IAEA-SM-345/37

Key Issues Paper

FIRE SAFETY ANALYSIS: METHODOLOGY

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1. INTRODUCTION

Should we be concerned about internal fires in nuclear power plants? Can we estimate the fire risk using quantitative methods? Are current state-of-the-art fire risk analysis methodology and practices adequate for decision making? Many believe that, given the changes that have been implemented in the older plants and the strict physical separations and fire protection equipment and practices that are incorporated in the modern plants, the issue of internal fires has been properly addressed for nuclear power plants, and the risk is sufficiently small. Much doubt is often expressed in our ability to model the fire phenomenon and thus in our ability to quantitate the risk of fires in a nuclear power plant. Thus, there are many who believe that quantitative fire risk analysis does not provide the proper basis for making decisions on fire related issues. This is perhaps best manifested in the fact that often the influence of elaborate and complicated fire protection systems is not clearly demonstrated in a fire risk analysis results.

I believe that fire risk is significant, it can be quantified and the quantified risk can be used for making decisions. This article addresses these three issues.

2. RISK SIGNIFICANCE OF FIRES

History and past risk studies [1] tell us that fire can be a significant contributor to the overall risk of a nuclear power plant. A number of fires have occurred that have had severe impact, and a few of those caused the failure of a large number of safety systems. Because of those experiences, we have done much to protect the nuclear power plants from fires. We have improved the quality of the materials, incorporated strict physical separation and enhanced the fire detection and suppression capabilities. Thus, we have reduced the likelihood of ignition and spread of a fire, increased the likelihood of discovery and mitigation, and reduced it for a fire to fail a minimal cut set of equipment.

The core damage frequency from fires estimated in fire risk studies for a number of plants within the USA ranges between 10^{-6} and 10^{-4} per reactor year [1]. Thus, although the overall plant risk may be considered as acceptable, for a large number of the plants, fire is a significant fraction of the overall core damage frequency.

3. RISK SIGNIFICANCE OF FIRES IN THE MODERN PLANTS

There is no doubt that because of all the defenses that are now incorporated into the design of modern power plants, the fire risk in these plants is less than the older plants. However, in my opinion, we still need to be concerned about internal fires for the modern plants. This is simply because an important part of the defenses against the effects of a fire depends on active components and humans.

The central control room contains a portion of practically all the important control and instrumentation circuits of the plant. Thus, a control room fire can potentially affect a large number of these circuits at the same time. In such an event, the fire risk is influenced by operators' ability to use the remote shutdown panels and by the ability of isolate that portion of the control and instrumentation circuits that are inside the control room. The latter is sometimes not a straightforward application of a switch. An irrecoverable failure (e.g., valve gets jammed into its seat) may occur from the fire affecting the control circuits inside the control room before the control room portion of the circuit is isolated.

In the case of modern plants and older plants as well, a fire outside the control room, that affects control and instrumentation circuits, may lead to wrong and confusing information on the control board. Current fire risk studies have not addressed such scenarios. The potential severity of such scenarios is not known. We do not know enough about the possible errors of commission under such conditions.

In addition to the control room fires, short term effects of smoke and the failure modes of new equipment types may also be important influences on the fire risk of modern plants. New equipment (e.g. electronic and computerized systems, distributed control systems, and data highways) is being introduced into the plants. The behavior of these equipment has not been completely understood under fire conditions. Recent tests have demonstrated that contrary to what was believed previously, smoke can have short term effects on electronic equipment. Many modern plants do not have perfect separation between redundant trains. For example, fire dampers have to close to establish the separation. One can postulate a scenario where sufficient amount of smoke escapes through a normally open damper (before it closes) and affects an electronic cabinet in an adjacent compartment.

In summary, even for the most modern plant, the fire risk may be sufficiently significant to deserve detailed scrutiny. Detailed analysis needs to be done to insure that unusual, albeit unlikely, phenomena are considered properly. There is a relevant analogy here with the common cause failure phenomenon; that is, the reliability of a highly redundant system is limited by the common cause element.

4. QUANTITATIVE ESTIMATION OF FIRE RISK

The risk of all types of hazards, which include fires in nuclear power plants, can be characterized by a quantitative measure using the probabilistic risk assessment definition and approach [2]. This can be done regardless of our level of knowledge about the phenomenon. The differences in our level of knowledge in various hazardous phenomena affects our level of uncertainty in the risk measures. We always know something about a phenomenon. I cannot think of any examples where we have total ignorance. The opposite is also true. We never have perfect knowledge. We always have some uncertainty. In summary, probabilistic risk assessment can be used in all types of situations and it will always include some uncertainty.

The methodology for fire risk analysis has evolved over the last 18 years [3-5] and has been scrutinized extensively through its application in numerous fire risk studies [1] and through comparative studies [6, 7]. Therefore, the question is actually not about our capability of quantifying fire risk. The question should be whether the level of uncertainties are such that the fire risk quantified per current practices can be useful for decision making.

Uncertainties in fire risk is discussed in some detail in Ref. [8]. A summary is provided below.

5. UNCERTAINTIES IN FIRE RISK

Fire is a complex phenomenon. Its complexity comes not only from the ignition and combustion processes, but from its impact on equipment and on the response of the operators to those failures. The fire fighting activity adds to this complexity through its own unique effects. Uncertainties in the fire risk are directly related to how well we can model the different aspects of the fire phenomena .

We can start from the very first element of a fire event, that is ignition of a fire. The uncertainties in this parameter have two elements: statistical and its correlation with later stages of the analysis. Statistical uncertainties are simply a function of the statistical evidence and experience base. The analysis of statistical uncertainty is well established. In the nuclear industry, the Bayesian approach is used for this purpose. As the experience base or statistical evidence increases the uncertainties in the parameter values decrease.

There is also uncertainty in the correlation between the fire ignition process with other elements of the fire risk model. The fire events included in the statistical evidence must include a threshold severity level, otherwise it would not be reported (e.g., sparks from an electrical connector or a smoldering cigarette in a waste basket). This threshold is certainly poorly defined because a spectrum of severities can be found in the incident descriptions. For example, there is at least one incident that was a smoldering fire and there are many that included a switchgear fire. When fire propagation modeling is considered the initial severity level of the ignited fire needs to be taken into account. Currently the threshold severity is not established and therefore this mismatch is a source of uncertainty in fire risk analysis.

The uncertainties in fire propagation models are deemed to be excessive and often it is stated that such models are completely erroneous. Both concerns are not well founded. Although the existing fire propagation models do not include all possible thermodynamic, heat transfer and chemical reaction aspects of a fire event, Refs. [9, 10] demonstrate that fire propagation models are capable of predicting the propagation patterns for a compartment within a reasonable uncertainty level. A part of the uncertainty in fire propagation modeling is associated with the input variables. A range of possible ignition source locations and characteristics, and other variables need to be simulated. Only a few of the simulated fire ignition scenarios match actual fire events that have occurred and are considered in the statistical analysis. For example, a compartment may include two vertically stacked cable trays that are separated horizontally. The fire risk analyst must consider a series of possible fire ignition scenarios in this compartment and analyze their propagation patterns. A number of these ignition scenarios, that may include extreme yet possible conditions, would cause damage to a critical set of the cables and the rest would not. For those scenarios that can cause damage, the analyst needs to assign an occurrence frequency. The statistical evidence (i.e., the fires that have already occurred in the nuclear power plants) may not include such ignition scenarios. Thus, the challenge becomes to estimate these frequencies in the face of little statistical evidence, which will clearly lead to large uncertainties. The methods for quantifying such uncertainties using the Bayes Theorem are well established.

There are many other sources of uncertainty in fire risk analysis that are perhaps of lesser importance than those discussed above. They include such issues as the ruggedness of various equipment and electrical cables to damage from fire and their failure modes. Current fire risk studies have often assumed the active fire barriers as highly reliable, and very few have considered situations where active or even passive fire barriers may get overwhelmed and fail to protect the opposite safety train. Short term effects of smoke are another source of uncertainty. Recent tests have demonstrated that aside from its obstructive effects, electronic circuits are susceptible to smoke in the short term. There is a large variety of styles in modeling control room fires and their effects on the operators. The same can be said about the cable spreading room as well. Other sources of uncertainty include models for fire detection and suppression that should be coupled with fire propagation analysis. The effects of suppressing medium (e.g., water or CO_2) on equipment not affected by the fire (e.g., from misdirected water stream) are often not included in the fire risk analysis.

Overall, in my opinion, we have relatively good understanding of the key elements of a fire event and, if the proper data and methodology are employed, the final results of the fire risk analysis would not entail excessive uncertainties. However, there is no doubt that there is much room for improving our level of knowledge.

6. FIRE RISK AND DECISION MAKING

A probabilistic risk assessment provides a ranking of the contributors to the risk. The contributors are generally accident scenarios that start from a perturbation in the balance of the plant and lead to an adverse consequence. In the case of fire risk analysis, the ranking is done in terms of fire scenarios. Fire scenarios include ignition of a fire at a certain location involving a certain combustible with clearly defined dimensions and characteristics. The fire scenario also includes fire propagation pattern, equipment exposure to the fire, cables and circuit failures, equipment failure as result of these exposures, automatic systems and operator response to these failures, fire detection and suppression activities, failure of other equipment that is not affected by the fire, and finally core damage. It may be noted that fire will eventually get extinguished, which is immaterial if equipment damage occurs prior to extinguishment.

The main purpose of performing a probabilistic risk assessment is to support a decision. There are three types of situations that a decision maker faces: either the risk is acceptable, the uncertainties in the risk are sufficiently small and the risk is unacceptable, or the uncertainties in the risk are large. The decision maker can reach a decision in all cases.

Risk acceptability depends on the criteria set forth by a regulatory agency or by other established practices. Overall plant risk has to be examined to determine whether the risk is acceptable or not. Fire risk may be a significant contributor to the overall plant risk, and yet remain acceptable because of the acceptability of the overall plant risk. If the uncertainties are sufficiently small and the risk is unacceptable, the ranking of various fire scenarios can be used to identify and prioritize possible plant modifications to reduce the risk. The modifications may be in terms of changes to the hardware or to the administrative elements or both.

Decision making in the face of large uncertainties may not be straightforward. Making changes to the plant when uncertainties are large may not be prudent. The ranking of various contributors that involve hardware elements may be masked. For example, the final risk analysis results may not be able to demonstrate the risk benefits of a sophisticated automatic fire suppression system versus a less sophisticated one.

The simplest approach may be a re-analysis of those elements of the fire risk that have the greatest influence on the uncertainties. This may not be a simple task, and may require a major research effort. For example, fire propagation analysis may be the main contributor to the uncertainties or a fire scenario may include a condition for which little or no statistical evidence is available. Since, fire risk is the result of combining a multitude of parameters, the lack of change in the uncertainty of a single parameter will not render the fire risk analysis results useless. Other parameters may be used to achieve a reduction in risk and even in the uncertainties.

7. CONCLUSION

From a review of the fires that have occurred in nuclear power plants and the results of fire risk studies that have been completed over the last 17 years, we can conclude that internal fires in nuclear power plants can be an important contributor to plant risk. Methods and data are available to quantify the fire risk. These methods and data have been subjected to a series of reviews and detailed scrutiny and have been applied to a large number of plants. There is no doubt that we do not know everything about fire and its impact on a nuclear power plants. However, this lack of knowledge or uncertainty can be quantified and can be used in the decision making process. In other words, the methods entail uncertainties and limitations that are not insurmountable and there is little or no basis for the results of a fire risk analysis fail to support a decision process.

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