A Process for Estimation of Initiating Event Frequency Using Korean Industry Data Based on NRC Researches

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1. Introduction

An initiating event (IE) is an unplanned event that occurs while a nuclear power plant (NPP) is in operation and requires that plant to shut down to achieve a stable state. Analyzing IE frequency is important because it provides inputs to a probabilistic safety assessment (PSA). In case of U.S., the IE frequency indicates performance among plants and also several U.S. Nuclear Regulatory Commission (NRC) risk-informed regulatory activities such as plant inspections of risk-important systems.

NRC conducted various researches for IE frequency estimation and developed several reports about industry-average performance for IE at U.S. commercial NPPs and parameter estimation method for IE frequency estimation with the Idaho National Laboratory (INL) or the Sandia National Laboratory (SNL) such as EGG-RAAM-11088[1], NUREG/CR-5750[2], NUREG/CR-6823[3] and NUREG/CR-6928[4]. NRC also provides a software 'Reliability Calculator'[5] by NRC's website for parameter estimation about component reliability and IE frequency. The software developed by INL uses US commercial NPP data and statistical routines to provide statistical analysis of the data by using SAS language. Based on the parameter estimation method and the software, NRC updates IE frequency of NUREG/CR-6928 every 5 years and also reports time-dependencies, reactor-type dependencies, and between-plant variance by adding new IE data every year.

In case of Korea, many changes have taken place in estimating IE frequency based on the method of NUREG/CR-6928. By the recent PSA report, five kinds of IE frequency estimations were applied based on the characteristics of IE data occurred in Korea [6]. For IEs having experiences, IE frequencies were estimated with Korean specific data by using Bayesian update with a Jeffrey's noninformative distribution (JNID) as a prior, however there is no statistical backgrounds to determine a baseline period. Korea Atomic Energy Research Institute (KAERI) tried to determine an optimized baseline period by trend analysis and apply empirical Bayes (EB) estimation method to estimate IE frequency by using the Reliability Calculator [7].

The purpose of this paper is to compile the methods for estimating IE frequency from the various reports by NRC related to IE frequency estimating and to propose a process to estimate IE frequency with Korean specific experience based on the NRC's researches.

2. Review of Researches on IE Frequency Estimation by NRC

In this paper, four kinds of reports and the software 'Reliability Calculator' were reviewed. We summarized method for data analysis and characteristics in the chronological order in which those reports were published.

<u>EGG-RAAM-11088 (Events in Time: Basic Analysis of Poisson Data, 1994)</u>

- It presents basic statistical methods for analyzing Poisson data (number of events in some period of time) for point estimates, confidence intervals, and Bayesian intervals for the rate of occurrence per unit of time
    - Bayesian update with JNID as a prior
- It presents graphical methods and statistical tests to check the assumptions of the simple model
    - Chi-square test for variation between data source
    - Laplace test and Mann test for time trend
- It provides a method to model a variation between the plants
    - EB estimates with Gamma-Poisson Model
    - Kass and Steffey adjustment to account for the reduced uncertainty due to EB method

<u>NUREG/CR-5750 (Rates of Initiating Events at U.S. Nuclear Power Plants: 1987 – 1995, 1999)</u>

- It provides IE frequencies at U.S. NPPs based primarily on the operating experience from 1987 through 1995 grouped by the functional impact group and the initial plant fault group
- It eliminates learning periods (four months) to determine a baseline period
- It provides four models for IE frequency estimation after chi-squared tests to detect a statistically significant difference between years and between plants
    - Single constant rate: Bayesian update with JNID
    - Constant rate, differences among plants: EB estimates with the Kass and Steffey adjustment
    - Trend in calendar time, with no differences among plants: loglinear model

- Both trend in calendar time and differences among plants: extended loglinear model
- It suggests method for infrequent and rare events

NUREG/CR-6823 (Handbook of Parameter Estimation for Probabilistic Risk Assessment, 2003)

- It provides the basic information needed to generate estimates of the parameters for IE frequencies, component failure rates and unavailability
- It suggests two kinds of priors for Bayesian update such as JNID and constrained noninformative distribution (CNID)
- It presents a model validation about assumption of Poisson process
  - Chi-squared test for constant event occurrence rate
  - Chi-squared test and Laplace test for time trend
  - No multiple failures and independence of disjoint time periods
  - Consistency of data and prior by using Gamma-Poisson model
- It presents EB method with Kass and Steffey adjustment for a parameter estimation using data from different sources
- It presents a loglinear model for trend and aging by Bayesian estimation, frequentist estimation, and reweighted least-squares fitting
- It suggests a screening method for a baseline period
  - Elimination of the first year of operational data to remove unrepresentative events
  - Considering only the data from the most recent years of operation

NUREG/CR-6928 (Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants, 2007, Update 2010 and 2015)

- It documents updated industry-average component and IE parameter estimates representing current industry practices
- It provides EB estimates when sufficient data were available
- For few cases with the assumption of homogeneity, it uses Bayesian update with JNID
- It provides CNID results, however the CNID method has been discarded since the update of 2010
- It suggests to choose a baseline period that best characterizes industry performance centered about the year 2000 (a minimum of 5 years) depending upon whether a trend exists
- It mentions a baseline period with the least potential for a trend (the highest p-value from the trend analysis) to find the weakest evidence for existence of a trend

Reliability Calculator, Version 1.4.2.1, 2019

- It uses EB model for IE frequency
- It suggests Bayesian updates with JNID when EB analysis results are degenerate, indicating little variation between plants
- It presents the chi-squared test to check homogeneity and the loglinear model with reweighted least-squares fitting for trend

In summary, the methodology to evaluate IE frequency has been neatly established over time. In other words, unnecessary methods have been removed. However, the recent frequency calculation methodology may be a little confusing. That is, when the EB method is applied with the software by NRC, results can be derived, even though there is no evidence of a between-plant variation. However, the statistical theory description by the software suggests using the EB method if a between-plant variation exists.

3. Establishment of a Process to Estimate IE Frequency with Korean Specific Experience

In this paper, we propose a process to estimate IE frequencies for IEs with more than one occurrence based on the NRC's researches mentioned above. It is to complement the IE frequency estimation method for PSA, which has recently been used in Korea. The advantages of the process suggested in this paper are as follows:

- It presents a statistical analysis to find an optimized baseline period for which the conditions are both stable (i.e., the event rates are not trended) and representative of current industry conditions.
- It includes a statistical test to detect a between-plant variation and this test can be expanded to identify a between-site variation
- After the test above, one of the two kinds of IE frequency estimation methods is selected based on the existence of a between-plant variation
- It proposes a statistical analysis to identify a consistency of data and prior if results by NUREG/CR-6928 are used as a prior for a Bayesian update

The proposed strategy to estimate IE frequencies consists of four steps described below:

Step 1. Evaluate a trend within each potential baseline period (H_0: $\lambda(t)$ is constant)

- A potential baseline period for each IE starts a five-year period from end point adding one year in reverse order.
- The function $\lambda(t)$ is called the time-dependent event occurrence rate.
- A statistical test should be performed to detect a trend for each potential baseline period.
  - Chi-squared test for alternative hypothesis, H_A: $\lambda(t)$ is not constant
  - Loglinear model to test H_A: $\lambda(t)=\exp(a+bt)$

Step 2. Determine baseline period for each IE based on the Step 1

- It is to represent current industry performance and stable condition.
- A minimum of 5 years is guaranteed.
- A period that resulted in the highest p-value (lowest probability of a trend existing) from the Step 1 is chosen.
- If there were only one event during the commercial operations, then the entire period or a sufficient period can be used by an engineering judgement.

Step 3. Identify variation between plants

- It is to choose an IE frequency estimation method.
- Chi-squared test is used for H_0: λ is the same in all the data subsets.
- This test can be used to identify between-site variation by pooling data in some adjacent cells (identical site cells) based on engineering reasons for believing that the pooled cells are relatively homogeneous, that is, the event rates are similar for multi units at a site.

Step 4. Estimate IE frequency based on the Step 3

- EB estimate with the Kass and Steffey adjustment is proposed when there exists a between-plant variation.
- Bayesian estimate with JNID is proposed when there is no between-plant variation or the number of observations are too small.
- A check for consistency between the prior and the data should be performed first bases on Gamma-Poisson model when the industry-average frequency distributions by NRC are to be used as priors in Bayesian updates using plant-specific data.

4. Conclusions

The purpose of this paper is to compile the methods for estimating IE frequency from the various reports by NRC and to establish a process to estimate IE frequency for Korean industry data. The process proposed in this paper is for IEs with more than one occurrence. So far, there exist some rare IEs, but there exist also IEs with more than five occurrences at domestic NPPs.

The process we proposed can be feasible on the NRC's Reliability Calculator website. However, we are looking to implement the strategy without using the website to prepare for when the website is down.

With the IE frequency estimation process, it is expected that the reliability of the estimation results will be increases by using an optimized baseline period without trend and an appropriate estimation method due to a between-plant variation.

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