Methods to Quantify Smoke Detection Performance in Risk-informed Engineering Applications

Gabriel Taylor, Susan Cooper, Amy D'Agostino, Nicholas Melly
Nuclear Regulatory Commission, Washington, DC, USA

Thomas Cleary
National Institute of Standards and Technology, Gaithersburg, MD, USA

Abstract

The use of risk-informed, performance-based methods have gained popularity as an alternative to prescriptive fire protection requirements in the US commercial nuclear power industry. To achieve optimal benefit, quantifying the risk to a facility from the effects of fire in a probabilistic risk assessment is essential. An important element of this assessment involves quantifying the performance of smoke detection systems. The methods currently available to quantify their performance are presented, along with simulation-based method that has yet to mature into viable solution.

Keywords: Smoke detection, risk assessment, performance-based design

Introduction

When the current fleet of US nuclear power reactors were originally licensed, the requirements for protecting the facilities from the adverse effects of fire were generic in nature. As the industry and regulator matured, additional requirements and guidance on fire detection were put into place. These requirements were prescriptive, stipulating that the fire detection and suppression systems met the listing requirements, and little attention was paid to these systems other than the need for periodic inspection, testing and maintenance. However, other industries have progressed from deterministic requirements to allow for flexibility and innovation in design while achieving an equivalent level of safety. The nuclear power industry is now following suit, progressing towards more risk-informed performance-based regulations where the technology has been sufficiently developed.

Background

The U.S. Nuclear Regulatory Commission (NRC) has supported the use of risk-informed and performance-based approaches to ensure the safety of US nuclear facilities since a 1995 policy statement on regulatory use of probabilistic risk assessment (PRA). In 2004, regulations were amended to expand this technology into the area of fire protection. Since then, approximately one-half of the commercial nuclear fleet have pursued this voluntary initiative which has helped to identify plant fire vulnerabilities and make change to the facility to minimize those risks. Although not a requirement, the development of a comprehensive fire PRA is an essential tool to support full benefit of the amended regulation. Reference 1 is the principle document used for performing a fire PRA, including the fundamental approach for quantifying fire detection and suppression performance. Since its issuance in 2005, numerous studies have been conducted to refine the methodology and reduce uncertainties [2,3]. The most recent of these studies focused on quantifying the ability of a smoke detection system to detect during the incipient stage of a fire [4]. This paper provides a summary of existing, recently developed and a conceptual approach to quantify smoke detection and fire suppression for use in risk assessment.

Risk Quantification Model

Overall, PRA focuses on risk, defined with a “risk triplet”: 1) what can go wrong (e.g., a fire occurs), 2) how likely is it (e.g., frequency), and 3) what are the consequences of the event? Fire PRA, in its simplest form is a timing analysis between: 1) the time to damage of equipment whose function is necessary for plant safety, and 2) the time to suppress a fire. Fig.1 presents a conceptual illustration of this timing race between fire damage or exceedance of a critical threshold, and fire suppression. When the time to suppression is less than the time to damage, plant safety is maintained. However, the use of point estimates does not accurately reflect the uncertainty of these timing estimates (represented as bi-directional arrows in Fig. 1). As such, a simple numerical solution to assessing fire risk has been difficult to develop. As a result, numerous fire analysis tools, data and assumptions have been used to quantify plant risk, all of which include their own uncertainties.

Numerically, the calculation of risk is based on the frequency of a fire occurring, multiplied by numerous conditional probabilities that are scenario specific. The conditional probabilities include the likelihood of a fire damaging targets of interest, and the probability that the fire will not be suppressed prior to equipment damage. The complete numerical computation represents the total plant frequency of experiencing damage to the reactor core, commonly referred to as core damage frequency (CDF), from fire initiators. The total CDF is the sum of the CDF contributions from individual fire-initiated scenarios. A single plant may have over 1,000 scenarios.

The CDF contribution from an individual fire scenario can be divided into three principal components [5].

1. frequency of the fire scenario
2. conditional probability of fire-induced damage to critical equipment given the fire
3. conditional probability of core damage given the specific equipment damage

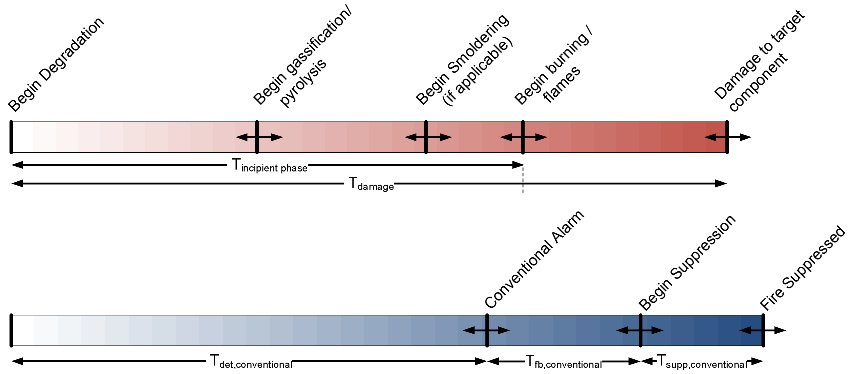

Fig. 1. Illustration of timing between fire progression (top) and human response to conventional smoke detection alarm (bottom).

Mathematically, the total CDF is characterized as:

$$CDF = \sum_i CDF_i = \sum_i \lambda_i \left[\sum_j p_{ed,j|i} \left(\sum_k p_{CD,k|i,j}\right)\right] \quad \text{Eq. 1}$$

Where λ_i, is the frequency of fire scenario i, $P_{ed,j|i}$, is the conditional probability probability of damage to critical equipment set (“target set”) j given the occurrence of fire scenario i, and $P_{CD,k|i,j}$, is the conditional probability of core damage caused by plant response scenario k given fire scenario i and damage target set j.

The probability of equipment damage is decomposed into two parts:

$$P_{ed,j|i} = SF_{j|i} \times P_{ns,j|i} \quad \text{Eq. 2}$$

Where $SF_{j|i}$, is the severity factor for damage to target set j given fire source i, and $P_{ns,j|i}$, is the probability of non-suppression before damage to target set j given fire scenario i.

The severity factor (SF) reflects the fraction of fires that damage the critical equipment in the fire scenario. This fraction is based on the plants physical configuration and fire modelling results. The non-suppression probability (P_{ns}) represents the probabilistic outcome of the fire damage versus fire suppression race given a fire that has the potential to damage critical equipment. It is this term that smoke detection and suppression system performance is quantified.

Approaches to quantify smoke detection performance

Smoke detection systems provide the signals and notification to initiate either automatic or manual fire suppression. Automatic fire suppression systems provide a valuable and reliable fire protection feature. However, these systems are not installed in all areas. Additionally, many fires observed in nuclear facilities do not develop and grow as postulated in performance-based methods (t-squared). As a result, actuation of automatic fire suppression systems is an uncommon event because manual suppression commonly occurs prior to actuation of automatic systems. Therefore, it is important to quantify the performance of on-site fire brigade response to ensure that the risk assessment is not overly conservative.

Numerical approach

Event trees are common decision tools used in reliability engineering and other fields to model a discrete number of events that occur in a specific sequence to achieve a desired outcome [6]. In the smoke detection and fire suppression context, a fire represents the initiating event, followed by automatic detection and suppression, and manual detection, fixed suppression and fire brigade suppression. An event tree structure for detection and suppression is shown in Fig. 2. At each branch point, the upper branch represents success of the event, while the down branch represents failure. A point estimate is used to represent the likelihood of failure and its complement, success, for each event. The end states shown on the right-hand side represent a sequence of events that results in: 1) a success, such as a fire suppressed (represented as OK), or 2) a failure, such as fire not suppressed (represented as NS). The numerical estimate for each end state is tabulated by multiplying the point estimates along the individual paths. The summation of all failure end states (i.e., D, H, I) represents the conditional probability of failing to suppress a fire prior to equipment damage. Typically, event trees are used to evaluate different end states (e.g., fire causes damage to 1. initiating component, 2. secondary targets, 3. room, etc.) and can be used to calculate the risk reduction provided by any detection or suppression system.

The performance of automatic systems is based on system reliability and availability estimates. Currently, the following point estimates are used to represent the failure of the system (down branch): wet pipe sprinkler – 0.02; preaction sprinkler – 0.05; deluge sprinkler – 0.05; carbon dioxide (CO2) – 0.04; and Halon – 0.05 [1]. The availability and unreliability of smoke detectors were not readily available when this guidance was developed, and as such, the Halon estimate of 0.05 is suggested to be a bounding estimate of smoke detector unreliability since most halon systems rely on smoke detector(s) activation [1].

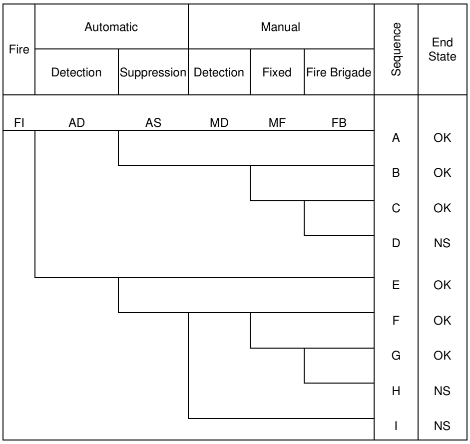

Fig. 2. Detection Suppression Event Tree.

To quantify manual fire brigade suppression, one common approach involves developing a probabilistic distribution based on actual plant personnel response time to suppress a fire. Multiple curves are developed for various fire hazards. Then, performance-based methods (e.g., fire modelling) are used to determine when fire detection system alarm, and when equipment important to plant safety is damaged. The difference between these two times is then used with the non-suppression probabilistic distributions to estimate the likelihood that the fire will not be suppressed prior to damage. Under this approach, the probability of non-suppression is calculated as an exponential complementary cumulative distribution function (i.e., survivor function), as:

$$P_{ns} = \Pr(T > t) = e^{-\lambda t} \qquad \text{Eq. 3}$$

Where λ, is the rate parameter (inverse of average suppression time from operating experience), and t, is the time available for response ('time to damage' minus 'time to detection').

Several non-suppression curves are presented in Fig. 3 [3]. The figure shows that as more time is available for fire brigade response, the lower the probability of not suppressing the fire prior to damaging some critical component or system (i.e., the likelihood of successful fire suppression increases). This non-suppression probability estimate along with the unreliability and unavailability of the detection system are used to estimate the risk reduction of the detection system and personnel response.

Based on the design fires used in fire models, the time to detection is typically less than 2 minutes. As such, if more effective detection is used, then there is earlier fire detection, increasing the time available for manual response and, thereby, reducing risk. The NRC and the

National Institute of Standards and Technology (NIST) have completed a confirmatory research program to quantify the risk benefit of using very early warning fire detection (VEWFD) systems to detect fires in their incipient stage [4]. The performance of aspirated smoke detection (ASD) VEWFD systems is quantified in an event tree similar to that shown in Figure 2, but also includes developing numerical estimates for events such as: 1) the fraction of fires which exhibit an incipient stage, 2) evaluating the effectiveness of ASD VEWFD systems, and 3) human reliability responding to an incipient fire stage. The event tree from this study is presented in Fig. 4. The experimental work has shown performance differences among detector technologies responding to aerosols produced from overheated electronic sources (Fig. 5). These results are used to support estimating the effectiveness term in the event tree.

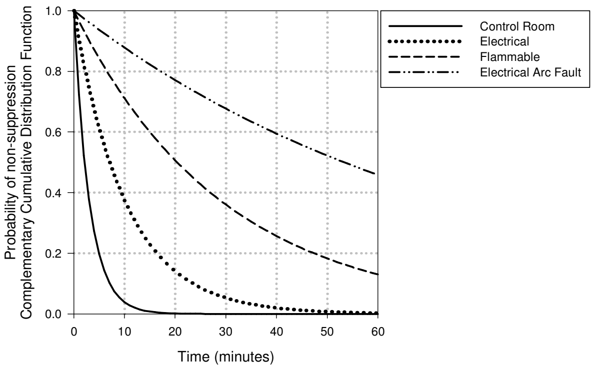

Fig. 3. Selected non-suppression probability distributions.

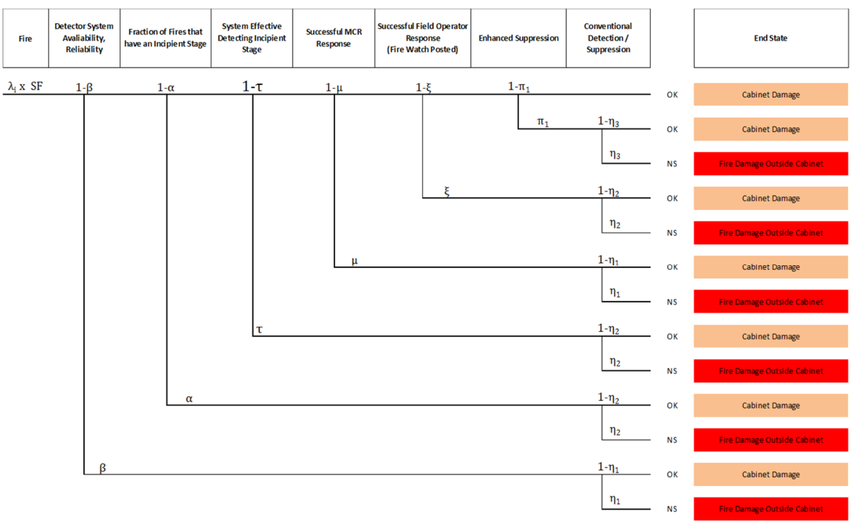

Fig. 4. Incipient detection event tree for ASD VEWFD installed inside ventilated electrical enclosures [4].

The final approach to estimating smoke detection and human performance is intrinsically time-based, but dependent on characterizing detector, human and fire modelling uncertainty. Under this approach distributions of detector response, time to equipment damage and human response (e.g., travel time, suppression timing) are developed. Then simulations using Monte Carlo techniques are performed. The fraction of the resulting distribution less than zero then represents the conditional probability of failure.

Under this approach, the response of the fire brigade member is broken down into several segments, developed into distribution, and then numerically compared to a distribution of likelihood for damage to the equipment important to safety. These simulations are performed several thousand to tens of thousands of times with the result being a distribution representing the likelihood of success (≥0) or failure (<0) of the response. A conceptual illustration of this approach is presented in Fig. 6. The fraction of the distribution below zero, represents the nonsuppression probability. While this approach eliminates some of the short comings of using event trees in a timing analysis, additional data and/or analysis is required to specify the distributions.

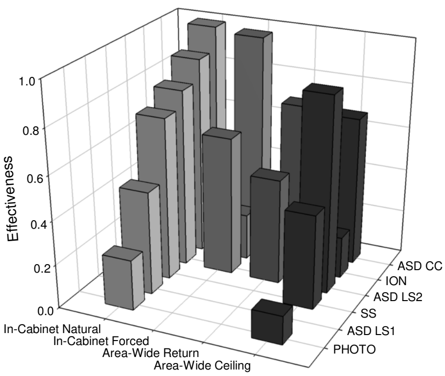

Fig. 5. Detector effectiveness in reaching 'alert' threshold during incipient stage by application.

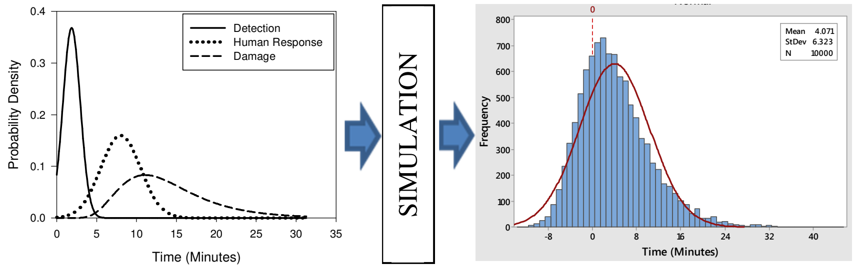

Fig. 6. Conceptual illustration of simulation based nonsuppression probability estimation.

Conclusions

The choice of methods to quantify risk reduction from the use of smoke detection systems is largely dependent on the maturity of the application, level of reporting on system successes and failures and the availability of either empirical or performance-based methods to characterize detector response and time to equipment damage or some other specified performance criteria. Although all of these methods are not difficult to implement, their accuracy is highly dependent on the simplifying assumptions and certainty in underlying distributions.

Acknowledgements and Disclaimer

This paper was prepared (in part) by employees of the United States Nuclear Regulatory Commission (USNRC). The USNRC has neither approved nor disapproved its technical content. This paper does not establish a USNRC technical position.

References

[1] EPRI TR-1011989, NUREG/CR-6850, "*EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities: Volume 2: Detailed Methodology*," Electric Power Research Institute (EPRI), Palo Alto, CA, U.S. Nuclear Regulatory Commission (NRC), Washington, DC 20555-0001, September 2005.

[2] EPRI 1019259, NUREG/CR-6850, "*Fire Probabilistic Risk Assessment Methods Enhancements: Supplement 1 to NUREG/CR-6850 and EPRI 1011989*," EPRI, Palo Alto, CA, and NRC, Washington, D.C., December 2009.

[3] EPRI 3002002936, NUREG-2169, "*Nuclear Power Plant Fire Ignition Frequency and Non-Suppression Probability Estimation Using the Updated Fire Events Database: United States Fire Event Experience Through 2009*," EPRI, Palo Alto, CA, and NRC, Washington, D.C., January 2015.

[4] NUREG-2180, "*Determining the Effectiveness, Limitations, and Operator Response for Very Early Warning Fire Detection Systems in Nuclear Facilities (DELORES-VEWFIRE), Final Report*," December 2016.

[5] Siu, N.O., et al., "*Fire Risk Analysis for Nuclear Power Plants*," Chapter 89, SFPE Handbook of Fire Protection Engineering, Fifth Edition, 2016.

[6] Modarres, M.M., et al., "*Reliability Engineering and Risk Analysis, A Practical Guide*," Third Edition, 2017.