Scientific paper

Designing an Underground Car Park Fire Scenarios on a Probabilistic Basis

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Dedicated to the memory of the late Prof. Dr. Valentin Koloini

Abstract

Designing a fire safety measures can be usually achieved in a two ways. One or we should say more conservative way is the use of prescriptive based codes, where all design prerequisites are mainly written in codes. Other or second option is the use of performance based design, where the group of designers, building owners and authorities having jurisdiction are setting up a milestone and design requirements. Simulation of fire and its consequences constitutes a cornerstone of modern fire safety engineering: the simulations enable to examine computationally the adequacy of the design with respect to a wide range of fire safety objectives including safety of life, directly exposed or neighboring property and infrastructure as well as the environment. Each simulation must be based on a realistic fire scenario, which technically formulates social expectation of safety. Designing realistic fire scenarios is even more important when underground car park is chosen as the subject of analysis. Setting the realistic goals and outcomes is a real technical problem that requires realistic and reliable inputs. It is found that fire scenario inputs can be statistical weighted and analyzed.

Keywords: Fire safety, underground garage fires, fire scenario, probability methods

1. Introduction

The fire protection engineer has a vital role to play to ensure reliable performance of fire protection systems in a car park structure and to ensure significant life safety for building occupants. The first role is establishing the performance objectives of the installed systems and design features. In performance based designs, the integrated fire protection strategy must respond to design basis events (fire scenarios). These objectives establish expectations placed on the system and define what constitutes a success or failure on demand. The challenge going forward is developing accurate quantitative predictions of when fire protection systems respond and how they influence on fire spread.

The second role is establishing the system reliability in terms of system integrity and performance. This includes provisions of survivability. These performance attributes assure the fire protection systems response, after fire starts, to meet performance objectives. Additionally, evaluating the influences of different component failure modes on system performance is useful to assure that sufficient robustness and redundancy are built into the design.

One of the major tasks of the shown probabilistic methods is to produce the base line for a performance-based fire designer who is using a simple zone or CFD computer codes. This process has been demonstrated for one single example such us fire growth prediction.

2. Fire Simulations

Although the fire safety computer models are going nowadays through the "judgment" phase, they can still represent good and economically qualified engineering tool. However, when fire safety models are used, a designer must know the model capabilities, limitations and uncertainties. All models are based on physical phenomena; they are abstractions and idealizations with inherent uncertainties that are both qualitative and quantitative. Models can not “predict” the phenomenon as such. They can be used to highlight the trend of certain dependent parameters that in themselves are abstractions and were manifestations of reality. Validation in its simplest form involves a comparison of model calculations with measurements of quantitative variables in a real case. A validation process should determine the degree of accuracy of fire calculation of fire parameters for hazard analysis purposes. It is clear that validation results will be better and closer to a real case if the model input parameters will address the real situations and will represent the “most likely” outcome.

Conventionally, simulations are performed in a deterministic way i.e., they are carried out using fixed parameter values selected by the user. However fire is by its nature a stochastic phenomenon which introduces a great deal of variability to the development of a fire incident.

The spread of fire in a building is governed by physical and chemical processes evolved by a variety of burning materials arranged in different ways. Multiple interactions among these processes at different times cause uncertainties in the pattern of fire development. Reliability of systems for fire detection, suppression and behavior of people in a fire are other sources of uncertainty.

Probabilistic techniques offer rational methods of dealing with the randomness of fire risk and effectiveness of fire safety measures. The estimates provided by these models can be used in conjunction with different fire design methods such us computational fluid dynamics tools for assessing underground car park fire spread.

3. Performance Based Design

Performance-based design is currently in development worldwide. As performance-based designs become more common, however, they present a special challenge to facility executives: maintaining fire protection features during future operations, maintenance or renovation work. The easiest way to understand the concept of performance-based design is to start with the traditional prescriptive-based design. Building codes have typically prescribed specific design criteria, such as the number of exits or the distance to an exit; these are numeric criteria that can be easily measured.[1,2]

By contrast, a performance-based code allows the use of any design that demonstrates compliance with the fire safety goals of the code. Those fire safety goals are explicitly spelled out in the code, as are methods that can be used to demonstrate compliance. A performance-based design starts with an analysis of *fire scenarios* to determine which design alternatives will meet those fire safety goals.[2–5]

The performance-based approach affords the design team greater flexibility than the prescriptive code requirements.

A performance-based design may incorporate any number of fire protection features. Use of performance based design in car parks structures can for example reduce sprinkler activation temperatures or decrease spacing to decrease anticipated fire sizes by reacting more quickly to a fire. On the other side, performance based design can reduce fire detection time or influence on underground garage fire load.

4. Performance Based Inputs

While in the performance based design the goals are often described with the lives and property saved criterion, the engineering requirements are expressed in technical terms, not in life and property safety goals.

Originally performance based methods suggested total illumination of regulatory decision making in the code enforcement method. Nowadays it is clear that the combination of performance based and prescriptive design codes is acceptable way of fire safety design.

Though we are developing performance based codes, regulation usually require a precise technical system for measuring design compliance with the social requirements. In the process of developing performance based codes these key steps was omitted. Even in instances where the actual hazard of risk can be evaluated, no one developed a comprehensive method for expressing social judgments about fire safety or fire hazards in useful regulatory terms.

Fire models originated in the explanation of specific fires whether in laboratory or in the real world. There were fires in which the modeler knew virtually all the key environmental variables of the fire. In these fires the “hard” part of the task was reliably modeling the thermodynamics, mass loss, ventilation etc.

In a performance based design process, the design inputs have to be carefully developed and well understood. Their effect on the design is critical for the development of car park fire safety. The process of a performance based fire safety design must properly assess model inputs.

A performance based fire safety analysis uses many different types of inputs. It is possible to identify both “hard” and “soft” inputs. Hard inputs are usually based on precise laboratory findings, but data on human behavior and similar variables for which no standard exists, are often very “soft” variables. Regarding car park fire scenarios “hard” variables are the laws of thermodynamics, mass loss, combustion properties etc. Defining fire scenario characteristics for car parks, “soft” variables can be human behavior, fire load, building condition, initial fire conditions, fire brigade response, active and passive fire protection system response etc.

5. Defining Car Park Fire Scenarios

A fire scenario is a generalized, detailed description of an actual or a hypothetical, but credible, fire incident.[6] Such scenarios identify chains of events leading to deaths and other fire losses.

The fire scenario is mainly just a set of fire conditions. The building fire safety design concept is the solution of more or less well defined predefined variables.

Each fire scenario includes all details relevant to the development of a fire and a subsequent behavior of people and mechanisms of protection. When properly developed, a fire scenario describes all essential element of fire incident. The components which make up the events and conditions of a fire scenario are not fixed. They may include events such as:

– ignition,
– fire spread,
– extinction,
– evacuation,
– smoldering or flaming combustion,
– smoke production,
– flashover,
– back-draft,
– etc.

and conditions represented by materials, environment, energy sources, detection system, containment systems, life support systems.

Development of fire scenarios requires a constructive use of imagination and experiences. Judgment and extrapolation are very important because only limited data are available.

A design fire scenario might concentrate on the pre-flashover, when the evacuation from the structure will occur and on post-flashover stage, when the impact on the car park structure becomes important. The pre-flashover stage is associated with a growth rate, e.g. slow, medium, fast or ultrafast.

An analysis of the expected fire scenario is the initial focus of a performance evaluation. We may identify several steps of underground garage performance design evaluation:

– identify an area or room of origin to start the process of understanding the building,
– assess the barrier properties,
– select a fire growth hazard for the assessed room,
– estimate a fire duration from established burning (EB) to full room involvement (FRI) for floor of origin,
– estimate a fire duration from EB to FRI along a fire propagation path.
– etc.

Since traditionally fire scenario deals mainly with fire growth curve some other as well important factors must be included into a preparation stage for fire scenario (Fig.1).

When establishing fire scenario, we must determine the *fire characteristics*. Fire characteristics are ignition sources, growth rate, time to flashover or fully developed fire, fire location and fire duration.

When we determine the *building characteristics*, features such as architectural features, structural components, fire protection systems, building services/processes, building operations, emergency responder response characteristics and environmental factors must be assessed.

Final stage of designing fire scenario parameters is *determination of building occupants*. We must consider number of occupants, occupant distribution throughout the building, alertness (sleeping, awake, etc.), commitment, physical and mental capabilities, familiarity, social affiliation and physical and physiological condition.

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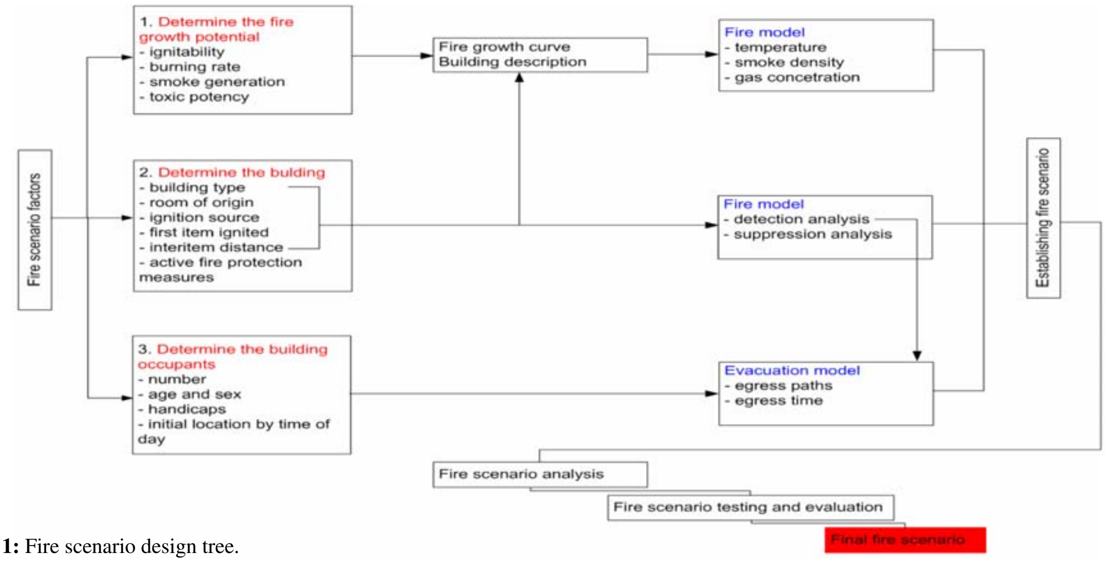

Figure 1: Fire scenario design tree.

luation:

a. identify an area or room of origin to start the process of understanding the building,
b. assess the barrier properties,
c. select a fire growth hazard for the assessed area or room,
d. estimate a fire duration from established burning to full room involvement for the single garage level,
e. estimate a fire duration from established burning to full room involvement for the multiple garage levels along the fire propagation path.

6. Evaluation of the Burning Vehicles Heat of Combustion

Full room fire involvement in large car parks initially starts with a fire in a single car. The fire size at this stage involves initial car and the proximity of an adjacent fuel package such as nearby cars. The process continues spreading to other cars until conditions reach a level where full room involvement or its equivalent is present. While hot layers do form at the ceiling and back radiation does pyrolize unburn fuels, the principal mechanism of fire growth is a direct radiation introduced fire propagation throughout the arrangement of cars in underground garage floor.

Fire scenario shall cover the real description of the fire development. Basic input information for the fire scenario is the heat of combustion and the quantity of combustion products. One aspect which must be taken into consideration, among others, is that fires described in the sources available (e.g. laboratory investigation reports, fire service operational reports, publications in specialist journals, newspaper articles) are not always described in sufficient details. Namely, problems related to fire protection and those encountered when fighting the fire need to be adequately assessed. Furthermore, the technical developments during the assessment period also have to be taken into account.

Some of the car fire test reports are summarized:

1. Mangs and Keski – Rahkonen fire tests based on two vehicles.[7] Heat release rate during their tests was 3.5 MW. Their experiment did not cover larger vehicles.
2. Researchers in Profile ARBED laboratories analyzed two and three vehicles in their fire test.[8] Their conclusions showed that the heat of combustion generated during the burning of two vehicles after 4 minutes was 1.5 MW. It remains constant until about 24 minutes, when it rises to 8.5 MW. In 26 minutes the amount heat of combustion reaches the top value. Fire enters the declining phase at about 70 minutes. Three vehicles reached release rate of approximately 4 MW of heat after 12 minutes and reached the 16 MW at 26 minutes. The fire went to the declining phase after about 38 minutes.
3. In years 1995 and 1996, Schleich has shown that the amount of heat of combustion from the vehicle made in 1995 doubled in relation to older vehicles.[8]
4. Tests at EUREKA laboratory showed that a single vehicle reaches about 5 MW, while two to three vehicles reaches approximately 8 MW of heat.[9]
5. The results of other tests have shown that burning of single car can reach up to 8.5 MW, while 2 cars can reaches up to 15 MW.[10] The results of the tests have shown that, for example large off-road vehicles emit significantly larger amounts of heat than normal cars.
6. In year 2000 Steinert tested two vehicles simultaneously.[11] The distance between the test vehicles was 80 cm. In most of the fire tests, fire spread (jump) from one vehicle to the adjacent vehicle. Some of the fire tests lead to a flashover.

Following the measurements and experimental results we can assert that car burning heat release rates are in upwarding trend (Fig. 2). The statement supports Schleich test report where he stated that the amount of heat of combustion from the vehicle made in 1995 doubled in relation to older vehicles.

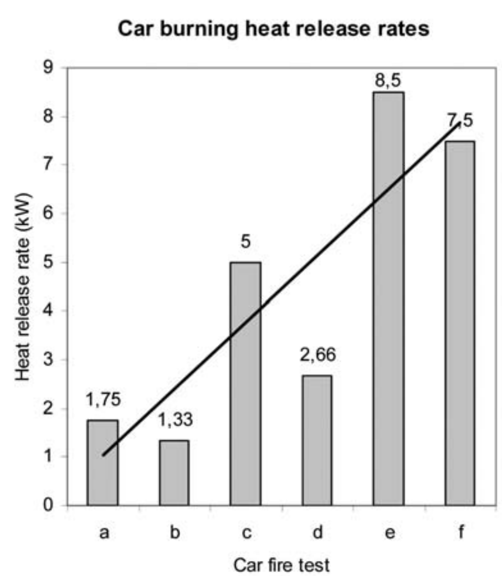

Figure 2: Summary of car fire HRR rates.

Heat release rates influence significantly fire growth from ignition to flashover. During this period, many complex phenomena occur. The rates of flame spread, heat release, smoke formation, and flow of fire gases depend on fire environment characteristic. The compartment effect, size of the compartment, ventilation opening, nature of combustibles, furnishings, and finishing all play important roles in the growth of fire.

7. Fire Growth Potential

A fire in a room starts with an ignition in a fuel package and the fire either grows or dies out depending upon the conditions in the room that influence its behavior.[12] The interior design of the car park area, including the number of cars, type of cars and their arrangement, as well as the level size, shape and ventilation characteristics have an important influence on the potential for fire growth in car park buildings.

Until now several car fire tests were performed as it was shown previously. Usually as the fire developed, the closed windows on the nearby car broke and fell out.

It is important to note that in evaluating the fire growth potential it is assumed that no automatic or manual type of suppression operates. Evaluations are based only on the natural fire characteristics and behavior of the expected combustion in the space.

The dominant mechanism for reaching garage floor involvement is flashover. Flashover in a closed underground car park building is characterized by following:

- Fire starts somewhere underneath a car or in a car.
- A fire plume forms and a hot layer of heated gases of combustion and soot develops at the generally low ceiling.
- Ventilation provides sufficient air to support combustion.
- Hot layer radiation and some radiation from the flames pyrolize other unburned fuels (adjacent cars) in the garage floor.
- Ignition of adjacent cars in the garage floor occurs.

The described fire development requires some time, depending on floor size and fire load.

There are approximately 6 benchmarks and realms linked to a fire growth potential:

1. pre-burning – the period of heating and volatilization due to overheating until ignition occurs.
2. initial burning – the period during which the first fragile flame that defines ignition attempts.
3. vigorous burning – the domain in which an established burning grows within the fuel package and develops strength and stamina of its own.
4. interactive burning – the fire exceeds the enclosure point and continues to grow. This is usually a result of interactive burning between adjacent cars. The fire power when the flames touch the ceiling in normally in range of 800 kW or 1MW.
5. remote burning – fire ceiling jet develops and radiates heat energy to other fuels causing an increased rate of volatilization. Some cars remote from the initial ignition may experience autoignition and additional fires may start in the underground car park.
6. full room involvement – flashover will occur as a rapid fire involvement of all of the exposed cars.[13]

Conduction and convection are mayor energy feedback mechanisms during the pre-burning. On the other hand, the vigorous burning and the developed burning stage are mostly supported by thermal radiation. Room geometry and ventilation plays its role when the fires become fully developed.

8. Fire Growth Analysis and Predictions

The fire growth potential is a key descriptor that identifies the relative hazard that is caused by the garage content like number and type of the cars, their arrangement, as well as the room geometry and thermal conditions that affect fire development in the space. Key point that we all are aware of is full room involvement, when fire in underground garage will mainly become uncontrolled.

As a fire growth analysis presents a fire scenario key parameter, there are two ways to analyze and predict the fire growth: probabilistic and risk assessment tools. To prepare a realistic input parameter for a car park fire scenario, we are trying to define and analyze the predictions and chances that fire will terminate before:

- it grows to the enclosure point,
- it grows to reach the ceiling,
- it grows to full room involvement.

Fire development and growth to the enclosure point depend on fuel and room shape. Fuel characteristics are burning car size and production date, continuity, flame temperature, orientation and dimensions and ignition temperature.

In a typical underground car park building structure common fire scenario can be a car ignition, where we may assume that gasoline or diesel fuel will present one of the primary fuels.

Fire growth to the ceiling point generally depends on fuel, room or floor characteristics and ventilation. The important room and floor details are ceiling height, proximity of flames to walls and insulation. Ventilation factors are size and location of openings and active fire protection measures such us heating, ventilation and air-conditioning operation.

Fuel factors of major importance are fuel package size and fuel location and arrangement. Environment factors are smokiness and radiant heat transfer. Floor details that influence fire growth to fool room involvement are ceiling height, length to width ratio and room insulation. Ventilation as the last factor is influenced by openings (location and size), heating, ventilation and air- conditioning operation and venting in case of fire.

The smoke control influence can be analyzed using a risk decision trees as shown in Figure 3. For the present decision tree statistical data on underground garage fires in Slovenia in a 10-year period was used. Operational sta-

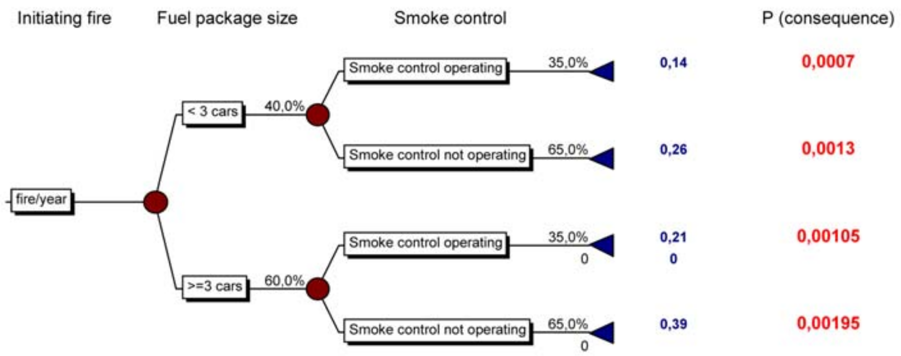

Figure 3: Risk decision tree for smoke control.

tus of smoke control systems was obtained from a national fire service survey.

The calculated results (Fig. 3) show that we may expect approximately 60% fires, where 3 or more cars were involved. In addition to that, smoke control operates properly in approx. 35% of analyzed car parks. The decision tree calculation shows, that the worst case scenario will apparently be the one with three or more cars involved in a fire and a non-operating smoke control. The results can somehow be compared with the fire growth potential, where it was shown that in many enclosed fires a non-operating smoke control will increase the speed of fire spread.

Possible fire development stages like fire growing to the enclosure point, fire growing to reach the ceiling, and fire growth to full room involvement can be analyzed using value networks. A fire curve can be designed in several continuous stages as follows (Fig. 4):

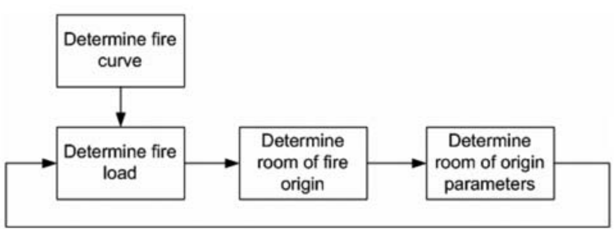

Figure 4: Fire curve design steps.

As a pre-stage when designing a fire curve, performance-based fire designer can used a Venn network diagrams. These diagrams are representing choice events and possible outcomes. The first requirement of Venn diagram is that probability must lie between 0 and 1. Mathematically, we write P(AđB) to represent the conditional probability of A that B occurs. Read it as "Probability of A given B" The definition is

$$P\langle A|B\rangle = {}^{P(AandB)}\!\!\diagup_{P(B)} \qquad (1)$$

Network diagrams are used to organize an analysis and to structure evaluation. A network is a semi graphical framework that can be used to establish and analyze established fire scenarios.

The fire growth model is capable of predicting fire conditions that develop during the pre-flashover stages of a compartment fire. The fire growth model consists of value network, where values are based on statistical, engineering and experienced data. A sample calculation is shown in Figure 5.

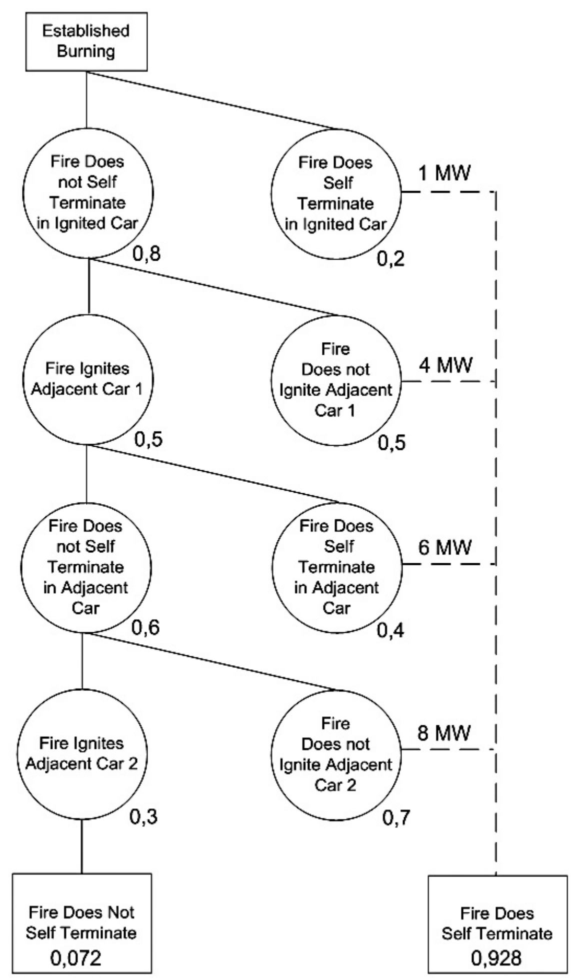

Figure 5: Value Network Solution.

Continuous value networks are used to describe the thought process for a scenario evaluation. There are several reasons for detailed analysis of a scenario:

– codes and regulations where the fire safety concepts and scenario are required,
– fire modeling software where pre-determination of fire input parameters and detailed description of fire scenarios is recommended and sometimes required as well.

Probabilistic values describe the judgmental estimate that an event will occur. The probabilistic descriptor and any documentation are based on the information and knowledge that is available at the time of the evaluation.

Detailed input parameters for a typical car park garage fires can be obtained from building fire design documents, statistical data and experienced engineer. Value network results can be compared to a numerical simulation and experimental data.[14] The CFD calculations show that extinction of the fire occurs due to lack of oxygen. The probability calculation that fire will self terminate (P = 0.928) can support the CFD analysis with some confidence. In addition to probabilistic values, user can find some significant fire growth data from past experiments and combine them with prescribed probabilistic values. For the present analysis, significant values were obtained from Mangs and Keski – Rahkonen experiment. Fire self termination is inherently linked with the buildup of other hazardous gases such as CO and HCN.

Using value network diagrams and decision trees several factors that influence on fire scenario were analyzed and calculated. Results for fire spread, smoke control operability and CO formation are shown in Figure 6.

There results are consistent with the results obtained experimentally and with CFD models. Where at some point results were inconsistent (for example CO formation at higher fire loads), the most obvious reason for inconsistency were over-predicted fire loads in CFD calculations.

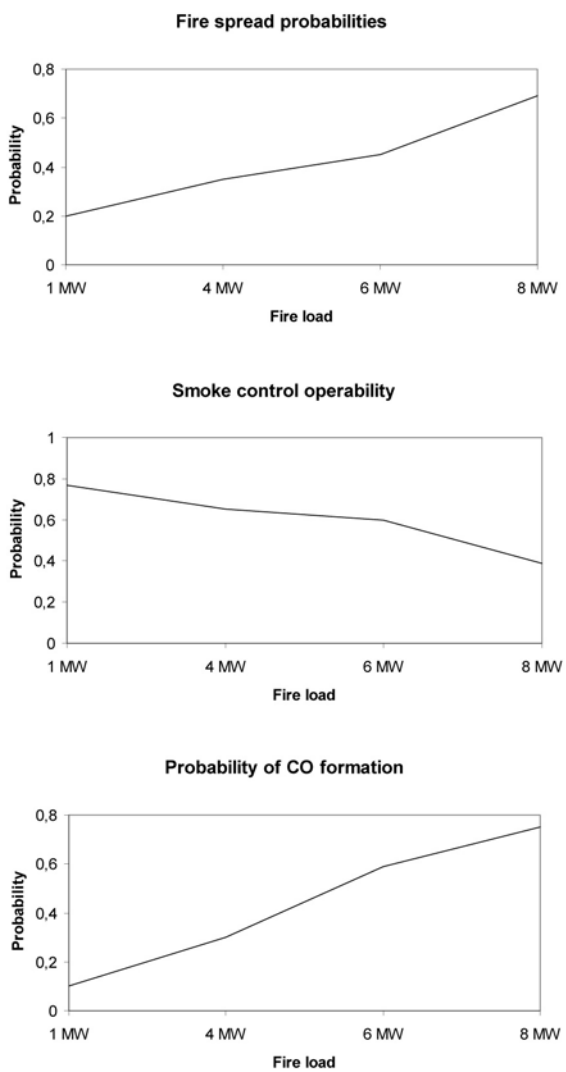

Figure 6: Calculated fire scenario probabilities.

9. Accuracy of the Fire Models

Performance-based design allows for significant design flexibility; however, therein lays a great responsibility to maintain fire protection features that might be beyond those normally required by code.[15] Since the fire models are often used tool in performance-based design responsibility based on fire models is significant. It was shown that in some cases the user over predicts fire loads and consequently calculate unrealistic fire scenarios.

The accuracy of a fire model may be assessed by its ability to predict the results of actual experimental data.[16] It was shown many times that some correlations over predict temperature rise while others tend to under predict it. It is important to understand how variation between predicted and measured values affects the use of correlations and models for performance-based design or evaluation.

Despite of model accuracy, several key factors must still be developed: standard fire scenarios or fire scenario lower and upper limitations, detailed procedures to establish, test and implement the fire scenario framework, and common and reasonable language for performance specifications.

10. Conclusions

The fire protection engineer has a vital role to play to ensure reliable performance of fire protection systems in the car park structure and to ensure life safety for building occupants. The first role is establishing the performance objectives of the installed systems and design features. In performance based designs, the integrated fire protection strategy must respond to design basis events (fire scenarios). These objectives establish expectations placed on the system and define what constitutes a success or failure on demand. The challenge going forward is developing accurate quantitative predictions and basis for reasonable fire scenarios of the fire protection systems response and its influence on fire spread.

The next role is establishing the system reliability in terms of system integrity and performance. This includes provisions of survivability. These attributes ensure that the fire protection systems response meets performance objectives. Additionally, evaluating the influences of different component failure modes on system performance is useful to guarantee that sufficient robustness and redundancy are built into the design.

One of the major tasks of the presented probabilistic methods is to produce the baseline case for a performance-based fire designer who is using a simple zone or CFD software. This process has been demonstrated for a single example such as fire growth prediction.

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Povzetek

Načrtovanje požarnovarnostnih ukrepov lahko dosežemo na dva načina. Medtem, ko je uporaba klasičnih predpisov bolj konzervativen način načrtovanja požarnovarnostnih ukrepov, je ena od sodobnih poti načrtovanja požarne varnosti uporaba inženirskih metod, kjer koncept požarne varnosti skupaj formulirajo projektanti požarne varnosti, investitorji in organi nadzora. Glavno orodje načrtovanja požarnovarnostnih ukrepov z inženirskimi metodami je simuliranje požarov z računalniškimi modeli, saj le ti ob upoštevanju dejavnikov, kot so varnost uporabnikov in premoženja ter vpliv na okolje, omogočajo analizo predvidene zasnove objekta. Ob uporabi računalniških modelov morajo vse predpostavke temeljiti na realnem požarnem scenariju, kar je v primeru načrtovanja požarnovarnostnih ukrepov v podzemnih garažah še toliko bolj pomembno. Vstopne podatke, ki jih uporabnik vstavlja v računalniški model, lahko predhodno statistično ovrednotimo in analiziramo, kar pripomore k večji zanesljivosti rezultata.