PROBLEMS AND ACTUAL SOLUTIONS IN QUANTITATIVE FIRE HAZARD ANALYSIS

UDC 614.841.3

Jovan D. Ristić

Electrotechnical Faculty, Pristine

Abstract. *Firs step in planning fire security measures is fire hazard analyses. Historically, most fire safety regulation has been on the basis of fire hazard analysis, where such estimations were based on the judgment of "experts." Today formal, scientifically based fire hazard analysis is common and increasingly being required at a means to avert certain outcomes, regardless of their probability. This paper will discuss the differences between hazard and risk analysis, the process of performing a fire hazard analyses, and resources available to assist in this process.*

Key words: *analyses, hazard, fire*

1. INTRODUCTION

The goal of fire hazard analyses is to determine the expected outcome of a specific set of conditions called a scenario. The scenario includes details of the room dimensions, contents, and materials of construction; arrangement of rooms in the building; sources of combustion air; position of doors; number, locations, and characteristics of occupants; and any other details that will have an effect on the outcome of interest. This outcome determination could be made by expert judgment; by probabilistic methods using data on past incidents; or by deterministic means, such a fire model. The trend today is to use models wherever possible, supplemented where necessary by expert judgment. While probabilistic methods are widely used in risk analysis, they find little direct application in modern hazard analyses.

Hazard analysis could be thought of as a component of risk analysis. That is, a risk analysis is a set of hazard analyses that have been weighted by their probability of occurrence. The total risk is then the sum of all of the weighted hazard values. In the insurance and industrial sectors, risk estimations generally target monetary losses, since these dictate insurance rates or dictate a level of protection. In the nuclear power industry, probabilistic risk estimation has been the basis for safety regulation. Here they most often

---

examine the risk of a release of radioactive material to the environment, from anything ranging from a leak of contaminated water to a core meltdown.

FHA performed in support of regulatory actions generally look at hazards to life, although other outcomes could be examined as long as the condition could be quantified. For example, in a museum or historical structure, the purpose of fire hazard analyses could be to avoid damage to valuable or irreplaceable objects or to the structure itself. It would then be necessary to determine the maximum exposure to heat and combustion products that could be tolerated by these items before unacceptable damage occurs.

2. PERFORMING A FIRE HAZARD ANALYSES

Performing the fire hazard analyses is a reasonably exact, engineering analysis with defined procedure. The steps in that procedure include: 1. Selecting a target outcome, 2. Determining the scenario(s) of concern that could result in that outcome, 3. Selecting design fire(s), 4. Selecting an appropriate method(s) for prediction, 5. Performing an evacuation calculation, 6. Analyzing the impact of exposure, 7. Accounting for uncertainty. At the rest of this paper all of said steps would be discussed.

2.1. Selecting a target outcome

The target outcome most often specified is to avoid fatalities of occupants of a building. Another might be to ensure that fire fighters are provided with protected areas from which to fight fires in high-rise buildings.

For energy objects, such request is wholly different: 1. Minimizing the potential for the occurrence of fire, 2. No release of radiological or other hazardous material to threaten health, safety, or the environment, 3. An acceptable degree of life safety to be provided for personnel, and no undue hazards to the public from fire, 4. Critical process control or safety systems that are not damaged by fire, 5. Vital programs that are not delayed by fire (mission continuity), 6. Property damage that does not exceed acceptable levels.

Resident objects have different requests for acceptable fire hazard level. These include: 1. Limit the probability of fatalities or major injuries to only those occupants intimate with the fire ignition, 2. Limit the probability of minor injuries to only those in the residence unit of origin, 3. No occupant outside of the residence unit of origin should be exposed to the products of combustion in a manner that causes any injury, 4. Limit the probability of flame damage to the residence unit of fire origin (this includes taking into account the possibility of flame extension up the exterior of the building), 5. Limit the probability of reaching hazardous levels of smoke and toxic gases in the residence unit of fire origin before safe egress time is allowed. At no time during the incident should the smoke conditions in any compartment, including the compartment of origin, endanger persons in those compartments or prevent egress through those compartments, 6. Limit the incident to one manageable by the Fire Department without major commitment of resources or excessive danger to fire fighters during all phases of fire department operation; i.e., search and rescue, evacuation, and extinguishment.

An insurance company might want to limit the maximum probable loss to that which is the basis for the insurance rate paid by the customer. A manufacturer wants to avoid failures to meet orders resulting in erosion of its customer base; and some businesses must

guard their public image of providing safe and comfortable accommodations. Any combination of these outcomes may be selected as appropriate for fire hazard analyses, depending on the purposes for which they are being performed.

2.2 Determining the scenarios of concern

Once the outcomes to be avoided are established, the task is to identify any scenarios that may result in these undesirable outcomes. Here, the best guide is experience. Records of past fires, either for the specific building or for similar buildings or class of occupancy, could be of substantial help in identifying conditions leading to the outcome(s) to be avoided. Statistical data on ignition sources, first items ignited, rooms of origin, etc., could provide valuable insight into the important factors contributing to fires in the occupancy of interest. Descriptive reports of individual incidents are interesting, but may not represent the major part of the problem to be analysed.

Murphy's Law (anything that could go wrong will) is applicable to major fire disasters; i.e., all significant fires seem to involve a series of failures that set the stage for the event. Thus, it is important to examine the consequences of things not going according to plan. In energy objects, one part of the analysis could bee to assume both that automatic systems fail and that the fire department does not respond. This is used to determine a worst-case loss and to establish the real value of protective systems. If nothing else, such assumptions could help to identify the factors that mean the difference between an incidental fire and a major disaster so those appropriate backups could be arranged.

Scenarios must be translated into design fires for fire growth analysis and occupant assumptions for evacuation calculation.

2.3. Selecting design fires

Choosing a relevant set of design fires with which to challenge the design is crucial to conducting a valid analysis. The purpose of the design fire is similar to the assumed loading in a structural analysis; i.e., to answer the question of whether the design will perform as intended under the assumed challenge. Keeping in mind that the greatest challenge is not necessarily the largest fire (especially in a sprinkled building), it is helpful to think of the design fires in terms of their growth phase, steady-burning phase, and decay phase. (See Figure 1.)

GROWTH: The primary importance of the appropriate selection of the design fire's growth is in obtaining a realistic prediction of detector and sprinkler activation time, time to start of evacuation, and time to initial exposure of occupants.

In 1972, Heskestad first proposed that, for these early times, the assumption that fires grow according to a power law relation works well and is supported by experimental data [5]. He suggested fires of the form:
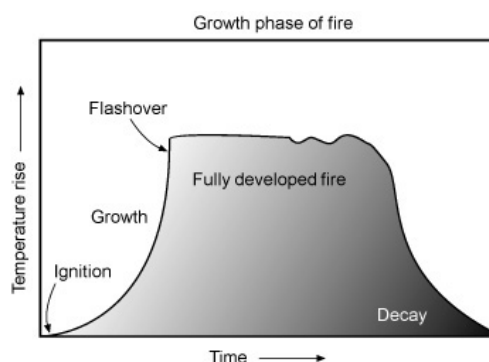
$$Q = at^n$$

Fig. 1. Design fire structure.

Where is: Q = Rate of heat release (kW), α = Fire intensity coefficient (kW/s^n), t (s) and n = 1,2,3.

Later, it was shown that, for most flaming fires (except flammable liquids and some others), $n = 2$, the so-called t-squared growth rate [11]. A set of specific t-squared fires labelled slow, medium, and fast, with fire intensity coefficients (a) such that the fires reached 1,055 kW in 600, 300, and 150 sec, respectively, were proposed for design of fire detection systems [6]. Later, these specific growth curves and a fourth called "ultra-fast," [12] that reaches 1,055 kW in 75 sec, gained favor in general fire protection applications.

This set of t-squared growth curves is shown in Figure 2. The slow curve is appropriate for fires involving thick, solid objects (e.g., solid wood table, bedroom dresser, or cabinet). The medium growth curve is typical of solid fuels of lower density (e.g., upholstered furniture and mattresses). Fast fires are thin, combustible items (e.g., paper, cardboard boxes, draperies). Ultra-fast fires are some flammable liquids, some older types of upholstered furniture and mattresses, or other highly volatile fuels.

In a highly mixed collection of fuels, selecting the medium curve is appropriate as long as there is no especially flammable item present. It should also be noted that these t-squared curves represent fire growth starting with a reasonably large, flaming ignition source. With small sources, there is an incubation period before established flaming which could influence the response of smoke detectors (resulting in an underestimate of time to detection). Adding a slow, linear growth period until the rate of heat release reaches 25 kW could simulate this.
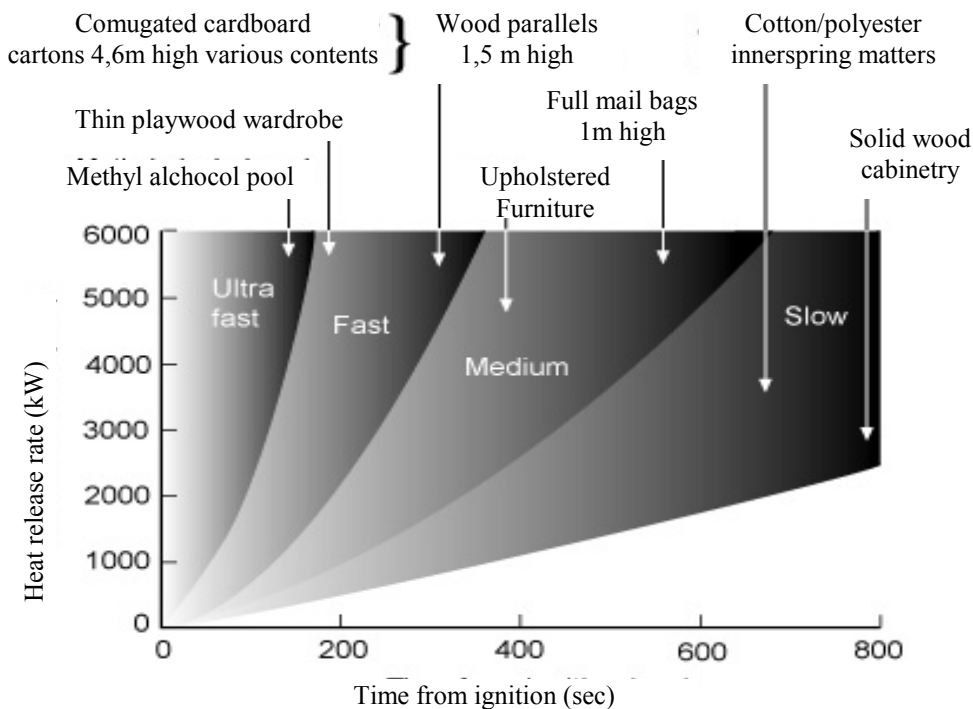

Fig. 2. Set of t-squared growth curves.

This specific set of fire growth curves has been incorporated into several design methods. They are also referenced as appropriate design fires in several international methods for performing alternative design analyses in USA, Australia and Japan, and in a product fire risk analysis method published in Japan [1]. While in the Australian methodology the selection of growth curve is related to the fuel load (mass of combustible material per unit floor area), this is not justified since the growth rate is related to the form, arrangement, and type of material and not simply its quantity. Consider 10 kg of wood: arranged in a solid cube, sticks arranged in a crib, and as a layer of sawdust. (See Figure3.) These three arrangements would have significantly different growth rates while representing identical fuel loads.

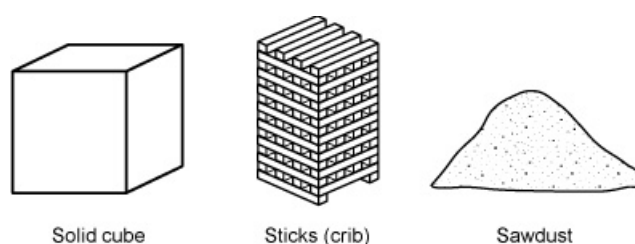Solid cube   Sticks (crib)   Sawdust

Fig. 3. Fire growth depends on fuel form and arrangements. 10 kg of wood represent
identical fuel loads but produce different rates of heat release in a room.

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

Most fires of interest will be ventilation controlled. This is a distinct advantage, since it is easier to specify sources of air than details of the fuel items. This makes the prediction relatively insensitive to both fuel characteristics and quantity, since adding or reducing fuel simply makes the outside flame larger or smaller. Thus, for ventilation-controlled situations: (1) the heat release rate could be specified at a level that results in a flame out the door, and (2) the heat released inside the room will be controlled to the appropriate level by the model's calculation of available oxygen. If the door flame is outside, it has no effect on conditions in the building; if in another room it will affect that and subsequent rooms.

DECAY: Burning rate declines as the fuel is exhausted. In the absence of experimental data, an engineering approximation specifies this decline as the inverse of the growth curve; this means that fast-growth fuels decay fast and slow decay slow. It is often assumed that the time at which decay begins is when 20 percent of the original fuel is left. While these are assumptions, they are technically reasonable.

This decay will proceed even if a sprinkler system is present and activated. A simple assumption is that the fire immediately goes out; but this is not conservative. A recent National Institute of Science and Technology (USA) study documents a (conservative) exponential diminution in burning rate under the application of water from a sprinkler [8]. Since the combustion efficiency is affected by the application of water, the use of values

of soot and gas yields appropriate for post-flashover burning would represent the conservative approach in the absence of experimental data.

2.4. Selecting an appropriate method(s) for prediction

A recent survey [4] documented 62 models and calculation methods that could be applied to fire hazard analyses. Thus, the need is to determine which ones are appropriate to a given situation and which are not. The key to this decision is a thorough understanding of the assumptions and limitations of the individual model or calculation and how these relate to the situation being analysed.

Fire is a dynamic process of interacting physics and chemistry; so predicting what is likely to happen under a given set of circumstances is daunting. The simplest of predictive methods are the (algebraic) equations. Often developed wholly or in part from correlation to experimental data, they represent, at best, estimates with significant uncertainty. Yet, under the right circumstances, they have been demonstrated to provide useful results, especially where used to assist in setting up a more complex model. For example, Thomas's flashover correlation [13] and the McCaffrey/Quintiere/Harkleroad upper layer temperature correlation [9] are generally held to provide useful engineering estimates of whether flashover occurs and peak compartment temperatures.

Where public safety is about, it is not suitable to rely solely on such estimation techniques for the fire development of smoke filling calculation. Here, only fire models (or appropriate testing) should be used. Single-room models are appropriate where the conditions of interest are limited to a single, enclosed space. Where the area of interest involves more than one space, and especially where the area of interest extends beyond a single floor, multiple-compartment models should be used. This is because the interconnected spaces interact to influence the fire development and flows.

Many single-compartment models assume that the lower layer remains at ambient conditions (e.g., ASET[3]). Since there is little mixing between layers in a room (unless there are mechanical systems), these models are appropriate. However, significant mixing could occur in doorways, so multiple-compartment models should allow the lower layer to be contaminated by energy and mass. (See Figure4.)
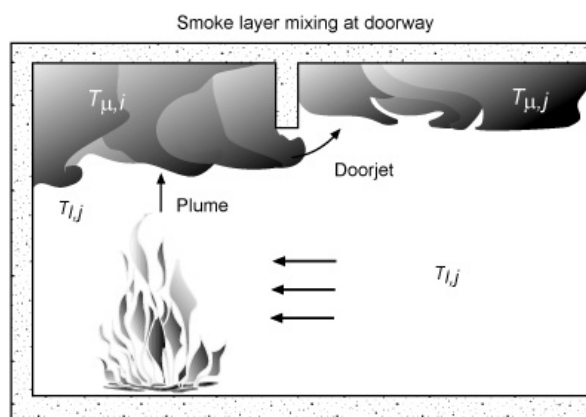

Fig. 4. Zone models assume that fire gases collects in layers that are internally uniform

The model should include the limitation of burning by available oxygen. This is straightforward to implement (based on the oxygen consumption principle) and is crucial to obtaining an accurate prediction for ventilation-controlled burning. For multiple-compartment models, it is equally important for the model to track unburned fuel and allows it to burn when it encounters sufficient oxygen and temperature. Without these features, the model concentrates the combustion in the room of origin, overpredicting conditions there and underpredicting conditions in other spaces.

Heat transfer calculations take up a Lot of computer time, so, many models take a shortcut. The most common is the use of a constant "heat loss fraction," which is user-selectable (e.g., ASET or CCFM[2]). The problem is that heat losses vary significantly during the course of the fire. Thus, in smaller rooms or spaces with larger surface-to-volume ratios where heat loss variations are significant, this simplification is a major source of error. In large, open spaces with no walls or walls made of highly insulating materials, the constant heat loss fraction may produce acceptable results; but, in most cases, the best approach is to use a model that does proper heat transfer.

Another problem could occur in tall spaces, e.g., atria. The major source of gas expansion and energy and mass dilution is penetration of ambient air into the fire plume. It could be argued that, in a very tall plume, this penetration is forced; but most models do not include this. This could lead to an underestimate of the temperature and smoke density and an overestimate of the layer volume and filling rate - the combination of which may give predictions of egress times available that are either greater or less than the correct value.

Documentation: Only models that are rigorously documented should be allowed in any application involving legal considerations. It is simply not appropriate to rely on the model developer's word that the physics is proper. This means that the model should be supplied with a technical reference guide that includes a detailed description of the included physics and chemistry, with proper literature references; a listing of all assumptions and limitations of the model; and estimates of the accuracy of the resulting predictions, based on comparisons to experimental data. Public exposure and review of the exact basis for a model's calculations, internal constants, and assumptions are necessary for it to have credibility in a regulatory application.

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

Input data: Even if the model is correct, the results could be seriously wrong if the data input to the model does not represent the condition being analysed. Proper specification of the fire is the most critical, and was addressed in detail in the preceding subsection on selecting the design fire(s).

Next in importance is specifying sources of air supply to the fire, i.e., not only open doors or windows, but also cracks behind trim or around closed doors. Most (large) fires of interest quickly become ventilation controlled, making these sources of air crucial to a correct prediction. The most frequent source of errors by novice users of these models is to underestimate the combustion air and underpredict the burning rate.

Two other important items of data are: (1) ignition characteristics of secondary fuel items and (2) the heat transfer parameters for ceiling and wall materials. In each case, the FIRE HAZARD ANALYSES should include a listing of all data values used, their source (i.e., what apparatus or test method was employed and what organization ran the test and published the data), and some discussion of the uncertainty of the data and its result on the conclusions.

2.5. Performing an evacuation calculation

The prediction of the time needed by the building occupants to evacuate to a safe area is performed next, and compared to the time available from the previous steps.

Whether the evacuation calculation is done by model or hand calculation, it must account for several crucial factors. First, unless the occupants see the actual fire, there is time required for detection and notification before the evacuation process could begin. Next, unless the information is interesting (again, they see the actual fire), it takes time for people to decide to take action. Finally, the movement begins. All of these factors require time, and that is the critical factor. No matter how the calculation is done, all of the factors must be included in the analysis to obtain a complete picture.

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

Another situation where models are preferred to hand calculations is with large populations where congestion in stairways and doorways could cause the flow to back up. However, this could be accounted for in hand calculations, as well. Crowded conditions, as well as smoke density, could result in reduced walking speed [7]. Care should be exercised in using models relative to how they select the path (usually the shortest path) over which the person travels. Some models are optimisation calculations that give the best possible performance. These are inappropriate for a code equivalency determination, unless a suitable safety factor was used.

Hand calculations: Evacuation calculations are sometimes simple enough to be done by hand. The most thorough presentation on this subject (and the one most often used in alternate design analysis) is that of Nelson and MacLennen [10]. Their procedure explicitly includes all of the factors discussed previously, along with suggestions on how to account for each. They also deal with congestion, movement through doors and on stairs, and other related considerations.

2.6. Analysing the impact of exposure

In most cases, the exposure will be to people, and the methods used to assess the impacts of exposure of people to heat and combustion gases involves the application of combustion

toxicology models. The HAZARD I software package contains the only toxicological computer model, called TENAB. TENAB accounts for the variation in exposure to combustion products as people move through a building, by reading the concentrations from the fire model in the occupied space during the time the person is in that space. If the person moves into a space with a lower concentration of carbon monoxide, the accumulated dose actually decreases. Details such as these ensure that the results are reasonable. It is important that these details be observed in hand calculations, as well.

2.7. Accounting for Uncertainty

Uncertainty accountability refers to dealing with the uncertainty that is inherent in any prediction. The origin of the uncertainty in calculations is assumptions in the model and not enough representative input data. In evacuation calculations, there is the added variability of any population of real people. In building design and codes, the classic method of treating uncertainty is with safety factors. A sufficient safety factor is applied such that, if all of the uncertainty resulted in error in the same direction, the result would still provide an acceptable solution.

In the prediction of fire development/filling time, the intent is to select design fires that provide a worst likely scenario. Thus, a safety factor is not needed here, unless assumptions or data are used to which the predicted result is very sensitive. In present practice for the evacuation calculation, a safety factor of 2 is generally recommended to account for unknown variability in a given population.

The fire hazard analyses report should include a discussion of uncertainty. This discussion should address the quality of the data used and the sensitivity of the results to data and assumptions made. If the sensitivity is not readily apparent, a sensitivity analysis (i.e., vary the data to the limits and see whether the conclusions change) should be performed. This is also a good time to justify the appropriateness of the model or calculation method.

2.8. Final Review

If a model or calculation produces a result that seems contrary to a belief, there is probably something wrong. Conversely, if the result is consistent with logic, sense, and experience, it is probably correct.

This is also a good time to consider whether the analysis addressed all of the important scenarios and likely events. Were all the assumptions justified and uncertainties addressed sufficiently to provide a comfort level similar to that obtained when the plan review shows that all code requirements have been met?

3. CONCLUSION

Quantitative fire hazard analysis is becoming the fundamental tool of modern fire safety engineering practice, and is the enabling technology for the transition to performance-based regulations and standards. The tools and techniques described in this paper provide an introduction to this theme, and the motivation for fire protection engineers to learn more about the proper application of this technology.

REFERENCES

1. Bukowski, R. W., "A Review of International Fire Risk Prediction Methods, Interflam '93," Fire Safety 6th International Fire Conference, March 30–April 1, 1993, Oxford England, Interscience Communications, Ltd., London, UK, Franks, C. A., ed., 1993, pp. 437–466.
2. Cooper, L. Y. , and Forney, G. P., "The Consolidated Compartment Fire Model (CCFM) Computer Code Application CCFM.VENTS - Part 1: Physical Basis," NISTIR 4342, National Institute of Standards and Technology, Gaithersburg, MD, 1990.
3. Cooper, L. Y., and Stroup, D. W., "Calculating Available Safe Egress Time (ASET) - A Computer User's Guide," NBSIR 82-2578, National Bureau of Standards, Gaithersburg, MD, 1982.
4. Friedman, R., Survey of Computer Models for Fire and Smoke, 2nd ed., Factory Mutual Research Corporation, Norwood, MA, 1991.
5. Heskestad, G., "Similarity Relations for the Initial Convective Flow Generated by Fire," FM Report 72-WA/HT-17, 1972, Factory Mutual Research Corporation, Norwood, MA.
6. Heskestad, G., and Delichatsios, M. A., "Environments of Fire Detectors - Phase 1: Effect of Fire Size, Ceiling Height, and Material," Vol. 2, Analysis, NBS-GCR-77-95, National Bureau of Standards, Gaithersburg, MD, 1977, p. 100.
7. Jin, T., "Visibility Through Fire Smoke," Report of Fire Research Institute of Japan, 1971, 2, 33, pp. 12–18.
8. Madrzykowski, D., and Vettori, R. L., "Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System," NISTIR 4833, National Institute of Standards and Technology, Gaithersburg, MD, 1992.
9. McCaffrey, B. J., Quintiere, J. G., and Harkeleroad, M. F., "Estimating Room Temperatures and the Likelihood of Flashover Using Fire Testing Data Correlations," Fire Technology, 17, 1981, pp. 98–119.
10. Nelson, H. E., and MacLennen, H. A., "Emergency Movement," The SFPE Handbook of Fire Protection Engineering, 2nd ed., DiNenno, P. J., et al., eds., National Fire Protection Association, Quincy, MA, 1995.
11. Shifiliti, R. P., Meacham, B. J., and Custer, R. L. P., "Design of Detection Systems," The SFPE Handbook of Fire Protection Engineering, 2nd ed., DiNenno, P. J., et al., eds., National Fire Protection Association, Quincy, MA, 1995.
12. Stroup, D. W., and Evans, D. D., "Use of Computer Models for Analyzing Thermal Detector Spacing," Fire Safety Journal, 14, 1988, pp. 33–45.
13. Thomas, P. H., "Testing Products and Materials for Their Contribution to Flashover in Rooms," Fire and Materials, 5, 1981, pp. 103–111.

PROBLEMI I SAVREMENA REŠENJA KOD KVANTITATIVNE ANALIZE OPASNOSTI OD POŽARA

Jovan D. Ristić

Prvi korak kod planiranja mera zaštite od požara je analiza opasnosti od požara. Tradicionalno, najveći broj zakona vezanih za zaštitu od požara baziran je na analizi opasnosti od požara gde su procene bazirane na iskustvu "eksperata". Danas se široko i sve više zahteva formalna, naučno zasnovana analiza opasnosti od požara u smislu sprečavanja neželjenih ishoda, bez obzira na verovatnoću njihovog nastajanja. U ovom tekstu podvući ćemo razlike između analize opasnosti i analize rizika, postupak kod analize opasnosti od požara i raspoložive resurse koji se koriste u postupku.

Ključne reči: *analiza, opasnost, požar*