of a new engineering method in a high profile project, can experience discomfort without some independent verification that the analysis has been done properly.

Selecting Appropriate Models/Methods

Fire Models

A recent survey [2] documented 62 models and calculation methods that could be applied to these uses. Thus there is a need to determine which ones are appropriate to a given situation and which are not. The key to this decision is a thorough understanding of the assumptions and limitations of the individual model or calculation and how these relate to the situation being assessed.

Fire is a dynamic process of interacting physics and chemistry; so predicting what is likely to happen under a given set of circumstances is daunting. The simplest of predictive methods are the (algebraic) equations. Often developed wholly or in part from correlations to experimental data, they represent at best, estimates with significant uncertainty. Yet under the right circumstances they have been demonstrated to provide useful results; especially where used to assist in setting up a more complex model. For example, Thomas' Flashover correlation [3] and the MQH Upper Layer Temperature correlation [4] are generally held to provide useful engineering estimates.

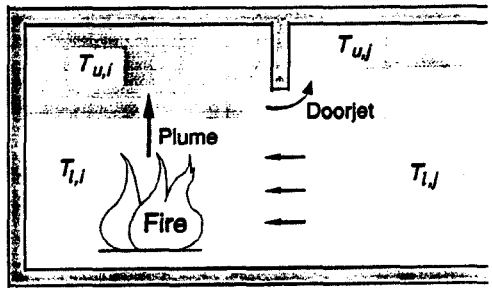
Many of the methods under development to support performance-based codes cite these algebraic equations as examples of how specific parameters in a sequence of calculations can be obtained. Such explicit inclusion implies that these methods are suitable for this purpose, which may not be the case. For example, the Draft British Standard Code of Practice [5], includes many such algebraic equations within each of its subsystems. The Japanese methodology [6] however, cites the predictive equations in their fully dynamic, partial differential form. From a technical viewpoint, the latter form is more appropriate where the steady-state solution would not produce sufficient accuracy.

Where public safety is at stake, some regulatory officials are beginning to question the appropriateness of relying solely on simple estimation techniques for the fire development/smoke filling calculation; rather, requiring that only fire models should be used. From the technical perspective, single room models are appropriate where the conditions of interest are limited to a single, freely connected space. Where the area of interest involves more than one space, and especially where they are on more than one floor, multiple compartment models should be used. This is because the interconnected spaces interact to influence the fire development and flows.

Many single compartment models assume that the lower layer remains at ambient conditions (e.g., ASET [7]). Since there is little mixing between layers in a room (unless there are mechanical systems) these models are appropriate. However, significant mixing can occur in doorways, so multiple compartment models must allow the lower layer to be contaminated by energy and mass produced by the fire.

The model should include the limitation of burning by available oxygen. This is straightforward to implement (based on the oxygen consumption principal) and is crucial to

obtaining an accurate prediction for ventilation controlled burning. For multiple compartment models it is equally important for the model to track unburned fuel and allow it to burn when it encounters sufficient oxygen and temperature. Without these features the model concentrates the combustion in the room of origin, overpredicting conditions there and underpredicting conditions in other spaces.

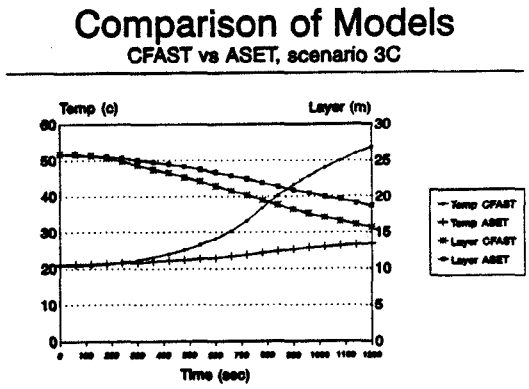


Zone models assume that fire gases collect in layers that are internally uniform.

Heat transfer calculations take up a lot of computer time, so many models take a shortcut. The most common is the use of a constant "heat loss fraction" which is user selectable (e.g, CCFM [8]). The problem is that heat losses vary significantly during the course of the fire. Thus, in smaller rooms or spaces with larger surface to volume ratios, assuming a constant heat loss can lead to serious errors. In large, open spaces with no walls or walls made of highly insulating materials the constant heat loss fraction may produce acceptable results, but in most cases the best approach is to use a model that does proper heat transfer.

Another problem can occur in tall spaces like atria. The major source of gas expansion and energy and mass dilution is entrainment of ambient air into the fire plume. It can be argued that, in a very tall plume, entrainment is constrained; but most models do not include such limits. This can lead to an underestimate of the temperature and smoke density and an overestimate of the layer volume and filling rate – the combination of which may give predictions of egress times available that are either greater or less than the correct value. For example, in the model CFAST [9], this constraint is implemented through an initial limitation on the height to which the plume rises based on its buoyancy.

Recently, NIST was asked to review a calculation utilized to support the variation with a code requirement for a large, enclosed shopping mall. The original calculation was performed with ASET, a single-room filling model which does not employ a limit on tall plume entrainment. Running the same calculation in CFAST yielded different results. Although the differences were not significant to the result in this example, it does illustrate the effect described above.



CFAST limits entrainment producing higher temperatures and a deeper layer, faster.

Documentation

Only models which are rigorously documented should be allowed in any application involving code considerations. It is simply not sufficient to rely on the model developer's word that the physics and numerical implementation are proper. This means that the model should be supplied with a technical reference guide which contains a detailed description of the included physics and chemistry with proper literature references, a listing of all assumptions and limitations of the model, and estimates of the accuracy of the resulting predictions based on comparisons to experimental data. Public exposure and review of the

exact basis for a model's calculations, internal constants, and assumptions as well as independent comparison with real-scale data are necessary for it to have credibility.

While it is not necessary for the full source code to be available, the method of implementing key calculations in the code and details of the numerical solver utilized should be included. This documentation should be freely available to any user of the model and a copy should be supplied with the analysis as an important supporting document.

Input Data

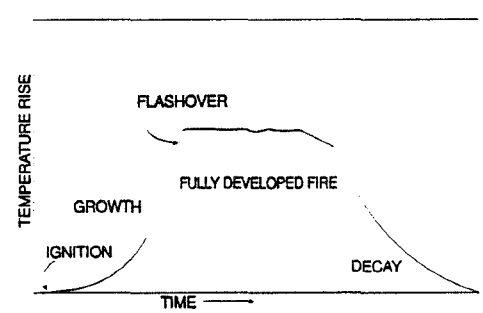
Given that the model is correct, the results can still be misleading if the data input to the model does not represent the condition being analyzed. Proper specification of the fire is the most critical, and will be addressed in detail in the following section on selecting the design fire(s).

Next in importance is specifying sources of air supply to the fire -- open doors or windows are obvious, but cracks behind trim or around closed doors are also important. Most (large) fires of interest in buildings quickly become ventilation controlled; making these sources of air crucial to a correct prediction. The most frequent source of errors by novice users of these models is to underestimate the combustion air and underpredict the burning rate.

Other important items of data include ignition characteristics of secondary fuel items and the heat transfer parameters for ceiling and wall materials. In each case, the alternative design analysis should include a listing of all data values used, their source (what apparatus or test method was employed and what organization ran the test and published the data), and some discussion of the uncertainty of the data and its result on the conclusions (see section, Accounting for Uncertainty).

Selecting Design Fire(s)

Along with selecting an appropriate model, choosing a relevant set of design fires with which to challenge the design is crucial to conducting a valid analysis. The purpose of the design fire is similar to the assumed loading in a structural analysis -- to answer the question of whether the design will perform as intended under the assumed challenge. Keeping in mind that the greatest challenge is not necessarily the largest fire (especially in a sprinklered building), it is helpful to think of the design fires in terms of their growth phase, steady-burning phase, and decay phase.



An idealized compartment fire has three, distinct phases

Growth

The primary importance of the appropriate selection of the design fire's growth is in obtaining a realistic prediction of detector and sprinkler activation, time to start of evacuation, and time to initial exposure of occupants. Thus this is the most important to an egress analysis which makes up the majority of alternate design analyses.

In 1972, Heskestad first proposed that, for these early times, the assumption that fires grow according to a power law relation works well and is supported by experimental data [10]. He suggested fires of the form:

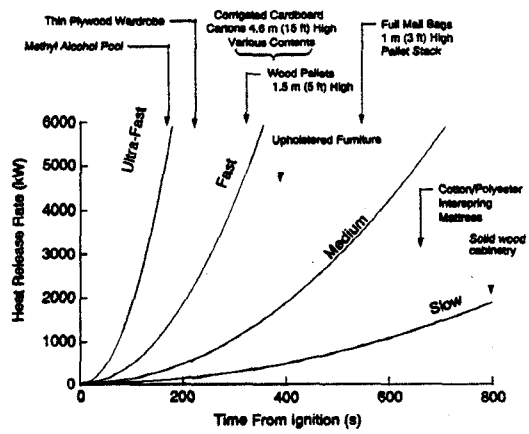
$$\dot{Q} = \alpha t^n$$

where: $\dot{Q}$ is the rate of heat release (kW)
α is the fire intensity coefficient (kW/s^2)
t is time (s)
n is 1,2,3

Later, it was shown that for most flaming fires (except flammable liquids and some others), n=2, the so-called T-squared growth rate was an excellent representation [11]. A set of specific T-squared fires labeled slow, medium, and fast, with fire intensity coefficients (α) such that the fires reached 1055 kW (1000 BTU/s) in 600, 300, and 150 seconds, respectively were proposed for design of fire detection systems [12]. Later, these specific growth curves and a fourth called "Ultra-fast" [13] which reaches 1055 kW in 75 seconds, gained favor in general fire protection applications.

This specific set of fire growth curves have been incorporated into several design methods such as for the design of fire detection systems in the *National Fire Alarm Code* [14]. They are also referenced as appropriate design fires for performing alternative design analyses in Australia and Japan, and in a product fire risk analysis method published in this country [15]. While in the Australian methodology the selection of growth curve is related only to the fuel load (mass of combustible material per unit floor area) this may not be the best approach since growth rate is related to the form, arrangement, and type of material and not simply its quantity. Consider 10 kg (22 pounds) of wood; arranged in a solid cube, sticks arranged in a crib, and as a layer of sawdust. These three arrangements would have significantly different growth rates while representing identical fuel loads.

This set of T-squared growth curves are shown in the adjacent figure. The slow curve is appropriate for fires involving thick, solid objects (solid wood table, bedroom dresser, or cabinet). The medium growth curve is typical of solid fuels of lower density (upholstered furniture and mattresses). Fast fires are thin, combustible items (paper, cardboard boxes, draperies). Ultra-fast fires are some flammable liquids, some older types of upholstered furniture and mattresses or other highly volatile fuels.



T-squared curves approximate fire growth in most fuels

In a mixed collection of fuels selecting the medium curve is appropriate as long as there is no especially flammable item present. It should also be noted that these T-squared curves represent fire growth starting with a reasonably large, flaming ignition source. With small sources there is an incubation period before established flaming, which can influence the response of smoke detectors, and result in an underestimate of time to detection. This can

be simulated by adding a slow, linear growth period until the rate of heat release reaches 25 kW.

Steady burning

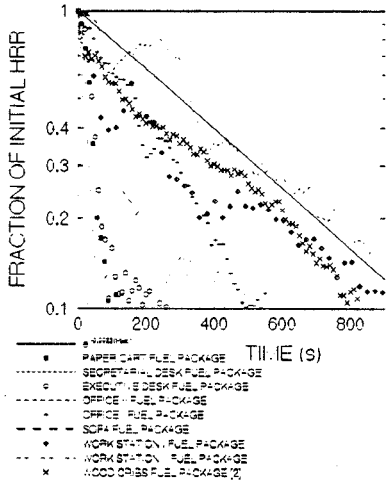
Once all of the surface area of the fuel is burning the heat release rate goes into a steady burning phase. This may be at a sub-flashover or a post-flashover level – the former will be fuel controlled and the latter ventilation controlled. It should be obvious from the model output (for oxygen concentration or upper layer temperature) in which condition the fire is burning.

Most fires of interest will be ventilation controlled; and this is a distinct advantage since it is easier to specify sources of air than details of the fuel items. This makes the prediction insensitive to both fuel characteristics and quantity since adding or reducing fuel simply makes the outside flame larger or smaller. Thus, for ventilation controlled situations the steady burning region can be specified at any level that results in a flame out the door and the heat released inside the room will be controlled to the appropriate level by the model's calculation of available oxygen. For the much smaller number of fuel controlled scenarios values of heat release rate per unit area at a given radiant exposure (from the Cone calorimeter, ASTM E-1354) can be found in handbooks and used with an estimate of the total fuel area.

Decay

The burning rate declines as the fuel is exhausted. This decline is often specified as the inverse of the growth curve; this means that fast growth fuels decay following the inverse of the fast curve and slow decay following the inverse of the slow curve. It is often assumed that the point at which decay begins is when 20% of the original fuel is left. While these are assumptions, they are technically reasonable.

Of course if a sprinkler system is present this decay will proceed as the fire is extinguished by the water. A simple assumption is that the fire immediately goes out; but this is not conservative. A recent NIST study documents an (conservative) exponential diminution in burning rate under the application of water from a sprinkler [16]. Since the combustion efficiency is affected by the application of water, the use of values of soot and gas yields appropriate for post-flashover burning would represent the conservative approach in the absence of experimental data.



Evacuation calculations

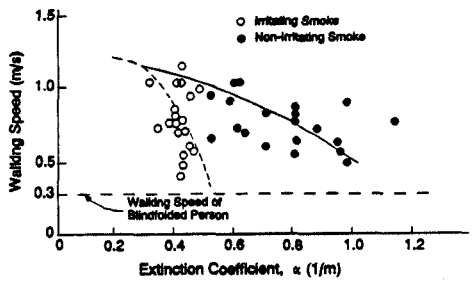
The prediction of the time needed by the building occupants to evacuate to a safe area represents the "time needed" side of the safe egress time calculation when compared to the "time available" computed in the previous steps. Whether the evacuation calculation is done by model or hand calculation, it must account for several crucial factors. First, unless the people see the actual fire there is time required for detection and notification **before** the evacuation process can begin. Next, unless the information is compelling (again, people see the actual fire) it takes time for people to decide to take action. Finally, the movement begins. All of these factors require time, which is the critical determinant of safety. No matter how the calculation is done, **all** of the factors

must be included in the analysis to obtain a complete picture. An excellent discussion of this topic is found in Pauls' [17] and Bryan's [18] chapters in the SFPE Handbook.

Models

The process of emergency evacuation of people follows the general concepts of traffic flow. There are a number of models which perform such calculations and which may be appropriate for use in certain occupancies. Most of these models do not account for behavior and the interaction of people (providing assistance) during the event. This is appropriate in most public occupancies where people do not know each other. In residential occupancies family members will interact strongly and in office occupancies people who work together on a daily basis would be expected to interact similarly. The literature reports incidents of providing assistance to disabled persons, again especially in office settings [19]. If such behavior is expected it should be included as it can result in significant delays in evacuating a building.

Another situation where models are preferred to hand calculations is with large populations where congestion in stairways and doorways can cause the flow to back up. Crowded conditions as well as smoke density can result in reduced walking speeds [20]. Care should be exercised in using models relative to how they select the path (usually the *shortest* path) over which the person travels. Some models are *optimization* calculations which give the best possible performance. These are inappropriate for a code equivalency determination.



A person's walking speed decreases in dense smoke until they move as slowly as if blindfolded.

Hand calculations

Luckily, most evacuation calculations are simple enough to be done by hand and they do not exhibit the same, time-varying characteristics as fire growth which usually demands iterative methods. The most thorough presentation on this subject (and the one most often used in alternate design analysis) is that of Nelson and MacLennen in [21]. Their procedure explicitly includes all of the factors discussed previously along with suggestions on how to account for each. They also deal with congestion, movement through doors and on stairs, and other related considerations.

Accounting for Uncertainty

This refers to dealing with the uncertainty which is inherent in any prediction. In the calculations this uncertainty derives from the models and from the input data. In evacuation calculations there is the added variability of any population of real people. In building design and codes the classic method of treating uncertainty is with safety factors. A sufficient safety factor is applied such that, if all of the uncertainty resulted in error in the same direction the result would still be safe. A formalized method of assigning safety factors which account for uncertainty is being studied by Magnusson et al. [22].

In the prediction of fire development and smoke filling time, the intent is often to select design fires which provide a *worst likely* scenario. Thus, a safety factor is not needed here unless assumptions or data are used to which the predicted result is very sensitive. Generally speaking, it is better for uncertainty to be addressed explicitly. This means that rather than making conservative assumptions it is better to make best estimates of the range

of what is expected and to account for uncertainty by applying appropriate safety factors afterwards.

Any report of calculations as discussed in this paper should include a discussion of uncertainty. This discussion should address the representativeness of the data used and the sensitivity of the results to data and assumptions made. If the sensitivity is not readily apparent, a sensitivity analysis (vary the data to the limits and see whether the conclusions change) should be performed. This is also a good section in which to justify the appropriateness of the model or calculation method in the manner discussed previously.

Establishing Acceptable Levels of Risk

The advantages of performance-based codes derive from the fact that they contain explicit objectives, but this can be a two-edged sword in that it requires some difficult public policy choices. It is simply not possible to eliminate fire losses, and determining what losses society is willing to accept is difficult. Generally, public policy decisions are made by government but public debate on acceptable levels of losses are rare, even in the context of war. Further, Brannigan states [23] that it is not correct to say that society accepts current levels of loss simply because there is no public outcry. He argues people generally do not protest that which is perceived not to effect them directly, and further they feel fire losses are inevitable.

It appears that these difficult decisions will have to be made through the existing codes and standards committees who have traditionally made them implicitly through prescriptive requirements. This would have the added benefit of providing some continuity with the level of implied risk extant in the current codes.

Certification of Methods

Considering the complexity of the methods and the criteria against which these methods should be judged, most code officials are not comfortable with making decisions about the appropriateness of a model's physics or some complex assumptions. But for projects where obtaining outside advice is not practical this is exactly what is required. For these cases the answer may lie in another approach familiar to the regulatory community -- third party certification.

Objective criteria can be developed and might be used to initiate a draft standard for models and calculations appropriate to engineering design analysis. Some such criteria are being developed by such groups as ISO and ASTM in the U.S. Following review and a consensus process, appropriate organizations might then certify or sanction specific models or methods for such, when used under specified conditions. This might be accomplished through the model code process since these codes already contain "sanctioned methods" for doing structural calculations. The civil and structural engineering societies are providing peer review of calculational methods affecting their disciplines through committees. The American Society for Civil Engineers (ASCE) and the Society of Fire Protection Engineers (SFPE) are jointly developing standards for calculated fire resistance, and the American Society of Structural Engineers has developed similar standards for structural calculations.

Concluding Remarks

Alternate design calculations provide a way to achieve design flexibility and code equivalence based on performance. The advantages of such a system are widely recognized and research is underway all around the globe to formalize the process through national and international standards.

The regulatory community is becoming more comfortable with the predictive methods and their assumptions, and the engineers are learning to utilize fire models as part of the engineering design process. Professional societies are providing peer review and establishing codes of practice. Educators are providing the training needed by both the practicing professionals who do the analysis and those who must review and accept or reject it. Finally, researchers are finding new ways to quantify the uncertainty of their approaches and validating them for use.

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