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THE ANGRA 1 FIRE PRA PROJECT

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ABSTRACT

The Angra 1 Fire PRA (Probabilistic Risk Assessment) is under development by ELETRONUCLEAR jointly with EPRI (Electric Power Research Institute). The project was started January of 2007 and it is foreseen to be finished in the middle of the next year.

The study is being conducted according to the newest methodology developed by EPRI and NRC/RES (U.S. Nuclear Regulatory Commission – Office of Regulatory Research) published in 2005 as Fire PRA Methodology for Nuclear Power Facilities (NUREG/CR-6850 or EPRI TR-1011989) [1].

Starting from the Internal Events Angra 1 PRA model Level 1 the project aims to be a comprehensive plant-specific fire analysis to identify the possible consequences of a fire in the plant vital areas which threaten the integrity of systems relevant to the safety, challenging the safety functions and representing a risk of accident that can lead to a core damage.

The main tasks include the plant boundary and partitioning, the fire PRA component selection and the identification of the possible fire scenarios (ignition, propagation, detection, extintion and hazards) considering human failure events to establish the fire-induced risk model for quantification of the risk for nuclear core damage taking into account the plant design and its fire protection resources.

This work presents a general discussion on the methodology applied to the completed steps of the project.

1. INTRODUCTION

The Angra 1 Fire PRA is a comprehensive plant-specific project planned for identification of the possible fire scenarios (ignition, propagation, detection, extintion and hazards) which impose a nuclear core damage risk based on the plant design and its fire protection resources.

The main aspects of the project can be summarized as follow:

- the fire PRA is an extension of the Angra 1 Level 1 internal events model to quantify fire risk (i.e. contribution to CDF due to fire accidents);
- an electronic cable database was created from paper pull-cards in support of this project for cable routing identification;
- the Fire PRA will produce models and results reflecting current configuration of Angra 1 for:
  - post-fire safe shutdown capability;
  - fire prevention and protection schemes;
  - risk-informed evaluation of the preliminary design change packages;
  - proposed design change package and revised Fire PRA.

The project tasks are the following:

1. Plant Boundary and partitioning;
2. Fire Ignition Frequency determination;
3. Fire PRA component selection;
4. Plant fire-induced risk model;
5. Identification of the Human Failure Events (HFE);
6. Fire PRA circuit selection, routing & analysis;
7. Detailed Fire modeling;
8. Post-Fire human reliability analysis (HRA);
9. Circuit failure modes and likelihood analysis;
10. Fire risk quantification;
11. Uncertainty and sensitivity analysis.

Currently the tasks 1 to 5 are fully completed. This paper presents a general discussion on the application of the adopted methodology to perform the completed tasks.

2. PLANT BOUNDARY AND PARTITIONING

Based on the adopted methodology the purpose of the plant partitioning is twofold:

- define the global plant analysis boundaries relevant to the Fire PRA, and
- divide the plant into discrete physical analysis units (fire compartments).

The Fire PRA methodology considers fire threats to safe shutdown primarily in the context of the defined fire compartments. The results of the Fire PRA will be presented in terms of the risk contribution from fires inside a compartment and from fires that impact multiple adjacent compartments.

The plant buildings are divided into fire compartments. Angra 1 document CNEN-NN-2.03 [2] and the procedure PPI-R 01 [3] provide the following definitions:

- *Área de incêndio* (Fire Area) – A space delimited by fire barriers or by a separation determined by the Fire Analysis intended to prevent a postulated fire to propagate to a different area or redundant safety trains;
- *Análise de Incêndio* (Fire Analysis) – Consequence analysis of a postulated fire in an Evaluation Zone. The analysis should determine necessary modifications in terms of fire protection;

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- *Barreiras corta-fogo* (Fire Barriers) – Passive elements such as doors, seals, fire dampers and walls with qualified fire resistance characteristics;
- *Incêndio postulado* (Postulated Fire Event) – Fire event considered as possible in a given Evaluation Zone;
- *Zona de Avaliação* (Evaluation Zone) – Plant space considered for fire analyses purposes. An evaluation zone may not have specific characteristics. It may be a fire area or a subdivision of a fire area.

The plant partitioning task includes the following activities:

- review of the fire areas defined in the Fire Hazards Analysis for Angra 1 [4];
- identification of fire compartments for fire PRA purposes at Angra 1.

Some of the fire areas defined in the Angra 1 FHA are relatively large, specifically in the reactor (containment) and turbine buildings. These areas usually consist of multiple rooms in the corresponding building elevations. Not all the zones are defined by walls. In some cases, the zones are delimited by spatial separation.

Fire compartments for fire PRA purposes should be well-defined volumes within the plant expected to substantially contain the adverse effects of fires within the compartment. A strict interpretation of this definition is difficult to implement in some buildings at Angra 1. The turbine and reactor buildings for example, consist of large general areas where thermal damage generated by fire is expected to be localized. Therefore, the plant has been preliminarily partitioned in terms of the currently defined zones (Zona de Avaliação), which will also be used for determining location of raceways and conduits in the cable and raceway database. As the tasks in the Fire PRA are completed, the appropriateness of this partitioning scheme may need to be re-evaluated. Further partitioning may be necessary depending on the amount of equipment in the different areas of each zone.

3. FIRE IGNITION FREQUENCY DETERMINATION

Fire frequencies are assigned to the fire compartments identified in the task of Plant Partitioning. The process of determining fire ignition frequencies for the identified fire compartments is based on the methodology and data provided in EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities [1].

The general formula for computing fire ignition frequency for a specific compartment is as follows:

$$\lambda_{J,L} = \Sigma\, \lambda_{IS}\, W_L\, W_{IS,J,L}$$

where:

λ_{IS} = Plant-level fire frequency associated with ignition source IS;
W_L = Location weighting factor associated with the ignition source;
$W_{IS,J,L}$ = Ignition source weighting factor reflecting the quantity of the ignition source type present in compartment J of location L.

The ignition frequency for a particular fire compartment is characterized by the contributions from fixed and transient ignition sources. Fixed ignition sources refer to the equipment and/or cables permanently located in the fire compartment. Transient ignition sources refer to combustibles and activities (e.g., welding) that may be brought into the room at any given time on a temporary basis.

The fire compartment frequency can be written as:

$$\lambda_i = \Sigma_{all\ k}\, \lambda_k\, W_{k,i} + \lambda_{GT}\, W_{GT,i} + \lambda_{WC}\, W_{WC,i} + \lambda_{CF}\, W_{CF,i}$$

where:

- λ_i is the fire frequency for fire compartment *i*;
- λ_k is the generic frequency for fixed ignition source *k* as listed in Table 6-1 in Ref. 1;
- $W_{k,i}$ is the ignition source weighting factor for fixed ignition source *k* in fire compartment *I;*
- λ_{GT} is the generic frequency for general transients as listed in Table 6-1 in Ref. 1;
- $W_{GT,i}$ is the ignition source weighting factor for general transients in fire compartment *i.* These parameters are generated using the maintenance, storage and occupancy influence factors described in Task 6 of Ref. 1;
- λ_{WC} is the generic frequency for fires caused by welding and cutting as listed in Table 6-1 in Ref. 1;
- $W_{WC,i}$ is the ignition source weighting factor for fires caused by welding and cutting in fire compartment *i.* These parameters are generated using the maintenance influence factor described in Task 6 of Ref. 1;
- λ_{CF} is the generic frequency for cable fires caused by welding and cutting as listed in Table 6-1 in Ref.1;
- $W_{CF,i}$ is the ignition source weighting factor for cable fires caused by welding and cutting in fire compartment *i.* These parameters are generated using the maintenance influence factor described in Task 6 of Ref. 1;

The ignition source weighting factor for fixed ignition sources is used to apportion the generic fire frequencies based on the amount of equipment in each room. Generic frequencies in Reference 1 for specific ignition sources were derived on a per-unit basis. For example, the frequency for electrical cabinets represents the total contribution from electrical cabinets in the unit. As such, it needs to be apportioned to the different fire compartments by multiplying it by the fraction of the corresponding ignition source in each fire compartment.

The ignition source weighting factor for transient sources is calculated using *influence factors*. Reference defines three influence factors: maintenance, occupancy, and storage. These influence factors differentiates fire compartments according to the level of maintenance activities, combustible storage, and occupancy levels. In general, high influence factor values would result in higher compartment transient fire frequency.

Currently, the ignition sources identified during plant walkdowns are maintained in a database which provides the flexibility for updating fire ignition frequencies in the future.

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4. FIRE PRA COMPONENT SELECTION

The Angra 1 Fire PRA model includes a comparatively broad set of equipment and operator actions utilizing much of the Internal Events PRA and examining potential fire effects on multiple trains of systems in the plant. The purpose of the component selection task is to develop the component list to be considered for inclusion into the Fire PRA model, subject to other tasks (e.g., fire modeling, circuit analysis, etc.) that may modify the final component scope. The output of this task is a final list of electrically dependent (motive power, control power, signal) components identified for inclusion in the Fire PRA model.

The equipment selection task is performed via an eight step process. The selection of equipment provides a starting point of equipment items for which subsequent analysis activities may be performed including identifying related cables and their locations, fire modeling (for instance, to see if certain components can be eliminated from further consideration as fire targets), and preliminary PRA modeling to see what compartments require more detailed analysis as a result of components or cables affected by each postulated fire. The procedural steps are summarized below.

Step 1 Identify electrically dependent components in the Internal Events PRA model.
Step 2 Identify Internal Events PRA Sequences to be Included (and those to be excluded) in the Fire PRA Model.
Step 3 Identification of components associated with fire-induced initiating events to the extent that each compartment has an assigned fire-induced initiating event assigned unless the compartment can be screened.
Step 4 Addition of components whose potential spurious actuations (considering multiples) could challenge the safe shutdown capability.
Step 5 Addition of instrumentation important to human response.
Step 6 Inclusion of components whose failure, by itself, could cause high consequence events (interfacing LOCA or steam generator tube failure).
Step 7 Addition of components identified by an expert panel.
Step 8 Finalization and documentation of the component selection process

5. IDENTIFICATION OF THE HUMAN FAILURE EVENTS (HFE)

The purpose of fire Human Reliability Analysis (HRA) is to identify, characterize and quantify events representing human failure events (HFEs) in the development and quantification of a fire PRA model. Fire HRA includes both modifications to existing HFEs that incorporate fire impacts and analysis of new fire scenarios to be included in the FPRA model.

5.1. Identification of Post-fire Operator Actions and Definition of HFEs

Following the methodology this section addresses (1) the identification of operator actions that are necessary for successful mitigation of fire scenarios, and (2) representation of these operator actions through the definition of human failure events (HFEs) that are modeled in the Fire PRA. There are three categories of post-initiator operator actions to be considered:

- Existing operator actions from internal events PRA model;
- operator actions explicitly called out in the fire procedures;
- undesired operator actions.

5.1.1. Internal Events PRA Operation Actions and HFEs

These are the existing operator actions modeled in the Level 1, internal events PRA. The existing internal events HFEs were revised for fire impact. All the assumptions and inputs used in the internal events HFE analysis were systematically considered for fire impact including:

- fire impact on instrumentation and indications credited for detection and diagnosis;
- fire impact on timing of: (1) cues, (2) response, (3) execution, and (4) time available;
- fire impact on success criteria;
- fire impact on manpower resources, which affect recovery;
- fire impact on local actions, e.g., accessibility, atmosphere, lighting.

Existing internal events HFEs that are not associated with any fire induced initiating events were screened from further consideration in the fire HRA. For example, on a PWR, steam generator tube rupture (SGTR) is not a fire induced initiating event, therefore fire impact on SGTR HFEs have not been considered.

5.1.2. Fire Response Operator Actions and HFEs

Fire response operator actions are new post-initiator operator actions required in response to a fire. These are typically directed by the fire response procedures. Angra 1 does not utilize fire response procedures. All operator actions are typically directed by the emergency operating procedures, alarm response procedures and/or abnormal operating procedures. Therefore, no fire response operator actions were identified using this methodology.

5.1.3. Undesired Operator Actions and HFEs

Undesired operator actions may result if operators respond to spurious indications. As operators are trained to believe their instrumentation and follow their procedures, it has to be assumed that operators would usually respond to a spurious indication as if it is real. A definition of an undesired operator action is a well intentioned operator action that unintentionally aggravates the scenario. The key criterion in identifying undesired operator actions is that the operator action must lead to a worsened plant state.

To reasonably bound the number of modeled, undesired operator actions due to spurious indications, it is recommended that human performance-based criteria be developed to be applied consistently in the identification process. Such criteria should be based on the plant specific factors that govern operator cognitive response to indications such as:

- cue parameters;
- cue (procedural) hierarchy;
- cue verification;

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- degree of redundancy for a given parameter.

Each of the above factors is shortly discussed below.

5.1.3.1. Cue Parameters

The cue for an operator cognitive response may consist of a single parameter or multiple parameters. For operators to be misled by a single parameter cue, a spurious indications on the single parameter would be sufficient, while for a multiple parameter cue, multiple spurious indications on different parameters would be required. It would generally be true that multiple spurious indications on different parameters are far less likely than spurious indications on a single parameter, but this would depend on the fire impact on instrumentation in a specific scenario.

5.1.3.2. Cue (procedural) hierarchy

Following a reactor trip, operator response is governed by procedure. The operators enter the emergency operating procedures (EOPs). During the initial EOP response, the crew basically focuses on plant parameters and alarms that are called out in the EOPs – other annunciator alarms may be ignored until the plant is stabilized, unless the cue is very pertinent to the scenario.

The operators also may have some cue-specific indication preferences based on ease-of-use, reliability etc. When a continuously monitored cue occurs, the operators may be required to suspend what they are doing and perform the instructions associated with this cue. Cues may be further prioritized e.g. in the Westinghouse EOPs cues are prioritized by (1) safety function and (2) severity of challenge to safety function, in the critical safety function status trees (CSFSTs) that are monitored from a certain point in the EOPs. Although there may be plant-specific deviations, operators generally prioritize the cues as follows:

- cues that are continuously monitored;
- cues that are called out in the EOPs as checks, but are not continuously monitored;
- cues that are not called out in the EOPs, but that may be very pertinent to the scenario;
- cues that are not called out in the EOPs and that are not pertinent to the scenario.

Operators are more likely to be misled by a spurious indication on a high priority cue than a low priority cue.

5.1.3.3. Cue verification

Certain cues may require an immediate response, while other cues may require verification prior to action. For example, a typical annunciator response procedure may require the operators to verify the validity of the cue by comparison with the other indications, local inspection etc.

Operators are more likely to be misled by a spurious indication of a cue that requires an immediate response than a cue that requires to be verified first.

5.1.3.4. Degree of redundancy for a given parameter indication

Most plant parameters have redundant instrumentation channels and indications. Operators are not likely to be misled by a spurious indication on one of several redundant instrumentation channels, but they may be misled by multiple spurious indications on redundant channels.

6. PLANT FIRE-INDUCED RISK MODEL

This section describes changes to the Angra Unit 1 Internal Events PRA model so that it can be used to quantify fire-induced conditional core damage probability (CCDP) and core damage frequency (CDF) in support of the Fire PRA.

Development of the Angra 1 Fire-Induced Risk Model is performed in three steps in accordance with the EPRI 1011989, NUREG/CR-6850, Volume 2, Section 5.5.1.1:

1. select appropriate fire-induced initiating events and sequences and verification against the component list and failure modes defined in the task Fire PRA Component Selection;
2. incorporate fire-induced equipment failure, and
3. incorporate operator actions in response to a fire.

6.1. Selection of Appropriate Fire-induced Initiating Events and Sequences

Under this step fire-induced accident initiators have been identified and Angra 1 internal events model has been modified to quantify fire-induced sequences.

Angra 1 does not have fire-specific procedures with the exception of those in response to fires in the main control room (MCR) requiring plant shutdown from outside the MCR. Therefore, the same fire risk model will be used for all fires initiating outside the MCR that will allow plant shutdown from the MCR. In case of fire in the MCR, or other plant locations, requiring plant shutdown from outside the MCR, the same model will be used with functions, systems, components credited in the MCR abandonment procedure.

In addition, event trees have been added to the model to incorporate the initiating event frequencies (fire ignition frequencies) to the quantification process. Currently the fire ignition frequencies incorporated in the model are at fire compartment level. This process has been automated. That is, the fire ignition frequencies currently reside in the Fire Modeling Database design and populated to maintain fire ignition frequencies and other fire analysis tasks. A computer routine has been developed to automatically generate the files that incorporate the fire ignition frequencies into the model.

6.2. Incorporation of Fire-induced Equipment Failures

This step requires that specific fire-induced equipment failures identified under Fire PRA Component Selection are properly incorporated into the fire risk model.

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Under this task the fire-induced equipment failures, including spurious operation, that directly disable or degrade systems, trains and functions credited in the fire PRA were added to the internal events logic. This includes incorporating the equipment, failure modes and logic necessary for the multiple spurious scenarios identified by an expert panel.

6.3 Incorporation of Fire-induced Human (Operator) Failure Events

In this step, fire-specific human (operator) actions where identified, human (operator) failure events (HFEs) were defined and included in the Fire Risk Model. The actions and the HFEs were defined in accordance with EPRI 1011989, NUREG/CR-6850, Volume 2, Section 12.5.1. Under this subtask following activities have been completed.

- The existing internal events HFEs were reviewed and updated.
- Angra 1 does not utilize fire response procedure. All operator actions are typically directed by the emergency operating procedures (EOPs), alarm response procedures (ARPs), and/or abnormal operating procedures (AOPs). Therefore, no fire response operator actions were identified.
- Undesired operator actions of concern in response to spurious fire-induced failure(s) of equipment or alarm(s) were identified through review of the EOPS, ARPs and AOPs.
- The specific method for incorporating these concerns in the Angra 1 Fire Risk model has been developed.
- The screening HEPs developed in section 2 of this interim report have been added to the Fire Risk model for initial quantification.

7. ADVANTAGES AND CHALLENGES

The objective of the ELETRONUCLEAR and EPRI joint project is to provide Angra 1 with a realistic state-of-the-art fire risk assessment that can be maintained and used in the future. Through this project Angra 1 has the opportunity to identify additional plant vulnerabilities due to fire scenarios besides other advantages, like the implementation of an automated fire model and the availability of an electronic database for cables (with applications outside PRA). It is also expected that the results can be used as a resource to define strategies aiming to fire protection improvements, like:

- development of studies to improve fire fighting and prevention resources;
- risk-benefit evaluation between design modification options;
- investigation on new improvement opportunities with previous risk impact analysis;
- evaluations with performance requirements to selected design aspects;
- risk-informed assessment of preliminary design modification proposals.

Otherwise, there are also some challenges which the plant staff has faced that still need additional efforts to be fully overcome, including all the drawing review work, performance of intensive plant walkdowns to identify all relevant information and to complete the electronic database of cable routes for non-safety related but important equipment according to the PRA context.

8. REFERENCES

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