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State-of-the-art design of 'design fires'

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Abstract

Life-safety is a fundamental objective of fire safety engineering. In order to achieve this objective, fire engineers use prescriptive guidelines from guidance documents or employ performance-based engineering to fulfil certain performance criteria as needed. Building pre-flashover design fires is the primary step in performance-based approach, however, the multitude of ways it can be done means that any two engineers will most likely come up with two different design fires for a particular project. This dissertation identifies uncertainties and complications within literature in regards to the methods of analysis, input parameters, codified prescriptions, models for representing fire development, and assumptions made throughout the pre-flashover design fire process. Having established the uncertain nature of the process, the research seeks to identify common practices, with the view to find out if the problems are addressed appropriately, amongst practicing fire engineers through surveys and interviews. The qualitative analysis of the responses shows how predominant the use of t-squared model is, despite having its limitations, and how the uncertainties related to input parameters such as heat release rate, and fire growth rate, are often inadequately understood in design fire context and superficially addressed. Influence of stakeholders, especially regulators, and practicality seems present to some degree in engineer's minds, possibly limiting the exercise of innovation and engineering robustness.

Introduction

Fire safety has been an important element in building design process for a long time. Fire engineering itself though is a relatively new branch of engineering which deals with complex and often vaguely understood fire dynamics. In the past, building codes prescribed set parameters to achieve a fire safe building design, where safety represents both life safety and structural safety (Babrauskas, 1996). Innovation and advances in technology, however, made it difficult for fire engineers to stick to those prescriptions if unique and novel architecture had to be introduced. Therefore, the prescriptions have been superseded, though not completely, by the concept of performance-based design, where performance criteria must be met while exercising freedom to design. This meant that as long as performance, or functionality of a criterion could be proven, any approach could be justified. Hence, focus has shifted towards performance-based engineering where engineers are allowed to deviate from the code prescriptions while meeting safety criterion (Kong et al., 2017).

Pre-flashover design fires are also a part of performance-based engineering which guides design of egress strategies, smoke control systems, and detection and suppression systems. Even though design guides provide a basic overview of the possible ways engineers can go about it, there is a multitude of ways it can be approached, and the guides do not mandate using prescriptions alone. Since, design guides such as BS 9999:2017 and PD 7974-1 allow engineers to use their judgement when selecting their ways and methods throughout the process, it logically follows that for any particular compartment, two engineers might come up with two different design fires. It clearly means that there is a lack of standardization in the concept of pre-flashover design fires which is fundamental for life safety in fires.

In this dissertation, a thorough review of literature has been conducted to identify some of the potentials sources of uncertainty in the pre-flashover design fire models, inputs and approaches. The complications identified underpin the industrial reconnaissance to understand how engineers deal with these complications. Two surveys discussing pre-flashover design fires and the t-squared model were floated, which were answered by 29 fire engineers; 23 interviews were conducted with fire engineers from the industry, including the Fire and Rescue Service, who had experience in the industry and had been involved in building pre-flashover design fires. A qualitative analysis of the resulting data has been carried out to understand industrial practices, and to see if they are being addressed. The analysis tries to understand how engineers circumvent or address these complications.

Literature Review

Fire Engineering Design – Performance-based and Prescriptive

What is Performance-based Design?

Buildings have a long history of being exposed to fire hazard, and can lead to loss of lives. The construction materials and items inside that makeup a particular building into a working system are many a time combustible in nature, which when ignited can lead to fire. The occurrence of fire can lead to a number of dangerous possibilities: smoke generation, flames and very high temperatures, and consequent loss of strength of building material itself. With experience and development of the body of knowledge in fire science, buildings were made safer. This body of knowledge informed the building codes that are commonly used for fire engineering design; these contain instructions on what should be the necessary characteristics to design a building so that it is safer against hazards, in our case: fire. Building codes in the past used to prescribe set parameters for different features of a building, for example, the length, width, of a corridor in a building was prescribed to make sure that the occupant can safely evacuate a building in time during a fire and the structure doesn't fail prematurely (Babrauskas, 1996). Codes containing mostly prescriptions such as these can be referred to as prescriptive codes, and were most common in the past. However, at present the focus has shifted towards performance-based engineering especially for high rise buildings (Kong et al., 2017, p. 772), and the codes that contain instructions for such process can be referred to as performance-based codes. However, not every code is exclusively one of these types, and contains elements of both.

It is important to understand what performance is referring to in performance-based design. (Babrauskas 1996, p. 87) thought that the performance is referring to risk statement. It essentially means that it basically tells how many fatalities could be expected in a certain time duration. The problem, however, still is that when dealing with probabilities that must be dealt with for a large number of parameters, the knowledge often is insufficient which renders the process incompletely probabilistic. He referred to the current design process, therefore, as FSE-based design instead although most common terminology at present still is performance-based design. Performance based design thus allows the design to bypass prescriptions, and engineer his own solutions as long as the risk can be shown to be acceptable and objectives have been met.

Objectives of Performance-based Design, and Compliance

The objectives of fire safety design in the Australian Building Code, the essence of which remains the same in most design guides in the UK and elsewhere, have been discussed by (Quaglia, 1992). The three main objectives have been detailed below:

1. Safety to the Occupants – safe egress from the building
2. Effective intervention of the fire brigade
3. Prevention of conflagration

Whether or not the objectives have been achieved in a design must be ascertained by an authority. According to (Baker et al., 2013), local government authorities alongside the fire service departments are responsible for evaluating compliance in a design, such is the case in New Zealand. In the UK, the relevant authorities include the Building Control and the Fire and Rescue Service. Compliance with the New Zealand Building Code (NZBC) can be shown in three ways:

1. Prescriptions which are deemed-to-satisfy in the Compliance Documents
2. Calculations available in the Compliance Documents
3. Solutions which are not available in the Compliance Documents, but meet performance criteria, such as those discussed in Verification Method (C/VM2 Verification Method)

Essentially, practicing both prescriptive and performance-based fire engineering is acceptable, in the UK as well since the compliance requirements are essentially similar, as long as the objectives of the fire safety design are being met.

Fire Safety Assessment Process: Deterministic and Probabilistic Approaches

The process of fire safety assessment has been summarised by (Bwalya, 2008):

1. Qualitative review: objectives and criteria are defined; identifying design parameters after carefully studying the engineering plans and safety features; identifying building and occupant characteristics; identifying fire hazards and their consequences; selection of fire scenarios for analysis; finding trial solutions; detailing methods used for analysis.
2. Quantitative analysis: this is the stage where quantification of the parameters and subsequent analysis is done using methods detailed already; this is where design fire fits as well.
3. Assessment: using the criteria established earlier, the results of the analysis are evaluated against these.
4. Reporting: findings are documented, and presented to the stakeholders.

(Hadjisophocleous et al., 1998) explained that in case of probabilistic design, the evaluation criteria is in terms of acceptable risk, whereas for deterministic design that is not the case. Deterministic design usually involves selection of a particular scenario for one problem, usually the worst credible case. Contrarily, probabilistic design incorporates uncertainties such as human behaviour, door conditions, combustible location and properties, ignition source, and fire safety systems; thus, more than scenarios might be evaluated for risks and consequences.

(Baker et al., 2013) have described development of the B-RISK fire model for use in New Zealand which uses Monte Carlo simulation techniques to build probabilistic design fires for egress calculations. The testing results showed good agreement with the internationally prescribed values and those in the New Zealand Building Code. Uncertainty in Heat Release Rates was studied by (Kong et al., 2013) using a similar Mote Carlo simulation technique. Other uncertain parameters were also analysed by (Magnusson et al., 1996) to study probability of egress failure in occupants. Many more models have been developed, employing techniques such as Bayesian networks (Matellini et al., 2013) and Markov chain (Chu et al., 2012) due to a lack of sufficient data about all the parameters leading to studying incorporation of risk in terms of fire safety design since long (Kong et al., 2017).

Usual Criteria for Performance-based Design

Two overarching criteria to meet building regulations for fire safety are as follows (Karlsson and Quintiere, 2022):

1. Life Safety Criterion: this criterion required that the occupants of a building must be able to evacuate within time without being harmed. This means that the building be designed in such a way that the Available Safe Egress Time (ASET) is larger than the Required Safe Egress Time (RSET) such that untenable conditions which include toxicity, invisibility and hot temperatures are avoided (Hadjisophocleous et al., 1998), (Borg et al., 2015). Various fire engineering guides including SFPE Handbook (SFPE) contain detailed prescriptions about the limits for these conditions; one example is shown in Figure 1 from the NFPA in the table below.

Criteria	**Value**			
Heat Effects	Air saturated with water vapour < 60 °C			
	< 2.5 kW/m^2 for periods up to 30 minutes			
Carbon Monoxide	Maximum (few seconds)	Average (first 6 minutes of exposure)	Average (first 15 minutes of exposure)	remainder of exposure
	≤ 2000 ppm	≤ 1500 ppm	≤ 800 ppm	≤ 50 ppm
Smoke Obscuration	80 lux sign discernable at 30 m			
	Walls and Doors discernable at 10 m			
Velocity	≤ 11.1 m/s air velocity along any path of emergency egress travel			
Height	1.8 m above the floor in the protected route			

Figure 1. Tenability Criteria, (NFPA, 2014)

2. Structural Resistance Criteria: in a fully developed fire, the goal of fire safety engineering is to maintain the load bearing capacity of structural members so to avoid building collapse. As such, all the load bearing elements such as beams and columns; all the non-load bearing members such as partition walls must be tested for three criteria (Hadjisophocleous et al., 1998).:
    a. Stability – to test strength

b. Integrity – to test overall intactness
c. Insulation – to test temperature transfer to unexposed side

Prescriptive Design vs Performance-based Design

In prescriptive codes, exact instructions are given which if followed will ensure compliance with the building code and hence be approved (Plank, 2013). These instructions can be widths of emergency exits, the distances to an emergency exit, the number of emergency exits and so on, with the idea being that the occupants will safely evacuate before untenable conditions arise if these prescriptions are followed (Sundstrom, 1997). To satisfy the structural resistance criteria, instructions are given for chosing the size of column and beam sections, cover thicknesses etc. and should be followed to ensure compliance (Plank, 2013).

There are many problems that are entailed in prescribing design solutions. Firstly, it becomes very difficult for designers to build innovative, complex and unique designs using new construction technologies and fire models that more accurately model fire physics. Secondly, sometimes there is no scientific or rational reason for instructions present in many codes which discredits its use when more scientifically sound methods are present (Hadjisophocleous et al., 1998). Thirdly, the will to save costs while coming up with a fire safe design is arguably there as costs for protection measures dropped by 60% in the UK between 2003 and 2013 and using prescriptions often leads to having redundant measures avoiding which might lead to reduced costs; regardless of whether performance-based design is cheaper or not, clients are increasingly asking for thorough performance-based analyses to get a reliable level of safety (Plank, 2013). However, it must be mentioned that Babrauskas' thought general concern was that performance-based design led to lesser fire safety than prescriptive design (Borg et al., 2015).

Design Fires

Design fire can be defined as the quantitative description of the time-varying fire properties which is dependent on several characteristics such as type of fuel, quantity of fuel, location of fuel, environmental conditions and fire spreading and decay (Bwalya, 2008). These characteristics are assumed for different design scenarios, and therefore inherently uncertain (Borg et al., 2015). The most common of these assumptions is the heat release rate which is the quantitative description of all the other fuel properties when burning. It is important here to elaborate on the concept of 'design scenarios'. According to (Borg et al., 2015), design scenarios are those fire events which are likely to happen and must be considered before quantifying any of them and developing a fire strategy. This involves considering the possibility of various ignition sources and their locations, fuel arrangement and types, ventilation conditions (open or closed doors), and any active or passive fire protection measures (Borg et al. 2015). According to (Hopkin et al., 2020), the uncertainty in these conditions means that regulations do not explicitly mandate use of fixed parameters, since standards and guidance documents contain different recommendations, for design fires and engineer is challenged to exercise their own judgement. This comes with the added responsibility of keeping the stakeholder's preferences of low cost, and functionality into account. Consequently, when demonstrating compliance using performance-based engineering, different engineers can come up with different design fires for the same project (Yung et al., 2002). (Borg et al., 2015) documented three possible ways of getting design fire scenarios:

1. Use scenarios provided in standards and design guidance documents, such as (ISO 165733-1:2015).
2. Establish a scenario with the fuel load, ventilation conditions and safety measures at hand such as sprinklers. Suppression systems such as sprinklers will modify the design curve at the time of activation, so must be considered (Quintiere, 2022).
3. Get scenarios through a thorough risk assessment of the project which assesses a number of parameters.

After having design fire scenarios, the next step is to get the design fire itself – the quantification of the scenarios. This is done using methods which are mostly empirical (Bwalya, 2008), and is done in using two different quantities for two different applications. The two methods are:

1. Pre-flashover design fire – here the quantification is done through a heat release rate curve. This is a relatively short design fire, not more than 30 minutes in practicality, since the goal is safe evacuation of the occupants and fire service is supposed to intervene in this time period (Quintiere, 2022).
2. Post-flashover design fire – here the quantification is done through a temperature-time profile, using one of the many empirical correlations available such as the (Parametric Fire Curve), or the (ISO Fire Curve). The goal here is structural stability and thus the temperature the structural elements will be exposed to is plotted against time thus giving us a design fire curve. This is not the subject of this thesis; our focus is on the pre-flashover design fires.

Heat release rate is perhaps the most important variable to describe fire hazard (Babrauskas, 1996). It can be defined as the product of mass loss rate and effective heat of combustion of a material. For composite materials, which is usually the case in real fires since most fuel in buildings is not pure fuel such as gasoline but combustible material such as upholstered furniture and tables composed of wood, polyurethane and PVC and other such materials, the heat release rate is usually obtained by bench scale tests such as the Cone Calorimeter test, or a full-scale Furniture Calorimeter test, both done using oxygen calorimetry principle under free-burning (well-ventilated conditions). (Borg et al., 2015) suggested that heat release rate obtained through cone calorimeter should be adjusted for compartment conditions that dictate radiative feedback since that cannot be simulated in free-burning.

Fire Development

Fires have a growth phase, a steady phase and a fully-developed phase. While modelling this, often simplifications are made and the shape can be simpler or more complex, depending on the presence of suppression systems or multiple fuel packages, than the one shown in Figure 2, and a steady phase maybe included in the pre-flashover fire taking a priori that flashover is not going to occur.

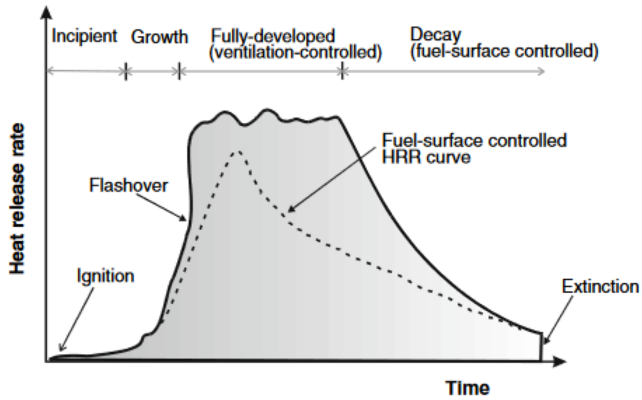

Figure 2. Stages of fire development in a compartment, (Bwalya, 2008)

The fire progresses in three stages, each is explained as follows:

1. Growth phase- this is the phase which starts sometime after ignition. Immediately after ignition, there usually is a delay in growth of the heat release rate curve in spontaneous ignition (Themelis et al., 2010). It could be because of smouldering combustion which releases smoke but not enough heat to start burning material close to ignition source right away. However, the smoke can activate the suppression system, such as sprinkler, which will modify the heat release rate.

   The heat release rate keeps rising and the burning rate of the material keeps increasing as the fire grows following a parabolic shape (Baker et al., 2013). The growth rate depends upon the surface material properties such as thermal inertia and fuel properties such as size, orientation, and composition (Bwalya, 2008). This is the fuel-controlled stage, because the oxygen at this stage is usually sufficient and complete burning is limited by fuel. Next phase is flashover, which is a very sudden increase in heat release rate and involves burning of all combustibles inside the compartment (Peacock et al., 1999). This occurs at around 600^0 Celsius, or when radiation flux is 15-20kW/m^2 (Haegglund et al., 1974). Before flashover, the goal of fire safety strategy is to save lives, but after flashover the focus changes to protecting the structure itself. Whether or not flashover occurs depends on geometry and surface properties of the enclosure, the fuel and ventilation conditions.

2. Fully-developed fire – this stage involves burning of the fuel at a steady rate often with lesser oxygen availability than before flashover, and is usually therefore incomplete combustion. It is the ventilation-controlled stage since fuel is still available for burning but the oxygen content is decreasing and is limiting the burning, unless the compartment is well-ventilated.
3. Decay phase - when most of the fuel is consumed, the fire starts to die and the heat release rate starts decreasing following an exponential law (Themelis et al., 2010). This stage is limited by fuel because oxygen is now sufficient for complete burning the small amount of fuel left.

In order to create a design fire which models the fire development explained above, several complications arise. The root of these problems is the existence of the innumerable possibilities in which a fire can occur inside a building or a compartment. The uncertainties associated with fuel type, size, quantity; ignition source, location; ventilation conditions: open or closed doors and windows. This means that there are two reasonable possibilities: either modelling using existing empirical evidence or testing under conditions which represent the actual reality, which is arguably constantly changing. The former is actually the only *practical* possibility which suggests modelling the fire using empirical data. In fact, most of the existing models for design fire are largely empirical (Bwalya, 2008). This is not to suggest that testing is not done ever because it is, sometimes on full-scale and will be discussed in a later section; as will be the question of whether test results are always useful, and if they can always be used.

According to (Themelis et al., 2010), a model design fire curve that very closely resembles a usual fire development curve thus can be characterised by the following parameters:

1. Time from ignition to growth - According to (Fitzgerald, 2017), a 25cm high flame, equivalent to 20kW heat release rate might be taken as the threshold to establish growth phase.
2. Peak Heat Release Rate (peak HRR) – this is the maximum value that will be achieved. It occurs when either: fire becomes under-ventilated; fire becomes fuel-controlled; a sprinkler or any suppression system activates. It is possible to have multiple peak HRRs if there are multiple combustibles burning (Bwalya, 2008), because each will likely have varying a growth rate and ignition time.
3. Time taken to peak heat release rate – it is an extremely important value which will dictate the design to life safety of occupants. From the start of the growth phase till the time to peak heat release rate, the curve is modelled mostly through the *Alpha-t-squared Model* which has been discussed in a later section (Bwalya, 2008). However, other models such as *linear, exponential, Gaussian profile* and *bell-shaped* are also available to model this stage (Sundstrom, 1997). Despite the t-squared model being the most popular, it has been criticised for lack of a grounding in Physics by authors such as (Babrauskas, 1996).

4. Start of steady phase and its duration – it starts when the peak heat release rate has been reached and continues till the decay phase begins. The HRR is constant during this phase.
5. Start of decay phase – this is when the fire becomes fuel-controlled and starts to die, because less fuel is burning. This phase can be a straight line, or can follow an exponential law as suggested by (Themelis et al., 2010).

t-squared Growth Model

According to (Babrauskas, 1996), the t-squared model was popularized for design fires by its incorporation in NFPA7230 despite it being developed for fire detector performance evaluation studies instead in the early 1970s.

(Sundstrom, 1997) mathematically breaks the t-squared model as a representation of following assumptions:

a) Velocity of flame front remains fixed over a surface
b) Velocity of flame front is not dependent on the HRR
c) HRR is directly proportional to the burning area
d) Burning area is directly proportional to $(burnt\ distance)^2$

Below is the mathematical equation reflecting this idea:

$$Q = \propto t^2$$

Here, $\propto$ is the fire growth rate with units in kW/s^2; t is the time from ignition with units in seconds (s), and it is 'zero' at the start of growth phase.

Typically, four fire growth rate values are specified in design codes and guides as shown in Figure 3, and represent test results. Mathematically, $\propto$ is calculated using the equation given above according to the time it takes to reach 1055 kW (Quintiere, 2022).

In guides such as the NFPA 204 and SFPE, different materials are assigned one of these growth rate values which fit the corresponding material's experimental results. For example, the fast growth rate curve worked well for *plywood* when it was tested using the ISO 9705 method, so it was assigned the *fast* curve. For reference, some materials with growth rate categories have been shown in the table below.

Growth category	Typical examples	Fire growth coefficient, α (kW/s^2)	Growth time, t_o (s)
Slow	Floor coverings	0.00293	600
Medium	Shop counters, office furniture	0.0117	300
Fast	Bedding, displays and padded work-station partitioning	0.0468	150
Ultra-fast	Upholstered furniture and stacked furniture near combustible linings, lightweight furnishings, packing material in rubbish pile, non-fire-retarded plastic foam storage, cardboard of plastic boxes in vertical storage arrangement	0.1876	75

Figure 3. Commonly used fire growth rates found, (Kong et.al., 2014)

The model, however, has been quite harshly critiqued by some authors. (Yung et al., 2002) pointed out the complete absence of effects due to compartment and environmental conditions including radiative feedback effect and fire spread. They also though that when used as a complete design fire model for pre-flashover fires, it does not suffice the purpose of facilitating life safety because it fails to integrate toxic gas computations which are necessary for design as well. (Babrauskas, 1996) thought that the curve could probably work for fires that evaluate heat detectors because they are usually small, such as 100 kW, however, using it for real fires of orders of magnitude could not be justified. He asserted that many items could not be assigned one of these four growth rates, as was evident in the Figure 4 from NFPA 72.

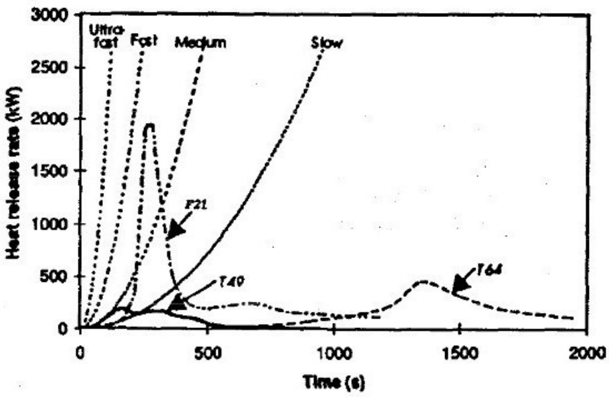

Figure 4. HRR curves for actual furniture items vs t-squared curves, (NFPA 72)

(Sundstrom, 1997) also highlighted this inadequacy when a burning acrylic curtain could not be described even with an ultra-fast t^2 curve, as shown in Figure 5.

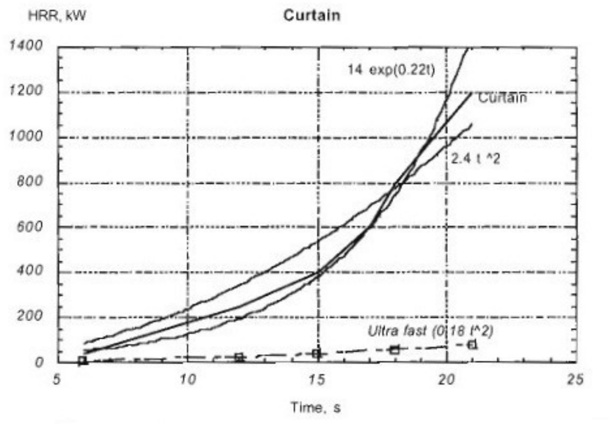

Figure 5. How a burning acrylic curtain is better explained by exponential curve, and 2.4 t-squared compared to an ultra-fast fire, (Sundstrom, 1997)

Lastly, t-squared model when used as a pre-flashover model, such as curves given in NFPA 72, is often chopped off at an arbitrary heat release rate value, which would otherwise have been infinity according to the curves, has no basis in fire science (Babrauskas, 1996). These arguments do tend to shake the foundations of the model as a pre-flashover model but there is evidence in favour of its utility as well. (Schifiliti, 1986) documented that test data agrees with the curves. Even though, it seems like arguments that lend scientific credibility to the model as a design fire tool have not been proposed, and NFPA justified the use of the method by asserting that it was sufficient for reasonable decision making.

Steady State Design Fire

Steady state design fire is another pre-flashover design fire model. As the name suggests, it uses a steady fire, meaning the heat release rate does not vary with time at all, unlike relatively recent design fire models. Historically, it has been used to design smoke control systems, and was originally employed mostly in enclosed or partially-enclosed commercial centres (Morgan et al., 1999). According to (BS 7974), the idea is essentially to use a constant maximum heat release rate that represents the largest fire likely to occur. An example of steady state design fire is shown in Figure 6.

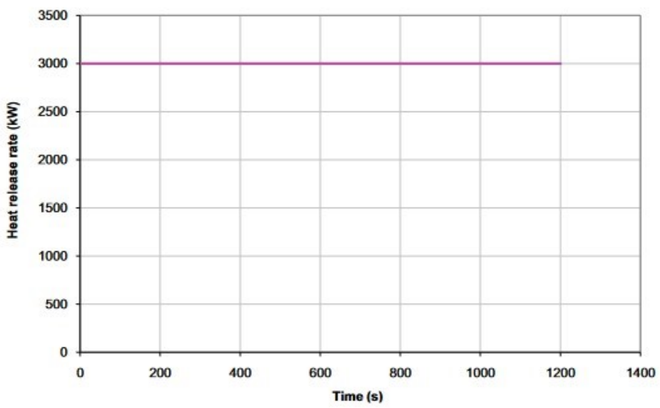

Figure 6. Steady State Design Fire, (Mayfield et al., 2011)

Naturally, the largest possible fire scenario will be adequate for smoke control at all stages of fire design, and will cover most fires. However, it is not a good idea if the design fire is going to be used to design detection systems since they are tested in the growth phase of the fire when heat release rates are supposed to be lower (Mayfield et al., 2011). Also, using the largest possible fire will most likely result in higher costs and an inefficient design, especially because it does neither reflects fire dynamics nor employs risk assessment at all to get an optimized design fire solution.

Complications in Code Solutions for Design Fire

There is a variety of ways a pre-flashover design can be approached. In practice it might not be the case because regulatory authorities, building codes and design guides do influence the process. This will be discussed in the later part of the thesis. In this section, major complexities have been discussed that can lead to confusion when designer is building a design fire for a project.

Firstly, the time from ignition to start of growth phase can be tricky. (Quintiere, 2022) recommends that this time should be incorporated into the final design but does not explicitly recommend how to decide on when the growth phase has begun. (Fitzgerald, 2004) suggested a fire with HRR equal to 20kW as the threshold. The transition from smouldering to flaming might not be very clear. It is difficult furthermore to take a generic ignition time value from literature because the ignition source, fuel type and many other properties will govern how much it will be. For example, ignition time for upholstered furniture with cigarette as the source of ignition can be 20 - 30 minutes (Babrauskas, 1985). The range and initial fire condition varieties can make a selection uncertain. This is not a trivial problem either because this uncertain period involves production of toxic gases that can be life-threatening (Themelis et al., 2010).

Secondly, t-squared fire as a pre-flashover design fire model has problems that have already been discussed in an earlier section. Despite being used very commonly, concerns about its representation of fire physics have not been addressed. At most, it could be argued that literature provides room for it because it happens to model some scenarios reasonably well. Further problems that concern the foundational parameters of the t-squared fire have been elaborated in the following paragraphs, especially the fire growth rate.

Thirdly, the fire growth rate used in the t-squared fire is not the same in different guide for same types of occupancies. For example, PD 7974-1:2003 and CIBSE Guide E recommend a medium fire growth rate (0.0117 kW/s^2) for dwellings in the UK whereas C/VM2 recommends a fast fire growth rate (0.0469 kW/s^2) for dwellings in New Zealand (Hopkin et al., 2020). Similarly, BSI DD240 (now withdrawn) and BS 9999:2017 recommends 0.012 kW/s^2 while MOC recommends 0.05 kW/s^2 for office buildings (Kakegawa et al., 2003). Apart from the obvious that different regions in the world are using different design parameters for arguably similar dwellings and hazards, it also raises the question of why fire growth rates are categorised according to occupancy types.

Fourthly, the fire growth rates specified based on occupancy types in guides like PD 7974-1:2003 (UK), CIBSE Guide E (UK), C/VM2(New Zealand) and Swedish National Board of Housing, Building and Planning (Boverket) do not consider the compartment characteristics and environmental conditions. (Wahlqvist et al., 2016) carried out CFD simulations for a Swedish residential compartment concluding that in certain conditions:

1. Building material might have a significant effect on the fire growth rate.
2. Insulation on wall surfaces will probably increase the fire growth rate, unless the building material itself is thermally thin or has a high specific heat capacity.
3. Better ventilation conditions might increase the fire growth rate due to better combustion.
4. The floor area of the room might significantly affect the fire growth rate.
5. Ceiling height significantly affects the growth rate.

Essentially, using fire growth rates based on occupancy types without further investigation into the initial fire conditions might yield erroneous design fires leading to faulty egress safety strategies.

Fifthly, when selecting Heat Release Rates suggested in building guides, there can be similar complications as for the fire growth rate discussed above. For example, the recommended HRR values in BD 2410 fall between 50-92 percentile range of HRR lognormal distribution generated by (Hopkin et al., 2020) who analysed the dwelling fires in the UK between 2010-2017. The range is quite broad because of differences in room types (Hopkin et al., 2020), which is often not taken as a variable, and occupancy types. Using occupancy type to suggest HRRs fails to incorporate initial conditions and environmental conditions might not be a sound idea since these conditions vary within similar occupancy types. This was demonstrated by (Wahlqvist et al., 2016) when they concluded that in certain conditions:

1. Ventilation factor in combination with building material affects the heat release rate in a compartment.
2. Floor area significantly affects the heat release rate.
3. Ceiling height significantly affects the maximum heat release rate.

Essentially, using a heat release rate based on occupancy type alone can result in a design that could cause safety issues for a project.

Sixthly, there is not a clear agreement on what fixed value of HRR is to be used for an occupancy type. For example, take residential occupancy type and look at the recommended heat release rates for such type in different documents:

1. BS EN 1991-1-2 – suggested HRRPUA (Heat release rate per unit area) is 250 kW/m^2.
2. (Law, 1980) – suggested HRRPUA is 290 kW/m^2.
3. (Klote et al., 2002) – suggested HRRPUA is 500 kW/m^2.

Seventhly, the heat release rate values found in the literature and guides for specific items like chairs, upholstered furniture, tables etc. are the result of free-burn testing in either ISO 5660 Cone Calorimeter or the Furniture Calorimeter. Using cone calorimeter is less costly option and is referred to as bench-scale testing while furniture calorimeter is used for full-scale testing. However, the problem with these tests is that they do not directly represent real fire release rate which are larger and more complex (Bwalya, 2008). This requires use of empirical models to be developed for scaling the HRR from bench-scale to real fires. The problem is that correlations do not always work: As an example, HRR predicted for upholstered furniture using correlations developed in CBUF was found to be inaccurate for furniture used in New Zealand. (Bwalya, 2008) asserts that due to inability in incorporating heat feedback effects in the calorimeter tests, using HRR to quantify design fires might not even be the most suitable way in the first place.

Eighthly, there remains a great variance in values of key parameters such as type and size of fuel load (kg/m^2) for similar types of occupancies which is necessary to get HRRPUA (Themelis et al., 2010) in certain situations, for deciding on the duration of the steady phase and subsequent decay in the heat release curve. Deciding on the fuel load can be a confusing job as well since not every enclosure will have the same fuel load.

Ninthly, before building a design fire, selecting design fire scenarios can also be done in a number of ways because engineering judgement is recommended to be used. ISO/CD 13388 recommends that fire incident statistics should be used to identify scenarios that consider information such as common ignition source, location of fire source and suppression system activation. Even though there is guidance available, such as ISO Technical Report 13387-2:1999(E) which suggests a risk-ranking process to select design fire scenarios, the process inherently entails the possibility of different engineers selecting different design scenarios which will most likely lead to different design fires for same project.

Approaches and Solutions to Address Complications

There is no general consensus on which particular approach should be used. (Borg et al., 2015) mention that Babrauskas thought that a general concern was that performance-based design resulted in lesser fire safety than prescriptive-design. (Johnson et al., 2013) on the other hand preferred that engineers be provided a structured methodology to develop design fire scenarios. Another view is that only standardized design fires be used so that all engineers come to a similar curve in the end (Yung et al., 2002).

(Themelis et al., 2010) suggested a probabilistic approach whereby following parameters were to be defined by appropriate distributions instead of picking a rather arbitrary fixed value:

1. Fire load density
2. Fire growth rate, α
3. Maximum HRR for fuel type and size
4. HRR required for flashover under different ventilation conditions, and compartment properties
5. Maximum HRR in under-ventilated conditions under different ventilation conditions
6. Time when decay phase starts
7. Decay rate
8. Time period from ignition till the start of growth phase

This approach tries to address the many uncertainties regarding parameters that define the design fire curve but acknowledges that the suppression system activation should also be studied and incorporated. Another recommendation was to involve flame spread, also suggested by (Quintiere, 2022) although for a deterministic approach, from one fuel package (a group of similar or closely situated items) to another which generally makes the process a bit more complicated.

(Baker et al., 2013) used a similar probabilistic approach to develop a model called B-RISK which generated parametric fire curves and distributions for parameters such as fire growth rate and peak heat release rate. This use of distributions seems to be a fair choice going forward for design fires in enclosures, while also suggesting that these could be more optimal than using inputs directly from codes. (Hopkin et al., 2020) also developed distributions for fire growth rate and heat release rate from the *Dwelling Fire Dataset* covering residential fires from 2010-2017. They suggested that the 95th percentile of both parameters could be used for following a deterministic approach (similar to taking inputs from a design guide) since the values match those suggested in the design guides.

It seems that probabilistic approaches that treat input parameters and initial conditions as variables, though a lot more taxing, do address some of the uncertainties despite having inadequate datasets. However, this is arguably more of an engineering approach than simply using values from design guides for reasons discussed in the last section. Lastly, (Borg et al., 2015) suggested that some parameters can be prioritized depending on the application of the design fire. For example, peak HRR is the parameter of fundamental importance to design smoke ventilation systems whereas for egress calculations (ASET and RSET) and design of smoke detectors and suppression systems, fire growth rate becomes more important.

Project Testing or Using Existing Generic/Statistical Data?

Having established already the importance of heat release rate, in addition to numerous other parameters, a problem of practical nature often arises: in real projects should HRR values be obtained through testing or from existing data – which can also be categorized.

As such, (Sundstrom et al., 1997) presented three ways HRR could be obtained to be used for building design fires in real projects:

1. Testing materials directly, which I am going to refer to as project-specific testing for the sake of clarity in later sections where industry practice is addressed.
2. Using generic data, which refers to the use of HRR data available in literature and guides for similar items like upholstered furniture.
3. Using statistical data, which refers to using HRR values for occupancy types since they have been assigned to these types based on statistical likelihoods.

CFD

Computational Fluid Dynamics (CFD) employs Navier-Stokes equations to solve fluid physics. Since fire is also a fluid phenomenon involving mass, species, heat and momentum transfer, CFD tries to solve its governing physics too. The most commonly used CFD software for simulating fire is the Fire Dynamics Simulator (FDS) which was developed by National Institute of Standards and Technology (NIST) (Plank, 2013). CFD has very often been used to recreate past fire incidents for investigation and understanding purposes. (Hadijsophocleous et al., 2008) designed fuel packages through survey of commercial buildings and performed full-scale tests while also using computational fluid dynamics for comparison of results. They showed that FDS gave satisfactory shape of the heat release rate curve, the peak heat release rate and the time to peak heat release rate. Such results demonstrate that fire development can be represented with decent accuracy using CFD, and might therefore be useful for getting design fires according to (Quintiere, 2022).

Researchers have used the pyrolysis model in FDS (NIST) to evaluate predictions of heat release rate and fire growth. (Yang et.al., 2011) claimed that it could produce efficient and reasonable results, which would strengthen the case for it being used to build design fires whenever project-specific experimentation is not a financially viable option. This method utilizes the material decomposition reactions and 1-D heat transfer as the basis for predicting mass loss rate and subsequently, the heat release rate while also taking into account environmental and compartmental influences. It must also be mentioned here that the research in this area limited and so there is no consensus on it being a very credible approach.

There are a few reasons that the use of computational fluid modelling is still limited to certain situations. One of them is the processing-time associated with simulating large projects, and therefore most buildings in the United Kingdom have used traditional design fire curves (Plank, 2013).

Methodology

The topic and description of the dissertation was already defined by the supervisor. The scope of dissertations and the main idea was defined as well. However, in the initial period data collection was not progressing at all because the fire engineers contacted were reluctant to share case studies or project data due to confidentiality and bureaucratic concerns. The dissertation scope therefore had to be altered to address these concerns.

Searching and Screening Literature

In order to find out the latest relevant literature, Google Scholar, DiscoverEd and LUBSearch were used. DiscoverEd and LUBSearch, platforms managed by The Unversity of Edinburgh and Lund University, provided free access to many resources that eventually informed and became part of this study.

Keywords were used to find the latest relevant literature. Some of the keywords used are:

- Design fire
- Pre-flashover design fires
- t-squared
- CFD fire
- Life safety fire

Reviewing Literature

It is very important to note here that the amount of literature published relevant to the dissertation topic is not very exhaustive, though present. The literature review therefore very often cites literature that might be considered old. However, it would be unfair to call that literature outdated keeping in view that new literature has not replaced it yet. Many of the concerns from old literature have yet to be addressed and thus are deemed relevant to this study too.

Most guidance documents that are practiced in the United Kingdom, some from other countries, in the realm of fire safety design have been reviewed to substantiate the study. The textbook that has been cited quite often is called ‘Enclosure Fire Dynamics’, by James Quintiere and Bjorn Karlsson.

Identifying Research Problems

The logical culmination of literature review was identifying problems in the pre-flashover design fire process. Problems were identified in the methods used, in the guidance documents, in the way uncertainties are dealt with at every step. It must be noted that problem identification does not intend to put blame or on a method, author, or a publication, but rather to portray the difficulties and confusions that engineers building pre-flashover design fires encounter during the process.

Collection of Case Studies

This step was the primary step before revising the scope of this dissertation. The intent was to collect case studies of unique projects that could be helpful in analysing engineer's thought process while describing a pre-flashover design fire. However, after interviewing several senior fire engineers, nothing substantial could be obtained due to their reluctance to share information. It is understandable because employees need to respect confidentiality policies of projects and their company, and most were not willing to sign a non-disclosure agreement.

Selecting Participants

More than 300 fire engineers were contacted to participate in the surveys and interviews. When contacting potential participants, they were given a choice of either filling the survey or participating in an interview. This was to make sure that most of the people contacted participated in some form. Additionally, mostly fire engineers with at least 5 years of experience were targeted.

Out of the 29 survey participants, and 23 interviewees, only 3 participants had less than 5 years of work experience in the fire engineering industry.

Current job titles of some of the participants are as follows:

- Associate Fire
- Senior Fire Engineer
- Principal Fire Engineer
- Technical Director
- Group Fire Engineer
- Project Manager
- Director

The reason experienced professionals were targeted is to because they have directly or indirectly been involved in the design fire process, and possibly have an understanding of the general trends in their companies and the industry.

Floating Surveys

Two surveys were sent to more than 300 people. One survey was titled, 'Industrial Survey on Design Fires', which was filled in by 19 people. The other survey was titled, 't-squared Design Fire', and it was filled in by 10 people. Some of the responses to the surveys can be found in the appendix section of this dissertation. Some of the survey responses have also been attached in the appendix section without the details of the participants for privacy reasons.

Interviewing People

23 interviews were conducted and participants were exclusively experienced professionals with more than five years of experience, except two participants but their responses have not cited in the analysis.

Collecting Transcripts

Otter.ai software was used to record transcriptions of all interviews conducted. The transcriptions are available with the author of this dissertation. It must be noted that due to privacy concerns, anonymity has been maintained and none of the interviews can be found in the appendix or any other section of this dissertation. Only the excerpts from the interviews have been published in this dissertation with the permission from the participants.

Qualitative Analysis

Deductive analysis was done which is a form of qualitative analysis. The reason for not choosing to do quantitative analysis was twofold:

1. The questions have multiple dimensions to them and cannot easily be quantified without asking too many questions, which leads to lower response rate.
2. The number of participants for the surveys and interview were too small to yield credible quantitative answers.

Deductive analysis was therefore conducted which means that the transcripts and survey responses were analysed in such a way that answers to pre-defined questions were sought. Given more time, it might be possible to do an inductive analysis and read more into the transcripts because many issues were discussed that were not directly related to the questions asked in the thesis, but relevant to the topic nevertheless.

Results and Analysis

It must be noted that where multiple quotes or excerpts from interviews or surveys have been added, the attribution has been made as Engineer A, Engineer B, Engineer C, and so on for anonymity purposes primarily, but also to make sure that successive quotes are not mistaken to be belonging to the same interview where that is not the case.

Use of Performance-based Design in Fire Engineering Industry

How common is PBD?

The use of performance-based design to design infrastructure that can address fire hazards is not universal and very often code-compliant methods are deemed sufficient. In order to understand the frequency of its usage, and the circumstances where it is mostly used, the following dataset was used:

1. 1 survey which was answered by 19 fire engineers
2. 10 interviews with 10 fire engineers

Figure 7 shows results from the survey. At first glance, it seems that there is no clear indication of the frequency of using performance-based design. Almost one-fifth of the engineers almost never use it, and the same proportion uses it almost always.

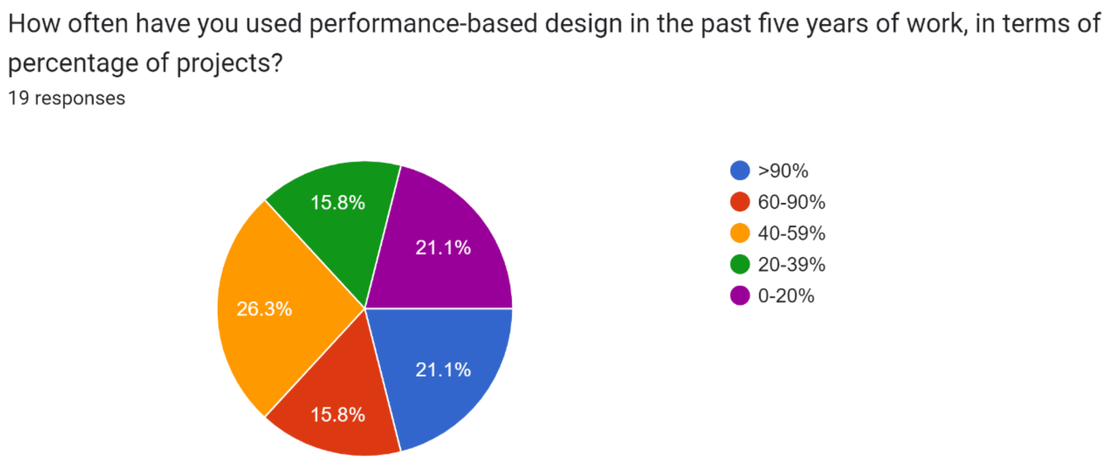

Figure 7. Proportion of performance-based design projects in the past five years of work.

This lack of clarity can be attributed to the fact that what constitutes 'performance-based design' is not clearly defined and completely understood. This becomes clearer in interviews when the participants are asked this question. One of the interviewees hinted at this confusion existing in the industry in this way:

"Performance based design gets used as a catch-all for all sorts of things. And I think it is a term that gets misused. Okay, so if you think about what performance based design means there has to be a performance. Otherwise, it's not performance based. And that performance, for me has to be something measurable. You have to define what performance you're trying to achieve out of your design, and then go about and show that you meet that performance and that performance could be, in a risk based world, a probability of loss of life. In a fire resistance world, it could be achieving a particular resistance standard, etc., but there needs to be a measure identified. And, and a lot of the time what people call performance based isn't actually performance based. In my mind, it's just alternative. You're just not following the code, but you're doing something that might be based on engineering judgments, it might be based on an analysis that might be based on anything but it's just an alternative method. So in terms of what you said just now I would agree in that. A lot of people, most fire engineers, are doing some form of alternative design all the time." - Engineer A

Some engineers who answered that they almost never use performance-based design had to say this:

"*I suppose my answer, my answer is kind of the assumption that there's been a really big performance based design element to it. So you've kind of said, this is our building, and we just can't apply the code to this building. So we're going to put this code to one side, I'm going to go first principles all the way through. But I would just for context, then maybe it's kind of one in four projects (which can be called performance based). There's something very niche there's this situation where you've got two cable trays really close to each other, and they've both got fire safety systems that should be segregated in a system A and a system B and they should be in two separate parts of the building, but actually quite close. And so then I just do quite a localized calculation on, well, if that cabled tray caught fire, what heat is going to radiate? And is it going to ignite this tray that's five meters away? Is there some resilience there? So that would be something that's certainly not captured within the code and is a sort of first principles performance based task, but it's very, it's very contextual and very localized to just a very small limit of a design. So yeah, I would say maybe you can kind of interpret that how you like, but maybe one in five or one in four projects have that kind of first principles calculation on quite a specific item." - Engineer B*

"We're dealing with the fire brigades, we're dealing with different stakeholders. So, if we stick to the plans, like codes and these guidance documents, it's much easier for us to go with the argument and it's much more widely accepted." - - Engineer C

Keeping the evidence above in view, it becomes very difficult to ascertain how common performance-based design usage is, especially in the UK since a large majority of the participants are stationed in the UK. It is very clear though that the term performance-based design is misunderstood in the industry, and engineers use both prescriptive guidelines and performance-based design to address fire hazards. It becomes important then to understand how engineers decide on when to deviate from the code and use a performance-based design - as we have defined in this thesis based on established standards: Essentially, meeting some performance criteria e.g., tenability conditions.

When Do Engineers Use PBD

Engineers had mostly similar reasons when asked under what circumstances they used performance-based design. Some of them are as follows:

1. Project objectives prevent strict compliance with prescriptive guides.
2. Too demanding legislative requirements.
3. Complexity of projects where clients are willing to pay for bespoke solutions.
4. Cost-efficient.

It can be seen that when the code compliance is not possible due to a lack of available prescriptive guidelines or due to an impossibility reconciling client's objectives with code requirements, alternative performance-based solutions are sought to. Also, some respondents thought that finances had nothing to do when deciding on carrying out a performance-based design. One of the interviewees had to say this:

"It's never to do with finances, we don't do cheaper solutions. With regard for safety what we do is, we find the best solution for the project and quite often the projects we work on don't fit within the code. So there's aspects that don't fit within the code, or the client has a higher objective than the code minimum for life safety, so we have to come up with solutions that will achieve that higher objective. So there's all sorts of reasons for doing performance based design, but it usually it's either because the building doesn't fit neatly within the code, or there's a higher client objective." - Engineer A

"It's usually not necessary or cost effective to do performance based design unless there's a specific feature of the building, which is unique or a risk that warrants it." - Engineer B

Some of the applications performance-based design as gleaned from the dataset are: fire safety of existing building undergoing a renovation, escaping via balconies overlooking atria, radiation assessments to maximise the extent of glazing in an external facade, validating extended travel distances, rationalising the extent of applied fire protection to the structure, and for evaluating smoke control systems in atria.

Deterministic vs Probabilistic Approach

Eleven interviews were conducted where participants were asked what approach between probabilistic and deterministic they most commonly used to build a design fire. As has been explained in an earlier section, the variability and complexity in the parameters involved in building a design fire makes it open to engineers to decide what is the best course of action. From the analysis of the interviews, it seems like most fire engineers used deterministic approach to build design fires. It was however seen that a number of participants asserted that even though most engineers do not use probabilistic approach, however, they did use it themselves. It is an important piece of information because it is not possible to quantify the evidence of deterministic approach being prevalent because of the small sample size. However, some interviewees who were senior fire science practitioners asserting this does at least show that many fire engineers do not use probabilistic approach and would rather follow guidance documents to get a deterministic design fire. One of the more experienced interviewees said this:

"*My guess is that most people do deterministic because it's easier, what should be done is probabilistic." - Engineer A*

"To be honest, that never occurred to me because, again, everything is based on code and guidance. Unless again, it is like a very strange design or I would say like there were like some more analysis that has been done, I haven't done it … I would say in the UK, 90% of the time, it is based on the code, it's just your take to consider the worst case scenario." - Engineer B

These statements suggest that in the industry deterministic approach is the go to approach while for specialised industries, unlike commercial and residential built environment, the situation might be different. However, it seems like some industry practitioners do feel like the engineers are not using more sophisticated methods that might be more suited because the code gives them an easier alternative which might not necessarily be the most optimized solution.

How Often Do You Use t-squared Model

The t-squared model is used to represent the growth phase of a fire which informs life-safety design in pre-flashover fires. The limitations of this model have been discussed in detail in the literature review section. Despite the problems associated with the model, it is used in the industry for several reasons. In order to understand how prevalent the usage of the t-squared model is for getting pre-flashover design fires, the following dataset was used:

1. 1 survey which was answered by 19 fire engineers
2. 10 interviews with 10 fire engineers

Figure 8 shows that all engineers who participated have used this model in a varying frequency the past for their fire safety designs. Clearly, it is very often used in the industry with one-fourth of the respondents using it for every pre-flashover design fire they build for a project.

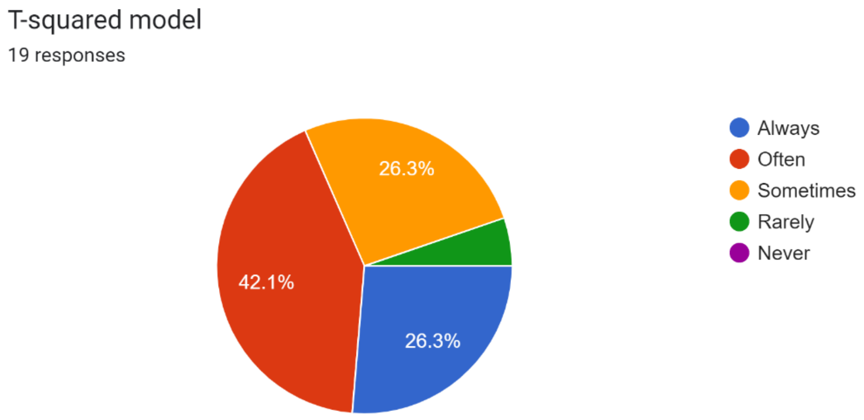

Figure 8. How often engineers have used t-squared model in the past.

It is no surprise that the model is so widely used for reasons discussed earlier. However, it is important to understand the motivation that directs engineers to use it.

When asked why they used the t-squared model for pre-flashover design fires, most engineers seemed to respond by saying that they used it because it is the most common approach, simple to use and the easiest to get approvals for. Here are some of the responses from the surveys:

"It is peer-reviewed by the industry and is the most acceptable and used method out there to get a curve." - Engineer A

"Most commonly used and easy to explain to building control." - Engineer B

"It is simple to use and provides a conservative estimate of time to flashover." - Engineer C

It can be seen that the commercial nature of the job which demands that projects be completed in the least amount of time using the least amount of money might have a slight influence on engineers choosing to go with this. This is not to say that using this model is wrong or the reasons given by engineers are wrong, but merely to point out the possibility that engineering judgement might be limited by constraints of a practical nature when it comes to choosing a design fire model. One of the interviewees had to say this about the common usage of this model:

"I think we always stick to an alpha t-squared fire, just for modelling purposes as well. Except that I think hardly anyone will ever argue with you that the alpha t-squared model is not correct. Well, if it's correct, that's another matter but it's about acceptance within the community." - Engineer D

Participants were also asked if they had used an alternate to the t-squared model. Some of them are listed below:

1. T-cube Model
2. Flame Spread Model
3. Steady State Model
4. Linear Model

The application details of these models were not investigated. However, it does seem like the T-cube model is often used for warehouses with high fuel loads. Many participants also mentioned the use of fire curves from guides, literature and project-specific testing, and these have been addressed in a later section.

t-squared Model

Incipient Phase

The question about incipient phase was asked to only three senior engineers so definitely does not say much about the industry. Anyhow these engineers normally did not take the incipient phase into account. The reason given was that ignoring incipient phase gives a more conservative design fire which is what they are mostly looking for. At the same time, engineers pointed out that they do not treat it as a conservative approach every time. Because when it comes to smoke detector design, the incipient phase becomes very important, and therefore you need to consider the incipient phase. The engineers had to say this:

"We don't take that into consideration, because the one line that completely invalidates those kinds of assumptions is that we have to go for the most onerous situation. So we assume that there is a fire and then suddenly everything starts to burn. And then in that kind of situation, whether the people can really evacuate or not. So anything less than that, definitely suitable for us to stay safer." - Engineer A

"In my experience, nobody ever does, because it's a more conservative approach. Yes, exactly. Well, in most circumstances, yes. I could probably come up with examples where it's technically not more conservative, but generally speaking, yeah, it's more conservative to assume there is no incipient stage." - Engineer B

Use of CFD in Industry to Get Design Fires

In order to understand if CFD is used in relation to design fires, the participants were first asked how frequently they have used CFD in general for their fire engineering projects. The following dataset was used:

1. 1 survey which was answered by 19 fire engineers
2. 10 interviews with 10 fire engineers

It can be observed from Figure 9 that barring a small minority, most fire engineers often use CFD at some stage during fire design for their projects. It is understandable because software employing CFD can model fire growth, spread and smoke movement which when used in conjunction with add-ons such as evacuation models can help build evacuation strategies, ventilation systems and more.

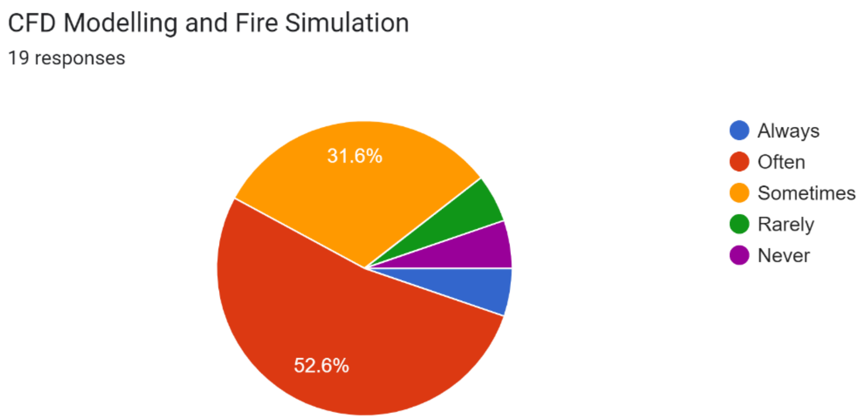

Figure 9. How often engineers have used CFD in the past (not just for design fires).

The follow-up question asked participants to detail their motivations for using CFD as a tool to get design fires, and whether or not pre-flashover design fires can be obtained through it. The answers suggest that CFD is mostly used to justify and demonstrate the performance of an alternative solution to approval bodies such as the Building Control, and not really for getting design fires. The most common usage cited was design of smoke control systems. Some other applications included:

1. To justify performance such as tenability criterion in and egress safety.
2. To justify performance of ventilation, smoke control and suppression systems.
3. To demonstrate external fire spread design validation.
4. To demonstrate performance in single-stair conditions and basement car parks.

The respondents were clear in establishing that design fires is almost always an input for the CFD simulation and is not itself generated by using CFD. Some excerpts from the interviews show this:

"*I would be surprised to know that it has been used for getting a design fire, because there is a lot of uncertainty with selecting materials and fire loads to get a prediction. It is also not a peer-reviewed method and would not be an acceptable method to use in the industry." - Engineer A*

"It is very rare to conduct actual pyrolysis calculations with FDS. This is mostly based on client demands" - Engineer B

"But when you talk about CFD, you might use CFD modelling but you still define your design fire. The design fire doesn't come out of the modelling. The modelling might give you temperature or give you something else but you still have to put your heat release in

and that heat release curve can be a t-squared. So the only way you can use let's call it an analytical model, I mean CFD is computational fluid dynamics, right? Now, there are tools out there, which allow you to do pyrolysis modelling, or whatever but they don't have to be CFD, I get very frustrated when people call it CFD, I go: CFD is the is the movement of the fluid. So you can have a pyrolysis model in a tool, right? We've got pyrolysis model into a zone model into B-risk. You could put pyrolysis model as an input into a CFD tool, or you could just do a pyrolysis model without putting it into any other thing. But that's not used very often." - Engineer C

Clearly, design fire generation using CFD and pyrolysis modelling is not a usual practice in the industry. In the literature, not enough research could be found which demonstrated its usage to be accurate for this purpose.

Use of Project Specific Experimentation in Industry to Get Design Fires

In order to understand how often project-specific experimentation to get design fires is used in the industry, the following dataset was used:

1. 1 survey which was answered by 19 fire engineers
2. 10 interviews with 10 fire engineers

Figure 10 shows the results from the survey. It can be clearly seen that using project-specific experimentation to get design fires is rarely the case. This could be due to a number of reasons which were shared by the participants when asked about it. Participants also mentioned that project-specific testing when carried out is used in tandem with existing data which is because not necessarily all of the data is unavailable.

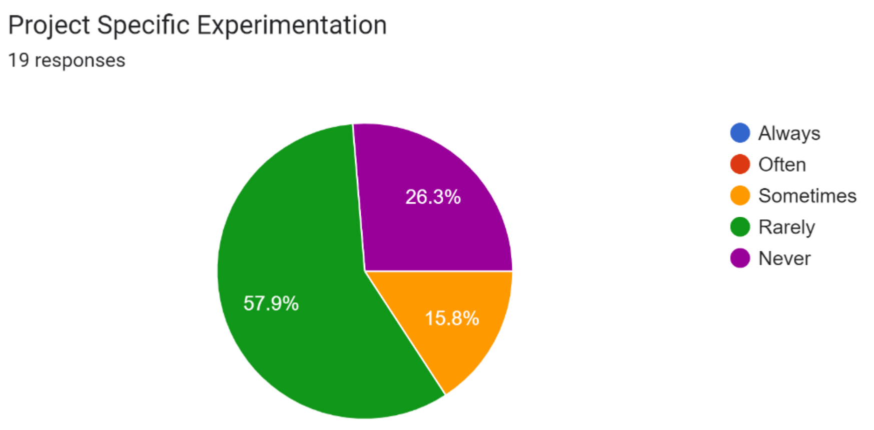

Figure 10. How often engineers have used project-specific experimentation in the past to get design fires.

According to the results, project specific-experimentation is mostly used when:

1. Material types and configuration is new and existing data, like HRRPUA, is unavailable.
2. Specialised projects or industries like nuclear facilities, industrial hazardous material processing plants, electric vehicles and biological research facilities may have very specific needs and materials that need to be tested.
3. For research and development in collaboration with universities and research institutes.

One of the interviewees also mentioned that most of the testing in their organization is less about determining the design fire parameters and more about get the fire resistance properties of materials that would then be used in structures:

"*To be honest, when we do project experimentation, most of the time, it's not about defining design fire. So, if we want to define the design fire size associated with rolling stock, it might help a client. You develop some fire tests for that to define the fire size. We've done that before. And I know that we're working on some research projects in Australia where the fire department are very keen to understand the fire size with electric vehicles. To know if it is different from regular petrol vehicles? So I think when the hazard is unknown, and there's no data then we may work with client to just find the design fire. It's actually more often not the experimental testing that we're doing, it isn't necessarily about the fire but it's about testing the fire resistance or testing the reaction to fire properties of a product or a material.*" *- Engineer A*

Essentially, project specific experimentation is rarely used in the industry to get design fire parameters possibly because most applications do not involve new materials and novel configurations, hence the existing design parameters can be taken from guides and literature.

Use of Existing Curves in Industry to Get Design Fires

In order to understand the frequency with which existing design fire curves are used in the industry, the following dataset was used:

1. 1 survey which was answered by 19 fire engineers
2. 10 interviews with 10 fire engineers

By existing design fire curves we mean HRR curves obtained through testing in the past which have been published in the literature or can be found in guidance documents. The results from the survey are shown in Figure 11. It can be seen that mostly the models available to get the pre-flashover design fire are used and existing curves are rarely used.

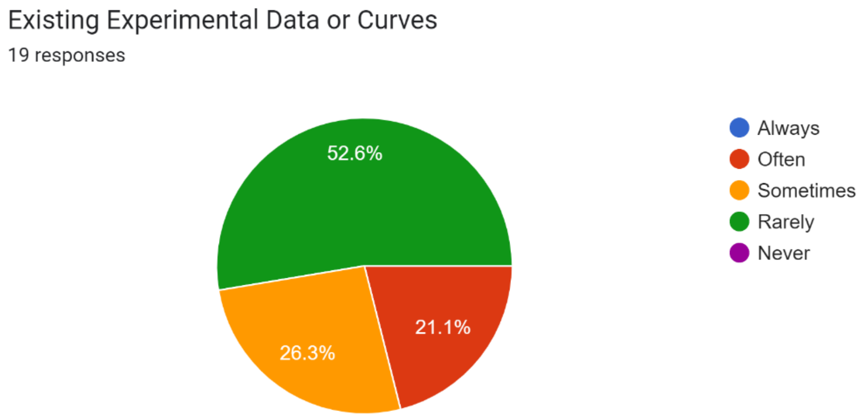

Figure 11. How often engineers have used existing data in the past to get design fires.

Participants detailed the following reasons for using existing design fire curves:

1. To inform the choice of design fire in our project by looking and comparing with similar design fires from literature.
2. To substantiate our engineering judgement that flashover condition will not occur when the code recommends that flashover condition be assumed.

Even though most participants said that they had not used design fires from any source directly without adjusting them to the project, some did say that because of their ease of use, they used them often from sources such as the SFPE Handbook for Fire Protection Engineers.

This approach in the industry therefore is more of an aid to building design fire and provides some credible reference for engineers to substantiate their choices. This can be seen from the following statement from one of the interviewees:

"*If we're designing the fire resistance of say a bus station and we want to know the size of a bus fire, then, you know, you'd look in all the available literature to see what different sizes of a heat release rate you get for buses, or you know, another common one is Christmas trees and atria and that kind of a thing. So, we tend to scroll the data to justify the fire size that we're proposing. And to show that the fire size we're proposing is conservative." - Engineer A*

Selecting the Fire Growth Rate

In order to understand how engineers went about selecting the fire growth rate, two surveys with 29 participants and around 20 interviews were conducted. From the data obtained, it is pretty clear that in the UK engineers select the value of fire growth rate predominantly according to occupancy type or fire loading, if known, from one of the compliance documents/design guides. The documents that were cited are:

1. BS9999:2017
2. BRE 368
3. CIBSE Guide E
4. C/VM2 New Zealand
5. Enclosure Fire Dynamics
6. BS PD 7974
7. SCA Guidance
8. SFPE Handbook
9. NIST
10. NFPA 72
11. NFPA92B

It was observed that engineers from the UK cited documents from other countries like C/VM2 from New Zealand. The problem associated with it was discussed in the literature review section of this report that C/VM2 and BS 7974 suggest different growth rate values for same occupancy types. It was also seen that no engineer said that they had used any literature themselves to get the fire growth rate, which means that only literature in the compliance documents are referred to.

Since many engineers are using occupancy types to select fire growth rate, it follows that many a time the variations in the compartment characteristics such as insulating materials, building materials, floor area and ceiling height might be lost. However, engineers did respond by citing a practical reason which was twofold:

1. When using codes, the most conservative values are mostly chosen, and the codes have conservatism built into them at every step.
2. Standards such as BS 9999:2017 class built environment according to risk profiles, and the low risk profile buildings do not need a lot of conservatism so code values still work.

One of the engineers said this:

"You can use that in the confidence that a lot of these figures that we get from guidance documents have a significant degree of conservatism built into them. So you're choosing a worst case scenario, but as you go and use all these conservative values, obviously, it becomes exponential." - Engineer A

Selecting the Heat Release Rate

In order to understand how engineers went about selecting the fire growth rate, two surveys with 29 participants and around 20 interviews were conducted. Just like for the fire growth rate, it was concluded from the data that in the UK engineers select the value of fire growth rate predominantly according to occupancy type or fire loading, if known, from one of the compliance documents/design guides. The documents that were cited are:

1. PD 7974-1-2019
2. BS 9999:2017
3. BRE Document FB29
4. CIBSE Guide E
5. BRE BD 2410
6. SFPE Handbook
7. BD 2552
8. NFPA 92
9. SCA Guidance
10. BRE 368
11. Enclosure Fire Dynamics

Two main selection methods were highlighted. When the fuel load is given, the peak heat release rate can be taken from one of the guidelines listed above. In the other case, the occupancy type is known and the heat release rate per unit area (HRRPUA) is taken from the guidelines and can then be translated to the peak heat release rate for the compartment area.

When engineers were asked what they did when in the guidance documents, such as PD 7974-1, the HRR value given was not a fixed number and instead a range such as 320-570 kW/m^2; the engineers had differing responses:

1. Some engineers said they used the mean value.
2. Some engineers said they used the maximum value to stay on the conservative side.
3. Some engineers said they chose a value according to the risk profile of the building.

Some of the responses illustrate this:

"*I would say take the most conservative in terms of giving you the worst fire condition. But again, you should really be understanding what the basis of the standard is because some of them may have been developed with older furniture or older materials. And so the mix of materials it's good to have a big influence on you know, what the fire dynamics properties are. So if you're just applying a value without knowing where it comes from, again, you have a problem but if you can determine from the test data, which one fits better the materials and you know, that you're looking at and the composition of those materials, then you should go to those data." - Engineer A*

"*You know, the conditions change all the time. So if you take the higher end, I usually do that. It has also been the case that I have looked at different research papers, looked at different readings from different tests, and I just use the mean value of those heat release rates." - Engineer B*

"If you are to follow the range, normally you take the most onerous situation, let's say, but if you have extensive fire protection system, for example, like automatic detection sprinkler system, fast responsive sprinkler system, fast response detection system, then normally we go easy because there is a clear declaration in BS 9999 that we can reduce the safety to the lower levels, the risk profiles to the lower levels, if we have certain steps, certain protection system and detection systems. So those kinds of things, then we can lower our risk profile. Once we lower our risk profile. We can argue that okay, well, the risk profile is low. We don't need to go for this most onerous situation, then we can go downward, something like that." - Engineer A

Another question of interest was to see if engineers are taking into account conditions insulation materials, ceiling heights, and building materials while taking HRR and fire growth rate based on occupancy types. From the interviews, it seems like input parameters like HRR and fire growth rate are not necessarily altered based on these conditions usually. However, engineers do think that some of these conditions are addressed in other ways such as ceiling height is addressed when using Alpert's correlation for determining sprinkler activation time. Some of the interviewees had to say this:

"The honest answer has been most of us don't. If we take the deterministic approach, most people take their five growth rate from BS-9999 based on the occupancy type, max heat release rate, they'll take it from one of the PD 7346 standards or BRE 368. So the honest answer to that question is, we don't really capture that. In terms of let's say we have an office building where it's got different rooms, I'm trying to think of an example. So sometimes we have buildings that are kind of mixed use, right. So, we might have a residential building that has a portion of it that's effectively like an office. It's a social space, we might apply office design fire parameters to that space differently than we would to a residential space. But in terms of what you said, like capturing ceiling heights, the way we'd capture that, assuming for example, it's a sprinkler building, is would that be captured by when the sprinkler is estimated to activate. That would be captured in the sense of the output in terms of the smoke layer, in terms of entrainment, and all of these sorts of things in your model, but in terms of explicitly capturing it in your input parameters, my experience says that most people don't essentially. They kind of make a crude approximation based on the standards." - Engineer C

"If it starts to kind of diverge from that then we check them one by one. So each one of them is a risk area that we need to check. So if this ceiling is higher which is interestingly, it can be an atrium, it can be a high ceiling atrium, right? That's when we don't know what's going to happen to the smoke layer. So that's when we suggest that we cannot do it as a relevant building. We have to do extra analysis either we need to do hand calculations to see how much smoke is being produced, and how much like smoke will grow from the ceiling down and how can it affect other areas. That's one thing we can do. And if it is a certain material, like for example, like when it comes to materials also like it's not just one material you're looking at, sometimes you end up with a

composite material that it's made of five different materials. So, that's when you need to check test data; when you need to check like all other data you might be able to get from the project to make sure that it is reasonable. So I would say you need to also I tend to also rely on engineering judgment." - Engineer D

When it comes to variance in code recommendations for similar buildings or occupancy types, engineers were clear that the local standards and guides must be followed. This question was based on the fact that one of the participants from the UK mentioned the use of CV/M2 from New Zealand which has some different recommendations for input parameters in design fires.

Another important question was the capping of heat release rate in the pre-flashover t-squared model. The premise is that heat release rate in the design fire curve practically cannot go to infinity, so the engineers must be stopping the heat release rate at some point. There are a few approaches that were identified from the dataset:

1. In absence of sprinklers, the growth phase curve is stopped when the peak heat release rate identified for the compartment has been reached. From then on, the steady state phase is assumed.
2. When sprinklers are present, the growth phase curve is stopped when the sprinkler activates, the time for which is calculated using Alpert's correlation.
3. In absence of sprinklers, the growth phase curve is stopped when fire becomes ventilation controlled.
4. In absence of sprinklers, the growth phase curve is stopped when fire becomes fuel controlled.

The justification for using the first approach was in the conservative nature of it because you are stopping the curve at the maximum possible heat release rate as demonstrated by tests. Engineers also use ventilation or fuel controlled heat release rate on the other hand which might not be as conservative as selecting the peak heat release rate.

Role of Regulatory Authorities

The interviews conducted had a recurrent theme where engineers noted that the process of getting the fire safety designs approved is a lengthy process, often spanning 8-9 months. Due to these long waiting times, engineers do not feel incentivised to use innovative or alternate methods. The reason being, according to engineers, the regulatory bodies including the Building Control and the local fire service are usually more inclined to approve standardised methods. Some engineers thought that using non-traditional methods often raises eyebrows and strong evidence and justification is required to get any method besides those codified approved. A participant from the fire and rescue services clarified that the role of fire service is in fact not to approve, but to provide comments on compliance with *The Regulatory Reform (Fire Safety) Order 2005*, and functional requirements. They will express an opinion on the design approach used, but their role is always a statutory consultee or a non-statutory consultee, not the approving authority. The caution on the side of the regulatory bodies in the UK is understandable in the wake of the Grenfell Tower fire. Additionally, standardising does help fire service to perform more efficiently due to familiarity. One interviewee said this:

"Building safety is a global issue that has been around for ages. Everyone has their own preferences and agendas, and people tend to view the world from their own perspective. Firefighters, for instance, follow strict guidelines because they often risk their lives responding to fires in buildings they are unfamiliar with. If all buildings were similar, it would be easier for firefighters to operate in them. However, as a fire engineer, I find complex and challenging buildings fascinating, as they can be designed to meet human needs. There is a fine balance between a deregulated world and an over-regulated one, and the sweet spot is always in the middle. Human nature tends to swing from one extreme to another, but eventually, we will find that sweet spot." - Engineer A

An employee of the fire and rescue service was asked to give their opinion on this topic, an excerpt is as follows:

"I think what we want to see is that whatever approaches that's being applied is suitably justified by the design engineer and we want the building control body to have reviewed that primarily. Sometimes we see that the building control bodies, maybe they don't have the competence for in-house review. Whether its computational fluid dynamics modelling or whichever approach it is they may not have the competence to review it. In which case, we'd expect that they take it to suitably competent third party to peer review. What's been the design proposals as what we typically see for fire modelling? We very rarely see probabilistic approaches taken I think, as you say, a lot of that is because, there's a number of reasons, one of the concerns is that regulatory authorities won't (approve them readily) necessarily, but certainly we don't have a lot of experience with. We're familiar with probabilistic approaches. We do see them occasionally, but it's rare. Most of the time, except for where they're built into guidance already. Like open plan flat designs that approach in BS 9999 is based upon I think Monte Carlo analysis, for example. But, it's already built into the design. It's rare that we get sent probabilistic analysis that we have to then review. We're open to the receiving that I know does depend on having the regulatory authorities with the competence to be able to understand probabilistic assessments. We do need the detail of that usually so often what we will receive probabilistic assessments but we won't see any of the underlying methodology, and the input data. That's something we like to see. So that we understand where's the data coming from? It's been used to underpin the probabilistic analysis. So that can create quite a time consuming process even if the analysis itself is maybe less time consuming than computational fluid dynamics. It's ultimately the process of being able to demonstrate that potentially could take longer because you're relying on everyone in the process understanding the analysis." - Engineer B

To conclude the balance between giving engineers a free hand to regulating for fair practice and societal safety, efforts must be undertaken. It is clear that fire engineers, regulatory bodies and fire service are trying to uphold safety standards but maybe practicality can sometimes prevent them from taking up more robust analyses.

Discussion

Pre-flashover design fires are a fundamental input for performance-based fire safety calculations, and this research has tried to identify sources of uncertainties and complications in the literature underpinning the concept, due to which the process becomes less straightforward. The most optimistic expectation would then be that the industry be well-aware of these problems and possibly have ways to mitigate these problems. In this section we try to summarise the problems in the literature and the approaches industry uses to circumvent or address these problems, if there are any.

Firstly, there is not a lot of clear data available for the incipient phase duration of a fire since there are many factors which affect that duration even for the same fuel type. The industry addresses it, intentionally or unintentionally, by mostly discarding the inclusion of incipient phase in design fires with the justification that it is a more conservative practice, most of the times, because it means that untenable conditions, for example, are achieved quicker.

Secondly, having seen that the literature is not entirely convinced that the t-squared model represents the physics of fire phenomenon because it is not grounded in the first principles, the industry seems to be convinced that the model has represented most fires reasonably well, so there is no incentive to look toward more rigorous approaches. However, many engineers justified their choice of the t-squared model on it being the most common and easy to use model which reflects a possible lack of depth on the topic.

Thirdly, the problem of selecting pre-flashover design fire input parameters according to occupancy type does not seem to have been addressed. The problem is because of the possibility that code recommended values do not include conditions such as ceiling height, environmental factors, insulation and building materials. Most engineers do not directly address these problems in design fire calculations but believe that they are dealt with separately in the fire engineering process. When it comes to selecting a value from a code recommended range of values, the choice varies amongst engineers: Some people select the maximum value to create the most conservative solution, some select the mean value, and some select a lower value based on the risk profile of the occupancy in question. It was also seen that engineers might use guidance documents from other countries, although they mostly stick to the local performance guides, which can make the process irregular because of potential disagreements within guides. This necessitates the guides in such cases should be used with an extra bit of caution. Hence, there seems to be a variation in understanding of engineers when it comes selection to input parameters.

Fourthly, in the t-squared model the capping of heat release rate is an issue which engineers deal differently with, because In principle the curve can go up to infinity. The guiding principle in this case seems to be the presence or absence of sprinklers. In the absence of sprinklers engineers can either choose to cap the HRR at the maximum possible value which might have been obtained for codes or existing data, or they can choose to cap it when the fire is supposed to become fuel/ventilation controlled. This depends a lot on the judgement of the engineer and what he feels will result in more safe design which is not impractical either.

Fifthly, out of the two possible approaches for getting pre-flashover design fire curves, deterministic and probabilistic, the probabilistic approach is very rarely used. This is despite the fact that the literature that provides distributions of input parameters are present, and software such as B-Risk allows easier use of this approach. While most senior engineers agree that this is the approach that should ideally be used for comprehensive engineering analysis, it is very rarely done in practice by the industry at present, possibly because it is harder on time and resources.

Sixthly, options for building design fire models like project-specific experimentation and CFD modelling are very rare. In fact, CFD modelling is almost never used to do that except when doing pyrolysis modelling in FDS, but that too is not fluid dynamics technically. Project specific experimentation is carried out mostly for very unique projects which might have novel materials or an unusual array of combustibles in the compartment, if permitted by financial resources. Existing curves are however used mostly in instructional capacity, in that engineers often use them to guide their judgement for projects involving similar fuel loads, materials or occupancies.

In the realm of engineering solutions, it appears that engineers experience a sense of constraint when applying performance-based approaches due to various factors. One consideration is the possibility of designs being disapproved or facing delays in the approval process. Since the Grenfell Tower Fire in 2017, building control regulations and authorities have placed greater emphasis on scrutinizing and ensuring the safety of building designs. This increased scrutiny might have led to a perception among engineers that the approval process has become more stringent, causing them to approach their work with caution and potentially feeling restrained. A possible lack of competence and funding within regulatory authorities might also be a problem in this regards. In-house reviews of designs by regulatory authorities are often limited due to resource constraints, both in terms of expertise and financial support. As a result, they often rely on peer reviews as a preferred alternative but this reliance on external evaluations can be time-consuming and costly for all stakeholders involved. The need to seek external expertise and the consequent delays in the approval process might be exacerbating the engineers' apprehensions and may influence their decision-making process.

To summarize, when it comes to pre-flashover design fires, engineers may find themselves faced with a practicality dilemma. Engineers must navigate the complexities of fire safety regulations and ensure that the proposed designs meet the necessary standards while also considering the practical aspects of costs and implementation. The pressures stemming from the need to meet regulatory expectations, manage costs, and adhere to project timelines can influence their judgment and decision-making processes. It is important to acknowledge that building control authorities and fire and rescue services also operate with their own interests and the well-being of future occupants in mind. Their role is to safeguard public safety and ensure that buildings are constructed and operated in compliance with relevant regulations. By enforcing strict approval processes and fire safety standards, they strive to protect the lives and property of individuals residing or working in these buildings. The collaboration and coordination between engineers, regulatory authorities, and fire and rescue services are essential to strike a balance between safety requirements, practicality, and project efficiency.

Conclusion

There are a number of complications that an engineer can face when building pre-flashover design fires. The literature available and the prescriptions from codes, which the engineer usually bases their analysis can be dealt with by engineer in a number of ways. There is no standard procedure which would ensure homogeneity in design. One might argue that engineers are encourage to use their judgement in these matters, however, when the responses obtained in the ambit of this study show an array of quality of engineers' understanding of these complications.

The way the input parameters are selected, even though not always arbitrary, often does not involve a very careful digging of the literature and rests instead on basic understanding of the issue at hand. It can be seen that engineers do not really include conditions such as building and insulation materials while selecting a heat release rate for an occupancy which recent literature has questioned. The use of guides to ensure compliance is the predominant way of doing fire safety designs which means that engineers use input parameters according to occupancy types which might not ideal according to recent literature.

The approach taken to solve these problems is also a deterministic one: with conservatism guiding the process. A probabilistic approach where design fire scenarios, fuel loads, fuel arrangements, ventilation conditions, and input parameters such as heat release rates, fire growth rates etc., can be treated as variables is not practiced much in the industry. The common justification of the use of t-squared model as the default model for pre-flashover designs seems to be that it is the most widely-accepted does not really engender a lot of confidence in engineers' approach to this topic. On the plus side, a significant influence is the idea of conservatism in engineers' minds, such as when capping the heat release rate in the t-squared model, which guides their choices very often and can mean better safety, if not optimized results.

However, there are practical issues like delayed approvals and disapprovals, and problems with funding from clients which is needed to perform detailed analyses that might influence engineers' judgement to some degree when building design fires. It is understandable that engineers would rather follow the compliance documents if it meant that the project will progress unhindered due to long review times.

Bulleted Summary

Pre-flashover design fires play an important role when it comes to designing egress strategies, smoke control and suppression and detection systems. Since design guides do not mandate the use of any approaches and/or input parameters for design fires, the engineers use their judgement at many points during the process. The literature review conducted in order to identify potential sources of uncertainty and complications in the process can be summarized in the following points:

- The incipient phase, which precedes the growth phase of the fire, is not clearly defined in the literature and depends on ignition source, fuel load etc. which can create uncertainty in the output.
- t-squared model represents many experimental fairly fires well but there is controversy regarding it representing the actual physics of the fire.
- The recommended values of fire growth rate according to occupancy time can vary between different guides, especially if guides from different regions.
- The recommended values of fire growth rate according to occupancy type in design guides do not always capture the conditions of particular compartments such as insulation materials, building materials and ceiling heights.
- The recommended values of heat release rates in design guides do not always capture the conditions of particular compartments such as insulation materials, building materials and ceiling heights.
- The recommended values of heat release rates in design guides are based in literature but other literature with varying datasets recommends different values for similar occupancy types.
- The recommended values of heat release rates in design guides is often a range which means that engineers are not choosing a fixed value but deciding on which value to choose from a range, which can be chosen differently by different engineers.
- The input parameters including heat release rate, fire growth rate, fuel load, design fire scenarios and compartment conditions can be treated deterministically or probabilistically and datasets are available to treat some of these parameters as distributions.
- Experimentation, CFD modelling and use of existing curves are some of the identified alternatives to building a design curve using the model like the t-squared. Of course, the use of these techniques is not mutually exclusive as there is overlapping in the way they are carried out.

These complications mean that designers often face the challenge of making informed choices, to end up with what they consider to be the most appropriate design fire. The data collected from participants through surveys and interviews shows how designers approach some of these problems and what their preferred methods are:

- Performance-based design is not very often used in projects unless the particular infrastructure falls out of the realms of compliance documents. It does not mean that there is no aspect of performance-based design in most projects, but that most of the design is following the compliance documents.
- Performance-based design is used when legislative requirements are too demanding or the project cannot be designed according to the design guides because they do not address designs for specialized projects like nuclear facilities.
- Engineers mostly use deterministic approach when designing pre-flashover design fires because it is thought to be conservative and is also the easier approach. Many engineers have never used a probabilistic approach towards pre-flashover design fires.
- Most engineers use the t-squared model to represent the growth phase of the fire because it is the most commonly used, is simpler to use, and is easily approved by regulatory bodies.
- Most engineers do not include the incipient phase of when building the design fire, because it is generally thought to be a conservative approach.
- CFD software such as FDS are rarely used to build design fires using the pyrolysis model, which itself is not really CFD, but can be used in FDS and does not have wide acceptance in the industry.
- Engineers sometimes do conduct project-testing to get heat release rate values for novel materials or specialized projects, but it is not very often because such situations are not encountered very often and the resources can be limited.
- Existing design fire curves are rarely used as stock for projects but often guide engineers' judgement for their own design fires.
- Engineers mostly select fire growth rate values according to occupancy types or fire loading, if available, from design guides.
- Engineers might select fire growth rate values from design guides that might be from a different country, which might run the risk of getting differing outputs.
- Even though compartment conditions are dealt with in other steps, they are not exclusively dealt with while selecting input parameters for the design fire.
- Engineers mostly select fire growth rate values according to occupancy types or fire loading, if available, from design guides.
- When choosing from a range of recommended HRR values engineers chose the maximum or mean value. The most cited reason for it is that it is more conservative but often is limited to just that.
- HRR is capped according to presence or absence of sprinklers mostly, and in the absence of sprinklers either fuel/ventilation controlled fire is assumed or the max. HRR is assumed to represent the worst case scenario.
- Engineers felt that the design guides provided a conservative approach which works well in most cases but some felt that longer approval times, rigid demands of regulatory authorities and a possible lack of competent evaluation resources often discourage engineers from using more complex or optimized engineering methods.

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