AN APPLICATION OF THE LAYER OF PROTECTION ANALYSIS (LOPA) TO THE EVALUATION OF FIRE HAZARD ASSOCIATED TO SHUTDOWN CABLE ROUTES OF A NUCLEAR REACTOR

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ABSTRACT

The method of Layers of Protection Analysis (LOPA) is a powerful analytical tool for assessing the adequacy of protection layers used to mitigate process risk in an industrial process plant. LOPA applies semi-quantitative measures to evaluate the frequency of potential incidents and the probability of failure of protection layers. This paper presents an application of the Layer of Protection Analysis technique to a nuclear power plant. The objective is to propose the LOPA utilization to evaluate the fire risk associated to the routes of power cables of equipments necessary for a safe nuclear reactor shutdown, when a Level 1 Probabilistic Safety Assessment for internal events is unavailable. The consequences identified are listed as impact events and are classified as to their severity level. The initiating causes are listed for each impact event and the likelihood is estimated for each initiating cause. Independent Protection Layers (ILPs) are listed. The mitigated event likelihood is studied and additional ILPs can be evaluated and added to reduce the risk. Critical fire zones in a nuclear power plant auxiliary building are identified. The fire frequencies from each critical fire zone and the probability of failure on demand from the independent protection layers are determined. Using the Layer of Protection Analysis, the fire risks of critical zones are estimated and alternative fire protection improvement measures can be analyzed.

1. INTRODUCTION

Fire protection is one of the main aspects of nuclear power plants design and operation safety, because fires occur with relatively high frequency and have great potential to affect critical systems necessary to the maintenance of the plant safety and safe reactor shutdown.

Results of already performed fire risk assessments for nuclear power plants, in the USA in particular, have shown that fires must be considered as a significant core damage contributor. As a consequence of these results, in USA and partly in Europe, a full scale probabilistic safety assessment (PSA) including fire events is a common practice. [1]

When a PSA is not available, it is necessary to apply another tool to safety assessment to obtain the quantification of the risk associated with the electric cables routes of equipments necessary to the safe reactor shutdown, for the cases of fire in compartments.
The purpose of this paper is to consider the use of the Layers of Protection Analysis, which provides a simplified approach to evaluate the risk for the electric cables routes. LOPA provides specific criteria and restrictions for the evaluation of independent protection layers (IPLs), eliminating the subjectivity of qualitative methods at substantially less cost and time than fully quantitative techniques.

2. LOPA – LAYERS OF PROTECTION ANALYSIS

The primary purpose of LOPA is to determine if there are sufficient layers of protection, against an accident scenario. Many types of protective layers are possible as illustrated in Figure 1. A scenario may require one or many protection layers depending on the process complexity and potential severity of a consequence. For a given scenario, only one layer must work successfully for the consequence to be prevented. However, since no layer is perfectly effective, sufficient protection layers must be provided to render the risk of the accident tolerable.

![Figure 1. Layers of defense against a possible accident.](image)

LOPA is limited to evaluating a single cause-consequence pair as a scenario. Once a cause-consequence pair is selected for analysis, the analyst can use LOPA to determine which engineering and administrative controls (often called safeguards) meet the definition of IPLs, and then estimate the risk of the scenario. The results can then be extended to make risk...
judgments and to help the analyst decide how much additional risk reduction (additional IPLs) may be required to reach a tolerable risk level. Some of the LOPA benefits are:

- LOPA helps resolve conflicts in decision making by providing a consistent, simplified framework for estimating the risk of a scenario and provides a common language for discussing risk.
- LOPA provides a means of comparing risk from unit to unit or plant to plant, if the same approach is used throughout the company.
- LOPA provides more defensible comparative risk judgments than qualitative methods due to the more rigorous documentation and the specific values assigned to frequency and consequence aspects of the scenario.
- LOPA can be used to help an organization decide whether the risk is “as low as reasonably practicable” (ALARP), which may also serve to meet specific regulatory requirements.
- Information from LOPA helps an organization decide which safeguards to focus on during operation, maintenance, and related training.

The limitations imposed on LOPA result in a work process that is much less complex than quantitative risk analysis, while generating useful, somewhat conservative, estimates of risk.

LOPA can be divided into the steps described below [2]:

- Step 1: Identify the consequence to screen the scenarios.
- Step 2: Select an accident scenario.
- Step 3: Identify the initiating event of the scenario and determine its frequency.
- Step 4: Identify the IPLs and estimate the probability of failure on demand of each IPL.
- Step 5: Estimate the risk of the scenario by mathematically combining the consequence, initiating event, and IPL data.
- Step 6: Evaluate the risk to reach a decision concerning the scenario.

3. CASE STUDY

This application of LOPA to a nuclear power plant is based on the original work of CCPS [2], however some adaptations have been made to consider some appropriate typical fire factors, for example, fire probability in one determined area of the plant, according to the existing ignition sources, as well as the failure on demand probabilities for the appropriate ways of fire prevention and mitigation. The fire analysis applied here was based on the assumption that the damages are basically caused by the temperature rise that a fire provides. It is also assumed that fire in a compartment has the potential to damage all the existing equipments and cables, and the failure of a cable in any compartment can lead to the same consequence of the component’s failure itself.

3.1. System Analysed

This case study analyzed the elevation +5,15m from Angra 1 Nuclear Power Plant. The Elevation +5,15m from the safety and auxiliary (north and south) buildings concentrates the fire risk critical points that could affect the corresponding cables of redundant systems,
necessary for the safe reactor shutdown, and diverse compartments do not meet the physical separation criteria between redundant trains [3].

The elevation +5.15 m is divided into fire zones, as illustrated in Figure 2. The highlighted zones contain equipment or cable trays necessary for the safe reactor shutdown. These are the zones to be evaluated and for each one the main existing equipments, combustibles (ignition sources), fire loads and ways of fire detection and suppression have been identified [3].

![Figure 2: Fire Zones in the Safety and Auxiliary Buildings (Elevation +5.15m).]

3.2. Application of LOPA

In LOPA first step, the consequences are defined as cables damages (caused by fire) that can affect the safe reactor shutdown. The severity, or the consequence endpoint, is defined as the
number of redundant cables necessary to the safe reactor shutdown that would be affected by a possible fire scenario.

The next step consists of the scenario identification. An initial qualitative process is performed to identify critical fire zones. Only the zones that have redundant equipments and cables necessary to the safe reactor shutdown are selected for the application of LOPA. These are the zones EAN-1, EDS-1, EDS-2 and EAS-1.

The initiating event of each scenario is defined as the pilot fire in the determined zone. The candidate safeguards (potential IPLs) are: automatic fire detection and manual fire suppression. The automatic detection consists of ionic smoke detectors present in every zone. The manual suppression consists of operator action to extinguish the fire pilot using the existing extinguishers and hoses in the zones.

It must be checked whether there are interactions between zones so that possible risk situations involving more than a compartment can be identified. Zones EAN-1, EDS-1 and EAS-1 form a long corridor without barriers between the auxiliary and safety buildings. Therefore, the same consequence can occur due to different initiating events, i.e. part of the cables of a given zone can be damaged by a fire originated in the adjacent zone, which has developed and propagated due to the absence of a qualified fire barrier.

Eight scenarios were identified: 2 from zone EAN-1, 3 from zone EDS-1, 1 from zone EDS-2 and 2 from zone EAS-1.

In the next step, the objective is to determine the initiating event frequency of each scenario, i.e. the fire frequency of each zone. Historical data from the plant or similar plants were not available. The fire frequencies were estimated through a generic database [4]. Table 1 presents the fire frequency estimated values for each fire zone.

<table>
<thead>
<tr>
<th>Fire Zone</th>
<th>EAN-1</th>
<th>EDS-1</th>
<th>EDS-2</th>
<th>EAS-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Frequency (year⁻¹)</td>
<td>$1.53 \times 10^{-2}$</td>
<td>$6.09 \times 10^{-4}$</td>
<td>$4.05 \times 10^{-3}$</td>
<td>$3.26 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

In the fourth step, the candidates IPLs are analyzed to check whether they meet the IPL requirements. In order to be considered an IPL, a safeguard must be efficient, independent and auditable. Automatic detection and manual suppression cannot be considered IPLs separately, because manual suppression is not independent of automatic detection. Furthermore, only automatic detection is not efficient to prevent the consequence. In this way, the automatic detection and manual suppression combined action can be considered an IPL, since it meets the requirements of effectiveness, independence and auditability.

In the absence of specific plant data, the detection and suppression systems reliability data were obtained through generic sources of information. For the automatic system, the probability of failure on demand (PFD) used was $4 \times 10^{-2}$ [5]. For the manual suppression,
the PFD used was $1 \times 10^{-1}$ [2]. Combining both, the PFD for the identified IPL is obtained: $(4 \times 10^{-2}) \times (1 \times 10^{-1}) = 4 \times 10^{-3}$.

In the fifth step, the mitigated scenarios frequencies are estimated by means of Equation 1. For each identified scenario, the initiating event $i$ frequency is multiplied by the PFD of the $j^{th}$ IPL. For zones with more than one scenario, their frequencies must be summed, so that a zone to zone analysis can be done. Table 2 presents the results for the mitigation frequencies.

$$f_i^C = f_i \times \prod PFD_{ij} = f_i \times PFD_{i1} \times PFD_{i2} \times \ldots \times PFD_{ij}$$  \hspace{1cm} (1)

The risk of each zone is estimated through the Equation 2, combining the mitigation frequency $f$ with a factor $C$ related to the consequence magnitude. This factor is defined as the consequence endpoint, i.e. the number of redundant cables necessary to the safe reactor shutdown present in the given zone. It was assumed that all the compartment cables are damaged by a possible developed fire. Table 2 presents the results for each zone risk.

$$R = f \times C$$  \hspace{1cm} (2)

<table>
<thead>
<tr>
<th>Fire Zone</th>
<th>Mitigation Frequency (year$^{-1}$)</th>
<th>Number of Redundant Cables</th>
<th>Risk (Nr. of damaged cables/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAN-1</td>
<td>$6,36 \times 10^{-5}$</td>
<td>6</td>
<td>$3,81 \times 10^{-4}$</td>
</tr>
<tr>
<td>EDS-1</td>
<td>$1,94 \times 10^{-4}$</td>
<td>8</td>
<td>$1,55 \times 10^{-3}$</td>
</tr>
<tr>
<td>EDS-2</td>
<td>$1,62 \times 10^{-5}$</td>
<td>4</td>
<td>$6,48 \times 10^{-5}$</td>
</tr>
<tr>
<td>EAS-1</td>
<td>$1,33 \times 10^{-4}$</td>
<td>53</td>
<td>$7,04 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

The next step is the decision making process. The risk must be compared with tolerance criteria. If the risk is unacceptable, additional layers of protection must be added. A specific risk tolerance criterion for this case study does not exist, i.e. there is not a criterion that defines the maximum tolerated risk for damages to nuclear reactor shutdown cables. However, LOPA allows a better risk knowledge providing a base for judgment. A comparison must be made between the estimated risks from each zone, so that specific risk reduction decisions and actions can be prioritized, in accordance with the risk magnitude.

When completing the analysis, recommendations can be made to reduce the fire risk and also to evaluate the effectiveness of different proposed modifications.

As Table 2 shows, EAS-1 is the most critical zone. Therefore, it requires in additional mitigation measures. It is recommended to intensify the fire detection and suppression means with the following systems: anticipatory smoke detection system, automatic fire suppression system and a water curtain in the borderline between zones EAS-1 and EDS-1. The mitigation frequency and risk calculation is repeated, inserting one (or more) of these recommendations as IPLs, attributing specific PFDs to them. In this way, the results can be
compared to check whether the proposed recommendations provide a satisfactory risk reduction. The same procedure is applied to the other zones.

4. CONCLUSIONS

When a PSA is unavailable, LOPA provides fast results for the fire risk quantification, facilitating the decision making and providing insights of the fire protections impact.

LOPA results show the advantages of automatic fire detection and suppression systems, and also identify which areas must be well known by the fire brigade and the areas that must receive special attention during the staff training, being able to avoid the installation of redundant protection systems that would not contribute for the plant safety.

The application of LOPA to a nuclear plant is simple and can be executed in every compartment where safe reactor shutdown equipments are present. It is recommended to give priority to the compartments where the physical separation criteria between redundant trains are not met. LOPA can still be extended to other situations related to risk informed decision making, e.g. evaluation of project modifications, plant emergency response planning, events evaluation and classification, etc.

An updated database is extremely necessary for the performance of probabilistic fire analyses. The database must take in to account specific data from Brazilian nuclear power plants or even similar plants, to replace generic data from other databases and sources, reducing the analysis uncertainties.

REFERENCES