Modified-LOPA; a Pre-Processing Approach for Nuclear Power Plants Safety Assessment

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Abstract: Risk and safety assessment are important subjects in modern industries. Different methods have been proposed for safety and risk evaluation of high hazardous facilities. The risk assessments methods are classified in three main groups of qualitative, semi-quantitative and quantitative. The methodology is selected depending on scope and objective, level of details and requirements. Nuclear facilities regulations require more detailed assessment of system safety. Regulatory body requires utilization of probabilistic risk assessments (PRA) for appraisal of design, modifications and operation of nuclear power plants. This method usually is very complicate, expensive and time consuming. Significant amount of resources are needed for a PRA project completion which in some cases for preliminary safety evaluation are not justified. Simpler methods would be used for preliminary evaluation as a pre-processor to quick find out of the situations (especially in operational nuclear power plant). Layer of Protection Analysis (LOPA) is one of the powerful risk analysis methods. It is a semi-quantitative approach widely used in chemical process industry. This method is not a competitive alternative to full quantitative methods of risk analysis for nuclear facilities like PRA. However, it is simpler and less expensive methodology comparing to full probabilistic risk assessment methods. It evaluates the probability of failure per demand for the safety system failures and the resulting consequences. It is introduced here as a practical technique for early and quick risk assessing in many other industries. But if LOPA has been selected as a risk evaluator pre-processor in nuclear systems it requires some modifications in methodology structure.

This research examines utilization of LOPA method for nuclear systems as an order of magnitude evaluation of the safety status. Conventional LOPA method requires some essential modifications in methodology to prepare it as a suitable approach for nuclear systems, especially in its scenario development and quantitative calculations. The so-called modified layer of protection analysis (Modified-LOPA) methodology is based on improvement of some features of conventional LOPA. Some changes are proposed to the classic LOPA method by using event tree method and Bayesian logic. Since LOPA and event-tree methods use definition of scenarios to represent the paths of the accidents, therefore scenario development is completed in modified method by using event-tree method. Then initiating event frequency and probability of failure on demand (PFD) of independent protection layers (IPLs) estimations are updated by Bayesian approach which increases the reliability of results by combination of plant specific data with generic data from other similar industries.

In this paper "Modified-LOPA" method is proposed as a primary tool for quick hazard analysis, risk assessment and risk based decision in nuclear systems. This method is more accurate comparing to conventional LOPA. However it is not a complete substitute for Full PRA in nuclear systems. A simple example of a fire protection system shows application of this method and the results are compared with the results of a PRA approach.

Keywords: LOPA, Risk, Scenario, Event Tree, Initiating Event, Independent Protection Layer (IPL), Probability of Failure on Demand (PFD), Frequency, Bayesian, Nuclear Power Plant.

1. INTRODUCTION

Nowadays, different methods have been proposed for safety evaluation of high hazardous facilities. The methods include Probabilistic Risk Assessment (PRA), Failure Mode and Effects Analysis (FMEA), Hazard and Operability (HAZOP), Reliability Block Diagram (RBD) and Layer of Protection Analysis (LOPA) [1]. Depending on scope and objective, level of details and requirements, the methodology is selected.

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Nuclear facilities regulations require more detailed assessment of system safety. Regulatory body requires utilization of PRA for assessment of design, modifications and operation of nuclear power plants. Although it's essential to meet all safety criteria in nuclear systems, the extent and complexity of analysis usually make it difficult to reach the results in a limited time. Significant amount of resources are needed for a PRA project completion which in some cases for preliminary safety evaluation are not justified. Simpler methods would be used for preliminary evaluation as a pre-processor to quick find out of the situations (especially in operational nuclear power plant). If the finding concludes the need for a more detail assessment then PRA is recalled.
LOPA is one of the powerful risk methods which is a semi-quantitative approach. It's widely used in chemical process industry. Actually, this method is not a competitive alternative to the full quantitative methods of risk analysis for nuclear facilities, but the characteristics of this method makes it capable of performing a preliminary nuclear safety and risk analysis. They include:

- Being systematic and straight-forward.
- Expression of results as semi-quantitative.
- Affordable cost, time and effort requirement compared to Full PRA method.
- Capability of focus risk reduction efforts on impact events with high severity and high probability [2].
- Capability of quick system design weakness identification for improvement and modification.

In spite of the fact that LOPA has got many positive features, some difficulties in scenario identification and in using statistical quantities, has led many researchers to modify this method. In this paper "Modified-LOPA" method is proposed as a primary tool for quick hazard analysis, risk assessment and risk based decision in nuclear systems. This method is more accurate comparing to traditional LOPA which gets help from Event Tree structure for developing scenarios and Bayesian logic to update the failure data. However it is not a complete substitute for Full PRA in nuclear systems, but the highly reliable results justify the using of Modified-LOPA as a nuclear risk pre-processing method.

NOMENCLATURE

FMEA	Failure Mode and Effects Analysis
HAZOP	Hazard and Operability
I.E.	Initiating Event
IPL	Independent Protection Layer
LOPA	Layer of Protection Analysis
NPP	Nuclear Power Plant
OFS	Off-Site Fire Protection System
ONS	On-Site Fire Protection System
PFD	Probability of Failure on Demand
PRA	Probabilistic Risk Assessment
RBD	Reliability Block Diagram
SIL	Safety Integrity Level
SIS	Safety Instrumented System

2. LITERATURE REVIEW

LOPA has been presented in several works and the results of its successful implementation have been reported in the various literature. LOPA is used in [2] to evaluate a highly reactive process and illustrates the benefit of risk assessment to follow a HAZOP hazard analysis. Hydroxylamine production facility has been evaluated as a practical case study in this paper. LOPA has been described in [3] for determining the requirements for Safety Integrity Level (SIL) of a Safety Instrumented System (SIS). Summers [4] briefly described LOPA as a powerful analytical tool for assessing the adequacy of protection layers used to mitigate process hazards.
An overview has been provided in [5] that mainly discusses the commercially available explosion prevention and mitigation systems applicable to gas, dust, mist and hybrid (gas-aerosol) explosions, including basic principles and proper application for single and combined systems and their

Limitations. Another research [6] attempts to explain the principles of LOPA and the means by which it can be used within the accidental risk assessment methodology for industries.
In some articles it's attempted to develop LOPA in methodology. Yun and Mannan [7] presented a Bayesian–LOPA methodology which studied a LNG importation terminal as a case study to demonstrate application of the method. It proposes that the Bayesian–LOPA method is a powerful tool for risk assessment of not only the LNG facilities but also in other industries, such as petrochemical, nuclear, and aerospace.
LOPA is presented in [8] as an approach that may include human harm and is independent of the analyst. It also provided how to identify and evaluate scenarios for LOPA and briefly describes the contribution of human errors in accidents. Markowski and Kotynia [9] applied including an uncertainty aspect in LOPA to the risk assessment of a hazardous substance release. It has been provided by a "bow-tie" approach being a composition of fault and event tree. The quantitative application of the "bow-tie" model has been proposed in the methodology of LOPA.
Summers et al. [10] improved the frequency and risk reduction tables in the estimate of the hazardous event frequency, and how consequence severity tables can significantly increase confidence in the severity estimate have been showed.
A mixed integer nonlinear programming model is presented in [11] to improve the computational use of LOPA. The human role and activities is reviewed in [12] as potential initiating events and human performance within independent protection layers in LOPA methodology.

3. MODIFIED-LOPA DESCRIPTION

As told before, layer of protection analysis is a semi-quantitative approach to evaluate the risk of potential incidents and to provide guidance on the adequacy of independent protection layers (IPLs) to lower the risk. LOPA typically uses order of magnitude categories for initiating event frequencies and for the probabilities of failure of IPLs, which can mitigate the frequency or reduce the consequence of an incident [2].
LOPA focuses risk reduction efforts on impact events with high severity and high probability, so its primary requirement is to determine these sever events. As a result, LOPA often follows a qualitative risk analysis performed as part of a HAZOP, check list, etc. to identify and characterize hazards.
LOPA methodology typically builds on the information developed during a qualitative hazard evaluation. Then, layers of protection are intended to independently comply with three main functions: Prevention, protection and mitigation. To be considered as independent protection layers (IPL's), safeguards need to satisfy some characteristics: independence, specificity, dependability and auditability [4].
The methodology typically uses order of magnitude to express the initial event frequency, the probability of failure on demand of the independent protection layers and the magnitude of the consequence. This way of expression provides good achievement to simple comparison and calculation.
It's expected that the results of LOPA be accompanied by [13]:

- Providing rational, semi-quantitative, risk-based answers
- Reducing emotionalism
- Providing clarity and consistency
- Documenting the basis of the decision
- Facilitating understanding among plant personnel

According to the literature review, especially the research of Yun et al. (2009) and its proposal for using the Bayesian–LOPA method to risk assessment in nuclear systems, this decision was made to recommend a modification in LOPA method for this purpose. So Modified-LOPA method has been recommended which uses Event-tree method for better scenario development, and Bayesian probabilistic method for updating data and calculating uncertainty of results.

4. METHODOLOGY STEPS

Modified-LOPA is based on improvement of some features of conventional LOPA. Since LOPA and event-tree methods are using definition of scenarios to represent the paths of the accidents, therefore scenario development in modified method is completed by using event-tree method. Initiating event frequency and Probability of Failure on Demand (PFD) of Independent Protection Layers (IPLs) data are updated by Bayesian approach. Figure 1 demonstrates the flowchart and steps for Modified-LOPA method. This flowchart is adapted based on the previous researches done in [2,7]. The basic steps of this approach are described below:

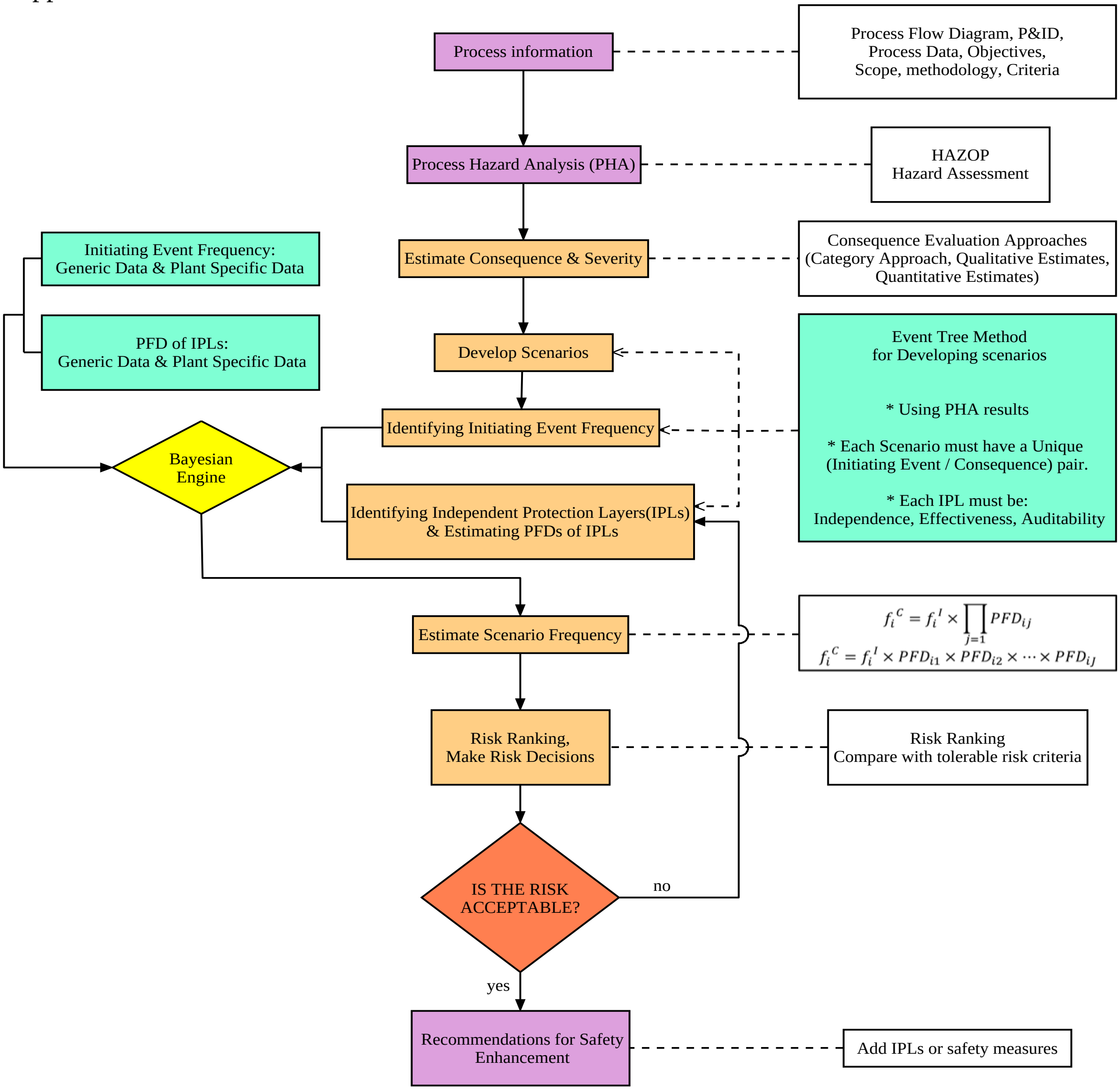

Figure 1. Modified-LOPA Process Flowchart

Step1: Process Information

First, a system should be completely identified. The piping and instrumentation diagram, process flow diagram, process data, objectives, scope, methodology, criteria and every data of maintenance and failures should be studied. It’s recommended that the criteria be provided in this step to determine the endpoint of accidents. Some examples for considering the endpoint of accidents are: overpressure, leak of toxic and flammable fluids, fire or explosion, etc.

Step 2: Process Hazards Analyses (PHA)

Qualitative hazard analysis is a fundamental step for identification consequences of events in LOPA, which is usually done by HAZOP which usually is used to identify all probable events. In a HAZOP study, the severity of events can be categorized and it helps the analyzers to opt just the critical scenarios for LOPA.

Step 3: Estimate Consequence and Severity

Consequences are the undesirable outcomes of accident scenarios. One of the first decisions of an organization must make when choosing to implement LOPA is how to define the consequence endpoint. Since the consequences must be categorized, special attention to primary steps of LOPA is very important.

There are some approaches for this purpose include [13]:

Method 1: Category Approach and using matrices.

Method 2: Qualitative Estimates; that use the final impact on humans as the consequence of interest.

Method 3: Quantitative Estimates with Human harm; which uses mathematical models.

Step 4: Developing Scenarios

A scenario is an unplanned event or sequence of events that results in an undesirable consequence. Each scenario consists of at least two elements which show the beginning and the end of an event. These elements are:

- An initiating event
- A consequence

A scenario in its perfect form, should illustrate the pathway of an event. Each scenario must have a unique Initiating Event-Consequence pair. Since the definition of scenarios in LOPA is similar to the Event-Tree method and both approaches are based on analyzing scenarios, it's considered to use the tree structures to clarify the principles of LOPA scenarios. However process risk assessment in nuclear systems requires all spectrums of possible accidents that subsequently may exceed the specified risk tolerance level, analyzing the worse cases of events is useful a pre-processing. In order to obtain more appropriate and accurate analysis, the complete accident scenario model is developed.

In the traditional LOPA, an accident scenario is defined as a single cause–consequence pair using an event tree approach. Only one path of the accident scenario, which merely leads to a major hazard, is analyzed. For more complex scenarios, LOPA should be used several times for each initiating event (IE) separately. Another limitation of LOPA is the fact that there is no separation of top event or loss event. As mentioned in literature review, Markowski and Kotynia [9] suggested bow-tie method, which is composed of a fault tree which identifies the causes of the top event or loss event, usually representing unwanted release of the substance and an event-tree showing what are the consequences of such a release. In the "bow-tie" model all connections between initiating events, loss event and outcome events are fully identified.

Although this method is a very comprehensive approach for improving accuracy of LOPA, but increasing the computation size, makes LOPA exceed a semi-quantitative method. For this reason it has been assumed that event tree method is approximately enough for developing scenarios in LOPA. Using event tree causes the accident path to be identified exactly, it also causes the IPLs be more transparent, and capability of linkage the results to Full PRA method be increased. Also existence of a schematic of a scenario facilitates its understanding.

Step 5: Event Tree Method

The event tree is a logical structure in the form of a tree branch that maps out the different pathways by which the bad event can come about. All of the paths that cause an adverse outcome must be included and analysts routinely rely on the experience of subject matter experts to know which events to include. The tree structure enables the analyst to order events (usually chronologically), to separate clusters of events from each other, and to show whether or not events are important. The branching structure shows how an initiating event that starts a sequence at the left side of the tree may lead to the bad event that is shown at the far right side. Events or options that depend on other events are shown to the right of those events on which they depend [14]. As mentioned before, both LOPA and Event-Tree method utilize the scenario concepts.

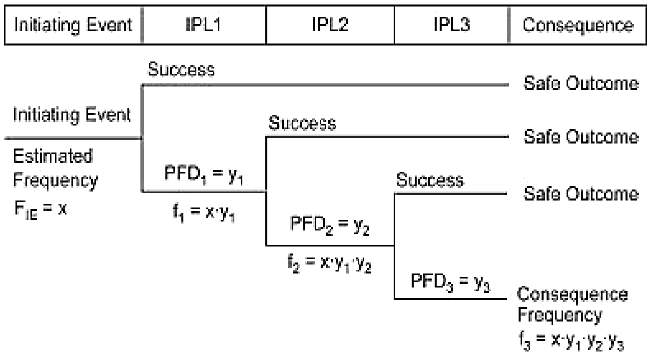

Figure 2. LOPA Event Tree Example [15]

Step 6: Identifying Initiating Event Frequency

For LOPA, each scenario has a single initiating event. The frequency of the initiating event is normally expressed in events per year. Some sources use other units, such as events per 106 hours [13]. LOPA uses order-of-magnitude to express the frequency of initiating events. In general, initiating events are divided in three main categories: external events, human errors and equipment failures. A HAZOP study should represent these initiators.

Step 7: Identifying IPLs and Estimating PFDs

An IPL is a device, system, or action that is capable of preventing a scenario from proceeding to its undesired consequence independent of the initiating event or the action of any other layer of protection associated with the scenario. An IPL must be:

- Effective
- Independent
- Auditable

Like the previous step, a HAZOP study should be able to illustrate the safeguards which are considered against the final consequence. Then LOPA analyzers have to separate the IPLs from other safeguards. For LOPA calculations, it is essential to know the failure rate or probability of failure of system's IPLs. Thus, the concept of probability of failure on demand is introduced. PFD for an IPL is the probability that, when demanded, it will not perform the required task [13]. PFD is a complement to availability and also is a probabilistic value.

Step 8: Bayesian Probabilistic Method

Bayesian estimation incorporates degree of belief and information beyond that contained in the data sample, forming the practical difference from classical estimation. The subjective interpretation of probability forms the philosophical difference from classical methods. Bayesian estimation is comprised of two main steps. The first step involves using available information to fit a prior distribution to a parameter, such as frequency of an IPL. The second step of Bayesian estimation involves using additional or new data to update the prior distribution. This step is often referred to as "Bayesian Updating" [16]. The generalized form of Bayes' theorem for discrete variables is:

$$\Pr\left(A_j|E\right)=\frac{\Pr\left(A_j\right).\Pr\left(E\ |A_j\right)}{\sum_{i=1}^{n}\Pr\left(A_i\right).\Pr\left(E\ |A_i\right)} \qquad (1)$$

The terms of this equation are:

$\Pr(A_j|E)$: The posterior probability of event Aj given event E or updated probability of event A_j

$\Pr(A_j)$: The Prior probability of event A_j

$\Pr(E|A_j)$Likelihood function based on sample data

$\sum_{i=1}^{n}\Pr\left(A_i\right).\Pr\left(E\ |A_i\right)=\Pr\left(E\right)$: Total probability

The above equation means that probability data can be updated by combining the prior probability (from previous information or generic data) and the relative likelihood (from plant-specific data).

Typically, the selection of the prior distribution is somewhat subjective, so a selection of a conjugate prior from the same family of distributions as the posterior can make the choice more objective for easier computation of the posterior parameters [7].
Since using Bayesian equation in its primary form is difficult in some cases, it's recommended to use conjugated distributions. In these cases, for example gamma and poison distributions are conjugated. If there is a prior distribution in the form of gamma and a likelihood distribution in poison, the Bayesian calculation will result in a gamma posterior distribution.

Step 9: Estimate scenarios frequency

After updating data, scenarios frequency is estimated. The following is the general procedure for calculating the frequency for a release scenario with a specific consequence endpoint. For this scenario, the initiating event frequency from step 5 is multiplied by the product of the IPL and PFDs from step 6 [13].

$$\begin{aligned} f_i^C &= f_i^I \times \prod_{j=1}^{J} PFD_{ij} \\ &= f_i^I \times PFD_{i1} \times PFD_{i2} \times \ldots \times PFD_{iJ} \end{aligned} \quad (2)$$

Step 10: Calculating Risk

In this step, the severity of categorized consequences from step 3 is multiplied by scenarios frequency from step 7.

$$R_k^C = C_k \times f_k^C \quad (3)$$

Step 11: Make risk decision

The calculated risk is compared with risk tolerance criteria for the decision-making. If, however, the calculated risk exceeds the risk criteria, the scenario is judged to require additional (or stronger) mitigation (IPLs), or to require changes in the design to make the process inherently safer, thus reducing scenario frequency or consequence, or (preferably) eliminating the scenario [13]. This change in accident path should be considered in event tree if other IPLs are needed to be added. Also the Bayesian calculations and scenarios frequency estimations must be repeated considering the effect of new changes.

Step 12: Safety Management

Risk management must be applied to the all levels of system including design, operation, monitoring, test, maintenance, etc. It's important to mention that LOPA do not suggest any way to control the risks, but it clarifies the way of decision making to help the management team.

5. Application OF MODIFIED-LOPA on NPP Fire Protection System

The methodology is applied on a fire protection system for a typical Nuclear Power Plant (NPP) which is designed to extinguish fires in this facility. Fire protection is considered a mitigation IPL as it attempts to prevent a larger consequence subsequent to an event that has already occurred. If a company can demonstrate that it meets the requirements of an IPL for a given scenario it may be used [13].

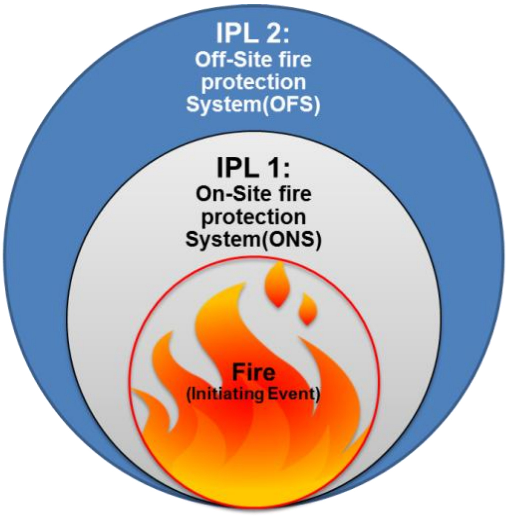

Figure 3. Layers of Protection Against a Fire Scenario.

Description of facility

This fire protection facility includes two separate systems, On-Site fire protection system (ONS) and Off-Site fire protection system (OFS). Each of the systems is a set of different components such as sensors, alarms, tanks, valves, pumps, etc. but it's supposed that ONS and OFS systems will meet all characteristics of the independent protection system.

Analysis by PRA

This system has been completely studied by PRA approach [1]. This method has considered all subsystems and equipment in order to get the most accurate results. Three different scenarios are defined, Fig. 4 shows the event-tree of these scenarios. PRA calculations shows the frequency of fire event in such plant is 7.1E-4, and PFD of ONS system is 2.8E-3, also PFD of OFS system is 1E-4 [1].

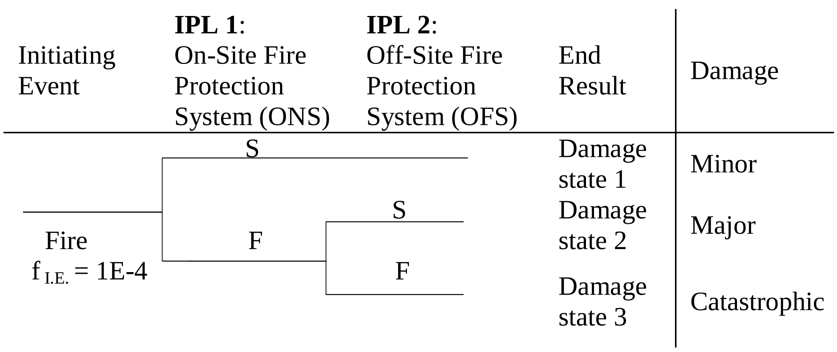

Figure 4. Scenario of Events Following a Fire Using the Event-Tree Method [1]

Modified-LOPA

Consider a change in components of primary ONS system. If this system be a fire protection of an in operation nuclear power plant, a new risk assessment will be needed. But PRA method requires a huge amount of calculations and resources. So Modified-LOPA would be used as a simpler method and a pre-processor. The pre-assumptions considered to analyze this system by Modified-LOPA are as followed:

- The same defined scenarios in Figure 4. Are also considered.
- The calculated results of PRA are used as mean values of prior data.
- Frequency of fire accident and PFD of OFS system are same as before, because of no change.
- New ONS system was tested in similar facilities for 1000 demands, and 3 failures were observed.

- The prior data will be updated by Bayesian method.

Bayesian Updating

The simplest type of prior distribution from the standpoint of the mathematics of Bayesian inference is a so-called conjugate prior, in which the prior and posterior distribution are of the same functional type (e.g., beta, gamma), and the integration needed to obtain the normalizing constant in Bayes' Theorem is effectively circumvented [17].

For prior distribution of PFD of ONS system, the mean value is 2.8E-3. And from engineering judgment its standard deviation is estimated 1.4E-3 and a Beta distribution has been assigned for it.

For the binomial distribution, the conjugate prior is a beta distribution. So in this case, the likelihood function is modeled by a Binomial distribution. Elements of Bayesian updating from Eq. (1) for updating PFD of ONS system are shown in Table 1 from Appendix A.

Risk Calculation

Table 2 in Appendix A, shows the results of risk calculation by Modified-LOPA and compares it to the result of PRA approaches. As observed in Table 2, a little increase in PFD of ONS system, the calculated risk of scenarios leads a larger discrepancy of the results between two approaches. Common cause failure is considered in the calculation of PRA but the events are considered independent in LOPA. This is another reason for the discrepancy between two methods. Another reason for this difference is due to the updated value of PFD using Bayesian formula.

6. CONCOLUDING REMARKS

The research demonstrated the application of modified LOPA methodology on safety evaluation of nuclear facilities. In classic LOPA, only the most severe consequences are often considered. However, Modified-LOPA considers all probable scenarios with assistance of Event Tree method. Bayesian updating makes estimation of the frequencies and PFD more accurate by utilization of historic and field data. In this paper Modified-LOPA is represented as a powerful pre-processing method in nuclear power plants. The example shows good agreement of its result in comparison with a full PRA approach.

The effect of using Event Tree structure could be better demonstrated if the studies consist a large scope system with very complicate components. Besides, for new designed systems with lack of failure data or in case of unreliable collected failure data, using Bayesian logic which gives analysers the ability of updating the plant specific data with generic data from other similar systems, can lead to more reliable results. Modified-LOPA will be known as the most comprehensive semi-quantitative method if economic survey be added to it.

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APPENDIX A

Table 1. Bayesian Approach for Updating PFD of ONS System [17-18]

Prior	Likelihood	Posterior
Beta Distribution $f(p) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha).\Gamma(\beta)} p^{\alpha-1}(1-p)^{\beta-1}$	**Binomial Distribution** $Pr(X=x) = \binom{n}{x}.p^{x}(1-p)^{n-x}$	**Beta Distribution**
$\alpha_{prior} = \mu_{prior}\left[\frac{\mu_{prior}(1-\mu_{prior})}{Var_{prior}} - 1\right]$ $\beta_{prior} = (1-\mu_{prior})\left[\frac{\mu_{prior}(1-\mu_{prior})}{Var_{prior}} - 1\right]$	x : No. of failures n : No. of demands	$\alpha_{post} = \alpha_{prior} + x$ $\beta_{post} = \beta_{prior} + (n-x)$ $\mu_{post} = \frac{\alpha_{post}}{\alpha_{post}+\beta_{post}}$ $Var_{post} = \frac{\alpha_{post}\cdot\beta_{post}}{(1+\alpha_{post}+\beta_{post})(\alpha_{post}+\beta_{post})^2}$
$\mu_{prior} = 2.8E-3$, $Var_{prior} = 1.96E-6$ $\Rightarrow$ $\alpha_{prior} = 3.986$, $\beta_{prior} = 1419.585$	$x = 3$ $n = 1000$	$\alpha_{post} = 6.986$, $\beta_{post} = 2416.585$ $\Rightarrow$ $\mu = 2.88E-3$, $Var_{post} = 1.18E-6$

Table 2. Modified-LOPA for NPP Fire Protection System

Scenario No.	Economic consequence severity	Category	frequency of I.E.	IPL(s)	Updated PFD	Calculating Risk from Updated Data (Modified-LOPA)	Calculated Risk from Primary Data (PRA)
1	$1,000,000	Minor	7.10 E - 4	$\overline{ONS}$ *	2.88 E - 3	≈ $ 708.0	$ 710.0
2	$92,000,000	Major	7.10 E - 4	ONS , $\overline{OFS}$	1.40 E - 4	≈ $ 188.0	$ 230.0
3	$210,000,000	Catastrophic	7.10 E - 4	ONS , OFS	2.88 E-3 * 1.40 E-4 = 4.03E-7	≈ $ 0.060	$ 0.018

* The sign " ¯ " shows successful operation of an IPL.