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EVALUATION OF HUMAN PERFORMANCE ISSUES FOR FIRE RISK*

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ABSTRACT

This paper summarizes the current status of the treatment of human reliability in fire risk analyses for nuclear power plants and identifies areas that need to be addressed. A new approach is suggested to improve the modeling.

I. INTRODUCTION

This paper summarizes the current status of the treatment of human reliability in nuclear power plant (NPP) fire risk analyses and identifies areas that need improvement. The current status of human reliability analysis (HRA) for fire risk was determined by reviewing the human performance modeled in fire risk analyses. Reports on human performance during actual fires were reviewed to develop an understanding of what should be modeled in fire risk HRAs. The shortcomings in modeling of human performance were identified by comparing modeled performance with that observed in actual fires.

This work has led to an identification of critical human performance issues that are important in fire risk analyses. These issues have generally not been addressed in previous fire risk studies. In addition, it has been verified that the general approach in the ATHEANA HRA method[1] is useful in addressing many human performance issues important in fire events that have not been addressed in current HRA methods.

II. APPROACH

This work consisted of four basic tasks:

1. collection and review of information related to human performance in response to fire events,
2. collection and review of information related to human performance/reliability in fire risk studies,
3. integration of review results, and
4. formulation of conclusions and recommendations.

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These four tasks are briefly discussed below. Since the purpose of this evaluation was to examine the treatment of human reliability in fire risk analyses for nuclear power plants, one relevant information source for review consisted of the existing fire risk studies. To identify any shortcomings in the treatment of human reliability, an understanding must be developed of what human performance issues should be addressed in fire risk studies. To develop this understanding, reports of past fire events in nuclear power and other industries were used as the other major source of relevant information. The basic principles and knowledge underlying the ATHEANA method[1] were used in reviewing information and making evaluations.

III. REVIEW OF FIRE EVENTS

A review of fire events was important in identifying the modifications that might be necessary in current approaches to fire HRAs. In particular, fire events were reviewed to:

- identify serious fires (e.g., events that involve loss of significant equipment),
- identify operationally challenging fire events,
- identify examples of error-forcing contexts (EFCs) found in fire events, and
- identify descriptions of human performance in fire events.

A. Identification of Fire Event Information

The identification of relevant historical experience related to fires was based in part on the approach and experience gained from the event analyses performed in the development of ATHEANA.[2,3] Event-based reports were found to contain the most detailed and useful information regarding human performance issues. However, since event-based reports are few, a brief search of licensee event report (LER) summaries (obtained from the Sequence Coded Search Scheme (SCSS) database operated by Oak Ridge National Laboratory) was also performed to obtain useful, general information and to identify fire events for which more detailed reports were available. Events that have occurred in other industries provided additional general insights.

The selection of relevant information was guided and aided by consultation with several experts on fires who helped to identify fire event databases, fire modeling approaches, and fire risk studies. The NUREG/CR-6544 report[4] provided some leads and insights on a few fire events, but was of limited value because the specific events were not identified. Three sources of relevant information were identified:

1. licensee event reports (LERs),
2 event-based reports of NPP fires (e.g., U.S. Nuclear Regulatory Commission (NRC) Augmented Inspection Team [AIT] reports, NUREG documents), and
3. reports on fire events in other industries.

The findings in subsections B, C, and D were obtained despite the following limitations:

- Few operationally challenging NPP events were identified.
- Little or no discussion of human performance was provided in reports for potentially challenging NPP fires (e.g., Browns Ferry, Narora).
- The focus of fire event reports appears to be more upon fire fighting, rather than controlling the plant.
- The relevance of fires in other industries to NPP fire events was limited because:
  - many non-nuclear fires are noncognitively challenging events,
  - many non-nuclear fire reports do not report operator actions,
  - many non-nuclear fires involve only the loss of equipment, and
  - many industries that frequently report fires (e.g., chemical, petrochemical) are not concerned with control operations once a fire occurs (which is not an acceptable option for NPPs because they do not have an "off" switch).

B. LER Reviews

The review of fire events involved reviews of 498 LERs identified through a search on the keyword "smoke/burning" for the period from the beginning of 1980 to May of 1988 and reviews of more detailed reports on a number of significant fire events in several industries, including nuclear power.

Based largely upon the events themselves, the following classification scheme was derived to provide consistency in the LER reviews, describe the nature of each event, and distinguish between more challenging events and those involving inconsequential effects:

- fire
- minor fire

- smoke
- defense deficiency
- no fire

Classification of the LERs yielded the results shown in Table 1. Of particular interest is the comparatively small number of events. Also, the large number of events describing defense deficiencies is considered potentially important to human performance during fires and to the underlying assumptions of fire probabilistic risk assessment (PRAs).

Table 1. Results of LER Review of "Smoke/burning" Events

Type LER	Number	Percentage
Fire	39	8
Minor fire	59	12
Smoke	55	11
Defense deficiency	158	32
No fire	185	37
Unknown	2	0
Total	498	100

C. Reviews of Fire Event Reports

The search for serious NPP fire events identified very few events that have occurred worldwide, including those that occurred at the following plants:

- Browns Ferry (U.S.)
- Narora (India)
- Griefswald (East Germany)
- Chernobyl (Ukraine)

Both the Browns Ferry and Narora events were reviewed for this work. The Browns Ferry event also was reviewed in detail using the ATHEANA perspective.

A few detailed reports for less serious fire events at U.S. NPPs were collected and reviewed by the team. The reports provided useful information on human performance in the following events:

Waterford 3 - June 10, 1995
Fermi 2 - December 25, 1993
Oconee 1 - January 3, 1989
Shearon Harris - October 9, 1989

These events, and an unnamed event described in NUREG/CR-6544, were reviewed and potentially important human performance issues were identified. In addition, the Waterford 3 event was analyzed in detail using the ATHEANA perspective.

In addition, reports of 5 fire events in various industries other than nuclear power were reviewed. The following events were reviewed for this analysis. They were chosen because they were the subject of detailed event investigations and extensive reports, largely because of the loss of lives not because of the challenging situation faced by operators. These events were:

- fire and explosion of the Piper Alpha gas production platform in the North Sea, 1988;
- fire on board Boeing 737 and crash at Kegworth, U.K., 1989;
- fire on board Boeing 737 at Manchester Airport, U.K., 1985;
- fire at Phillips 66 Houston Plant, Pasadena, Texas, 1989; and
- fire at Kings Cross underground station, London, U.K., 1987.

Reviews of fire event reports, especially those for NPPs, provided many insights too detailed to provide here. Some of the more important findings are summarized in Section V. Overall, the event report reviews indicated that:

- Serious fire events have occurred.
- Fire events can be operationally challenging.
- Important human performance issues, some of which appear to be fire-specific, have been identified.
- Combinations of unusual plant conditions and performance-shaping factors (i.e., error-forcing contexts) in fire events appear to strongly influence human performance.

IV. REVIEW OF FIRE HRAs

The review of fire HRAs was important to the identification of needed HRA improvements. The search for fire risk information identified the following sources:

- individual plant examinations of external events (IPEEEs),
- staff evaluation reports (SERs), technical evaluation reports (TERs), and requests for additional information (RAIs) regarding IPEEEs,
- IPEEE guidance documents (e.g., the Electric Power Research Institute's [EPRI's] Fire Implementation Guidance document,[5] EPRI's FIVE methodology,[6]
- other fire PRAs or risk studies, and
- interviews of experts knowledgeable about fires.

The bulk of the analysis of human performance modeling in fire risk studies was garnered from review of the IPEEEs, with the following results:

- 35% either did no HRA (screening or sensitivity analysis eliminated scenarios before an HRA would have been applied) or provided too little information to determine if an HRA was performed;
  - of these, half did no HRA and
  - half were indeterminate.
- 65% indicated that an HRA was performed (the following categories are not mutually exclusive)
  - of these, 25% limited their analysis to the human failure events (HFEs) suggested by the EPRI guidance and 33% used additional search techniques;
  - 75% modified the quantification only for very simple aspects of the fire-related context, i.e., only stress due to smoke and heat and the impossibility of reaching equipment engulfed in fire;
  - 25% used a very simple multiplier on the HRA values that was taken from the IPE internal events analysis, with no justification stated; and
  - one study investigated the aspects of context well beyond that normally considered for one set of scenarios.
- None investigated errors of commission (EOCs) resulting from fire-related contexts.

A review of NRC SERs and contractor provided TERs on the IPEEEs is consistent with the basic results cited above. Overall, the NRC reviews of IPEEEs found that the licensees' assessments of human performance in fire scenarios was generally a weak area.

V. SUMMARY AND INTEGRATION OF RESULTS

The review of fire events and current modeling of human performance in fire risk studies generated findings with respect to the requirements for informative fire HRAs, weaknesses in past fire event investigations, weaknesses in past fire HRAs, and weaknesses in the assumptions of fire PRAs. These findings and related conclusions are summarized in this section.

A. Findings and Conclusions

The reviews of fire event histories and of fire HRAs in the IPEEEs have led to complementary observations:

- Fire events can lead to cognitively challenging situations, particularly in cases involving fires that affect multiple pieces of equipment or fires that cause unanticipated progressions in failures of equipment. While such "significant" fires happen infrequently, the added challenges could make these types of fires the most risk significant of all fire events.
- Few investigative reports on fire events provide information on how the context of the fire affected human perception and performance in operating the plant.
- Current fire HRAs generally fail to adequately account for the special context produced by fires, both in the search for new HFEs[a] and in modeling and quantifying the impact of the context on human perception and performance[b]. This weakness may lead to inappropriate conclusions about the nature of fire risks and how quantitatively important (or unimportant) these risks are.

Three major conclusions from this review are that:

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[a]Most fire HRAs simply use the set of HFEs that was quantified in the IPE, a few extend that set by adding errors of omission identified in a review of the fire procedures or make minor but unsubstantiated adjustments to the IPE Human Error Probabilities (HEPs).

[b]Only the direct impact of flames that prevent access to certain locations and heavy smoke that physically interferes with implementation of a response are considered.

1. Investigations of future fire events should include not only the adequacy of controlling and extinguishing the fire itself (already covered by most investigations), but also a careful evaluation of how the context in which fire was generated affected the cognitive performance of operators. This should include both individual and team effects associated with continued safe operation of the plant.

2. Future fire HRAs should account for the special context produced by the fire, both unusual plant conditions (e.g., time-sequenced failures of otherwise unrelated equipment, unusual operational configurations) and complicating human conditions (e.g., PSFs that facilitate particular errors by humans in processing information). Specifically:

   - a structured search for HFEs, both errors of omission and errors of commission during fire-induced scenarios is needed and
   - a model and quantification process based on the effects of special contexts that can occur during fire scenarios is needed.

3. The ATHEANA method for HRA[1] can address all the needs identified in conclusions (1) and (2). ATHEANA provides:

   - a framework for retrospective analysis of operational events that would give event investigators a tool to address the cognitive performance of operators during actual fire events.
   - a structured search process for identification of potential HFEs,
   - a structured search process for identification of "error-forcing context" (a fire-generated, cognitively challenging context) and
   - a model describing how EFC affects human performance and a quantification process that combines the probability of developing a particular plant-specific EFC with the probability of an HFE, given that context.

B. Examples of Human Errors Observed in the Reviews of Fire Events

The reviews conducted indicated a number of ways that human responses can affect the course of a fire. They include:

- an erroneous assessment of the situation and consequent erroneous decisions that exacerbate rather than mitigate the fire,
- delayed assessment of the situation and delayed decision making,
- difficulties in controlling plant processes even after the fire is suppressed,
- initiation of fires,
- delayed detection of a fire, and
- delayed suppression of a fire.

In addition, preexisting equipment failures can complicate operators responses to a fire.

C. Potential Characteristics of Fire-Induced, Cognitively Challenging Scenarios

Fire-induced scenarios include a variety of factors that ought to be considered in performing HRAs in support of fire PRAs. These would form the EFC described by ATHEANA; i.e., complicating plant conditions and unfavorable PSFs. These elements of an EFC can affect all stages of information processing by operators: detection/monitoring, situation assessment, response planning, and response implementation. The most obvious characteristics or aspects of the fire-related scenarios that should be considered include:

- Timing of fire-induced equipment failures. Rather than the common assumption that all failures occur at the beginning of the scenario, failures are actually spread out over time, from tens of minutes to hours. Thus, operators never quite know the status of the plant (i.e., what equipment is currently unavailable and what may soon be lost).
- Unique failure mechanisms. Hot shorts, grounds, opens, and hot gases can induce effects outside the range of most operators' experience, such as spurious operation of equipment, fluctuating instruments and unusual equipment configurations.
- Knowledge of the fire. In some cases, the first evidence of a fire in the control room could be the initial equipment failures. Seemingly random failures in unrelated equipment can be very confusing.
- Fire brigade. The role of fire brigade members in responding to accidents and interactions between the fire brigade and operators is a plant-specific factor that can affect command and control. It is often the case that one of the operators is on the

fire brigade and in some cases it is the shift supervisor.

- Environmental conditions. Smoke, heat, and breathing devices can affect communication, vision, and judgment.
- Communication. Evacuation of fire, or smoke-affected areas of the plant and the burdens of breathing apparatus can interfere with effective communication.
- Information sources. The limited range of instrumentation at the remote shutdown panel can affect equipment failure scenarios not monitored there.
- Procedures. In many plants, there is very little operational training or special emergency procedures for conditions resulting from rapidly propagating fires. In others, there are very complicated procedures (e.g., plants with self-induced station blackout procedures). In either case, the impacts need to be considered.

D. Fire Design and the Assumptions of Fire PRA

The review of fire events provided good evidence that nuclear plants are generally built to be resistant to significant fires and that there have been few serious fire events. This suggests that the risks from fires are generally low, as is also indicated by the results of the IPEEEs.

However, the review of the LERs identified a surprising number of discrepancies between actual plant design and Appendix R expectations (e.g., inappropriate cable routing). This finding implies that fire risk study assumptions that all Appendix R expectations are met at the time of the fire are not as valid as generally expected. In addition to the potential to undermine the basis for many fire PRAs, such discrepancies could be part of an EFC for the appropriate fire event scenario.

VI. RECOMMENDATIONS

The findings and conclusions developed in this work suggest new approaches and considerations for fire HRAs, fire event investigations, and fire PRAs.

1. *"Table-Top" Fire HRA Study.* ATHENA addresses all the new issues associated with fire HRAs. Furthermore, the lack of new HRAs for fire PRAs indicates a strong need for guidance of the type provided for normal operations in the ATHEANA guidelines.[1] A small-scale test application of ATHEANA to a fire HRA, a "table-top" exercise, is recommended to develop the necessary extensions of the ATHEANA guidelines, if any, for third-party application of ATHEANA to fire HRAs. The study would compare the special needs of fire HRAs with the current guidelines; make any obvious extensions; test the process for several fire scenarios for a specific plant using that plant's design information, procedures, IPEEE, and Appendix R reports; and make final extensions to the guidelines.

2. *Fire Event Investigations.* Future fire event investigation teams should include expertise in human performance and the investigation report should address the issues included in the ATHENA multidisciplinary framework. Such investigations should not only examine fire control and suppression, but also the effects on operator performance related to continued safe operation of the plant.

3. *Fire PRA Assumptions.* The potential impact of incomplete Appendix R implementation on fire PRA results should be investigated. If the impact is found to be significant, new approaches to address this problem in terms of modeling or uncertainty analysis should be developed. As a minimum, it is suggested that walkdowns be required on at least a sampling basis to ensure that the condition of fire detection and suppression equipment as well as fire barriers is as "assumed" in order to properly screen out areas of the plant and possible fire growth scenarios.

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VIII. REFERENCES

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