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Site core damage frequency for multi-unit Nuclear Power Plants site

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ABSTRACT

The nuclear generating sites around the world are mostly twin unit and multi-unit sites. The PSA risk metrics Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) currently are based on per reactor reference. The models for level 1 and level 2 PSA have been developed based on single unit. The Fukushima accident has spawned the need to address the issue of site base risk metrics, Site Core Damage Frequency (SCDF) and Site Large Early Release Frequency (SLERF), on the site years rather than reactor years. It is required to develop a holistic framework for risk assessment of a site. In the context of current study, the holistic framework refers to integration of risk from all units, dependencies due to external events and operation time of individual units. There is currently no general consensus on how to arrive at site-specific risk metrics. Some documents provide suggestions for site CDF and site LERF. This paper proposes a new method of aggregation of risk metric from the consideration of operating time of individual units under certain assumptions with a purpose to provide a new conceptual aspect for multi-unit PSA. The result of a case study on hypothetical data shows that site level CDF is not sum of CDF of all units but around 18% higher than unit level CDF. When the CDF is considered to be a random variable then, the new methodology produces site CDF as 50% higher than single unit CDF. These two approaches have been detailed in the paper. For a general data set of CDF for individual units, site CDF would more than individual unit CDF however, it would not be multiples of a single unit value.

1. Introduction

PSA is an established systematic tool to assess of risk metrics from Nuclear Power Plant. It helps to improve NPP safety through design modifications and evaluation of human performance to reduce its contribution). In current understanding of PSA, there is no structured and universally acceptable treatment of multi-unit nuclear plant sites risk. With the advancement of types of reactor design where plants are designed to have interconnected units the methodology to assess risk does not exist. The question of multi-unit accidents is not one of possibility, but of probability (Schroer and Modarres, 2013).

Furthermore, the nuclear accident that occurred in March 2011 at the Fukushima Daiichi plant in Japan underscored the importance and relevance of accidents involving multi-units. In this context it has become necessary to determine the best way to address multi-unit site risk.

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The operating reactors around the world are in areas and sites that comprise of single reactors as well as multiple reactors. The reactor designs are also of different types at some of the sites. The multi-unit sites include such configurations where in the facilities are separate and independent, but also there are some sites where in the facilities have some kind of shared facilities/systems. In the future, there could be further additions to the existing reactors. The advancement in the site configuration of NPPs has necessitated the development of requirements of multi-unit risk indices. This paper outlines some of the technical issues involved with multi-unit NPPs and also proposes a new methodology for evaluating multi-unit risk metrics. The core damage frequency and large early release frequency have been used to define PSA based risk metrics. These were based on single unit NPPs. But the questions now being asked is what characterises the site based CDF and site based LERF. However, there is no straight forward answer to this question neither there exists a methodology that evokes consensus among the PSA community.

The Fukushima accident has generated the need to address the issue of site based risk metrics, Site Core Damage Frequency (SCDF) and Site Large Early Release Frequency (SLERF) on the site years rather than reactor years (Akl and Yalaoui). It is necessary to develop a holistic framework for risk assessment of a site, which is capable of integrating the risk associated with all sources at the site under consideration. The estimation of risk for a multi-unit NPP site, the units of measurement are to be in 'events per site year' instead of 'events per reactor year'

The simple addition of risks (direct addition of CDF) of individual units may not be the correct way of aggregating risks (Fleming, 2005). Some concepts on multi-unit risk have been detailed in (Schroer and Modarres, 2013). The aggregation of unit level CDF has been proposed to get site level CDF (Samaddar et al., 2012; Duy et al., 2014). The paper by COG (Vecchiarelli et al., 2014) sensitises on how to approach the CDF and LERF addition. The first is the simple addition of mean of the CDF and LERF. This appears to be simplest and widely endorsed approach due to ease of the mathematical process. However, the mean values for external hazards may be too conservative due to the combination of skewed uncertainty distributions in initiating event frequency and component fragility. The multi-unit aggregation can transfer that conservatism. Another way is to add the medians as a measure of central tendency for aggregation. The basis for this idea is that the PSA results are represented in terms of probability distributions, hence a method which considers convolution of different contributors may be required. Median is chosen because it is less sensitive to long distribution tails, which characterize the low likelihood event frequency probability distributions. Mean is sensitive to the tails of distributions. The pitfall is that the sum of a set of median values is not itself a median.

The confidence level in internal event PSA is high because of the experience in technology with the development of PSA and the industry experience. Many events have occurred in NPPs which provide data for PSA. In addition, deterministic analyses have been used for the events which have not occurred. In comparison there is less experience with external events PSA and the associated data. The scarcity of data is mainly because of large return period, for example, in seismic events. There is higher level of bias in carrying out the external event PSA. This leads to probability distributions which do not reflect the realistic scenarios.

The other approach suggested is to compare individual site-based results for various hazards against the safety goal independent of one another. However, this is not the risk aggregation in true sense. Alternately, apportionment of safety goal frequency between hazards can be considered and compared against risk for particular hazard type. In this approach it may be possible to show that risks from a number of hazards meet their individual goals. But the question remains is how to apportion the safety goal. It is mentioned in the paper by COG (6Vecchiarelli et al., 2014) that it can also be an approach that establish different safety goals for internal events and external hazards, in effect two different aggregations. Then the question remains which approach to follow to aggregate the risks from internal events only for multi-unit site for comparison against a separate set of safety criteria and external events only for comparison against another set of safety criteria.

It is seen that there is no clear simple answer to multi-unit risk aggregation and a single approach which can be followed by PSA community. In this paper two methodologies are propose for risk aggregation to site level CDF. The site LERF is not touched upon in this paper though a similar approach can also be used for it.

2. Site CDF from combination of mean of unit level CDF

The site CDF may be obtained from the conceptualization of probability of core damage. In this manner, NPP units can be treated as components. The failure probability of component within a time 't', given as (Ebeling, 2008).

$$P(t) = 1 - e^{-\int \lambda(t)dt} \quad (1)$$

Where $\lambda(t)$ is the instantaneous failure rate of component which in general is not constant but depends on time. The failure rate of a component is considered similar to CDF for a NPP unit.

The following is proposed as methodology for the risk aggregation for multi-unit site. The illustration is presented for four unit site and this can be extended to multi units.

Let the average value of CDF for unit 1 over time T_1 be represented as λ_1, average value of CDF for unit 2 over time T_2 be represented as λ_2, average value of CDF for unit 3 over time T_3 be represented as λ_3 and average value of CDF for unit 4 over time T_4 be represented as λ_4. Also, let the unit 1 be in operation for T_1 years, unit 2 be in operation for T_2 years, unit 3 be in operation for T_3 years and unit 4 be in operation for T_4 years. Let the average values of CDF due to an external event in unit 1, 2, 3 and 4 be λ_{e1}, λ_{e2}, λ_{e3} and λ_{e4} over their respective operating times T_1, T_2, T_3 and T_4. The condition $T_1 > T_2 > T_3 > T_4$ is assumed for Scheme 1 as shown in Fig. 1. Let the average value of site CDF be represented as λ_s.

Let us assume that the units are independent with no shared components. This usually is the case for most sites.

P_1 = Probability of core damage of unit 1 only (due to internal events in unit 1)
P_2 = Probability of core damage of unit 2 only (due to internal events in unit 2)
P_3 = Probability of core damage of unit 3 only (due to internal events in unit 3)
P_4 = Probability of core damage of unit 4 only (due to internal events in unit 4)
P_{e1} = Probability of core damage of unit 1 only (due to external events)
P_{e2} = probability of core damage of unit 2 only (due to external events)
P_{e3} = probability of core damage of unit 3 only (due to external events)
P_{e4} = probability of core damage of unit 4 only (due to external events)

From Fig. 1 it is to be noted that the failure due to external events for time T_1-T_2 is accounted for in contribution from unit 1 as P_{e1}. While for units 2, 3 and 4 there is always overlapping time with

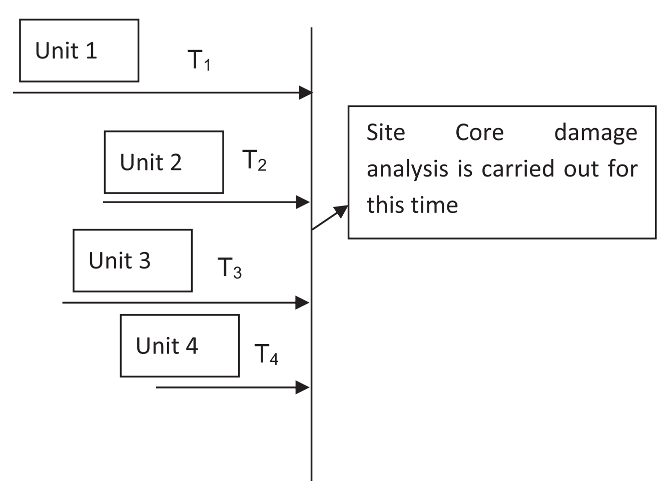

Fig. 1. Operation time schematic of NPP at a site (Scheme 1).