

Technical Approach for Safety Assessment of Multi-Unit NPP Sites Subject To External Events

Sujit Samaddar^a

Kenta Hibino^a

Ovidiu Coman^a

^aInternational Atomic Energy Agency

Abstract: This paper presents a framework and technical approach for conducting a probabilistic safety assessment of multiunit sites against external events. The treatment of multiple hazard on a unit, interaction between units, implementation of severe accident measures, human reliability, environmental conditions, metric of risk for both reactor and non-reactor sources, integration of risk and responses and many such important factors need to be addressed within the context of this framework. The framework facilitates the establishment of a comprehensive methodology that can be applied internationally to the peer review of safety assessment of multiunit sites under the impact of multiple external hazards.

Keywords: External Events PSA, Common Cause Failures, Multiunit Site, Multi Hazards

1. INTRODUCTION

The current energy demands and the difficulties in acquiring public support in establishing new sites for nuclear power plants is a powerful incentive for the nuclear industry towards the utilization of existing sites for the construction of new nuclear reactor units. The incentive is made even more attractive by the availability of many of the infrastructural and administrative resources that can be shared from the use of the same site. Thus for new builds the nuclear industry tends to gravitate towards using the same site, a multiunit site, as this choice is very practical and resource efficient (Ref. 1). Fig. 1 shows a distribution of the site housing more than three units in the world based on the IAEA's PRIS database (www.iaea.org/pris). As of 10 March 2013, a ratio of multiunit sites housing more than two units (including operating units, units under construction and long-term suspended units) for all sites is about 81%, and a ratio of multiunit sites housing more than three units is about 32%.

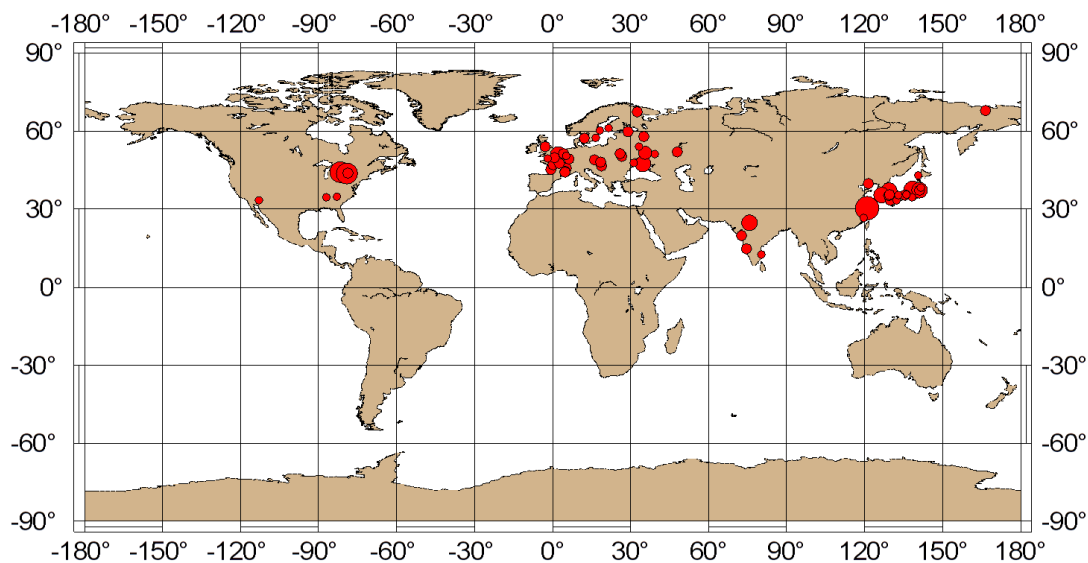


Fig. 1: Multiunit sites housing more than three units in the world (10 March 2013)

This move towards the use of a common site to house multiple reactor units and supporting facilities necessitates the regulatory authorities of the Member States to establish the “safety” of such a site. Safety assessments in the past have used a deterministic and probabilistic approaches considering that a site with multiple installations can be represented by summing up the risk metric of individual units. This simplified approach to establishing site safety had several limitations as it could not represent fully the many varied and complex interactions that would take place during a severe event impacting a multiunit site.

The Niigata-Ken Chuetsu-Oki earthquake (16 July 2007, Japan) which affected the Kashiwazaki-Kariwa nuclear power station provided a glimpse of how multiple correlated hazards can develop from a single external event (ground motion and fire). A site safety assessment should therefore, be capable of addressing multiple correlated hazards yet the available methodology for site safety assessment currently addresses one hazard at a time.

The Great East Japan Earthquake (11 March 2011, Japan) generated in severe ground motion causing the safe-shutdown of several reactor units at the Nuclear Power Plants of Onagawa, Fukushima Dai-ichi, Fukushima Dai-ni, Tokai Dai-ni and Higashi Dori. However, the ensuing tsunami at Fukushima Dai-ichi resulted in extreme flooding challenging the safety systems of all the six units, exceeding their capacities, breaching their defense-in-depth measures and eventually leading to severe core damage in three of the units resulting in a large radioactive releases severely restricting the deployment of severe accident management resources already reduced by the simultaneous demand from competing units. Heroic actions were taken to prevent additional release from the spent fuel pools. All entities putting additional demands on the single unit sized severe accident management resource (Ref. 2). All this, was aggravated by the severe loss of plant infrastructure caused by the immense destructive energy of the tsunami wave front.

The Fukushima accident underscores the need for a comprehensive site safety assessment methodology which can address the site safety in a holistic way. The fact that multiple hazard or hazard combinations need to be considered, the interaction between the units (be it from shared system, common cause, or interaction of responses), simple screening out of events based on rarity without consideration of combinations, the consideration of human reliability, severe accident management practice considering multiunit events, the contribution of release from other no-reactor sources on site and other such issues need to be addressed in a comprehensive framework.

In this framework of site safety assessment, the risk assessment should include sensitivities’ to determine the extent to which multiunit considerations increase or decrease the risk associated with a specific nuclear installation site. The quantification of such a risk at a site level allows the regulatory body to make risk informed decisions in their role as a regulator and protector of public health and the environment.

The Fukushima accident involving a combination of multiunit and multiple hazards highlighted the need for such a holistic framework for risk assessment of a site which is capable of integrating the risk associated with all sources that can be released from a site. This paper is an effort to bring into focus all the different issues that a generalized framework, for site level risk assessment, need to consider in the formulation of an site safety assessment methodology.

2. FRAMEWORK OF SITE SAFETY ASSESSMENT

The following presents the holistic framework for the risk assessment of a site with multiple units and other co-located installations with nuclear inventory. The framework has at its centre the reactor units and the other co-located nuclear installations which are challenged by the external events, the events cause one or more hazards which may challenge the safety of one or more reactor and non-reactor units on the site, the affected installation respond to the imposed challenges which in turn may or may not affect the installations on site, this interactions between installations continue till severe accident managements measures are brought in to play further interactions continue to occur into the release phase from one or more installations. The risk quantification of this release as a measure of its impact on human and environmental health will provide the final response to the site level safety assessment.

Given this framework as the scope of the risk assessment many issues unaddressed before comes to focus. The treatment of multiple hazard on a unit, interaction between units, implementation of severe accident measures, human reliability, environmental conditions, metric of risk for both reactor and non- reactor sources, integration of risk and responses and many such important factors need to be addressed within the context of this framework.

3. TECHNICAL APPROACH

3.1 Interaction

As illustrated by the Fukushima accident, multiunit accidents involve unique challenges to the structures, systems and components that perform the safety functions at each of the installations and the human and infrastructural resources that support the operation and implementation of severe accident management and offsite protective actions. The same hazard or hazard combination may lead to initiating events and accident sequences in multiple installations concurrently (common cause). An accident at one installation may affect the capabilities and compromise the resources available to support mitigational efforts in another installation. Hence the probability of preventing an accident in one installation cannot be assessed without considering the status of the other installations on the site. Consideration of interaction of structures, systems and components between the different installations, the response of the installation and its interaction with the response in individual installations, human reliability given these interactions and others that will result during the progression of an accident are essential interactions to be included in the holistic framework for site safety assessment.

3.2 Risk Metrics

If there is release from more than one installation during the same accident then the emergency planning and severe accident management will be grossly impacted. Considering the fact that the large levels of radiation exposure will quickly saturate the dose levels of the responders and as a result the concurrent release from more than one reactor unit may exceed the linear sum of the consequence of individual reactors. Given this and the fact the frequency of the release at a multiunit site is related to the number of units on the site, the risk metric of core damage frequency (CDF) and large early release (LERF) is no longer an adequate metric for the risk assessment of multiunit sites. A more general set of risk metrics that would apply to all types of accidents similar to that at Fukushima would be those associated with a Level 3 PSA in which the risk of consequences to public health and safety are fully quantified. Thus a new or modified set of risk metric need to be developed which can rationally quantify the risk associated with multiunit sites involving non-reactor installations.

Table 1 Summary of Risk Metrics for Integrated Site Safety Assessment

Risk Metric	Applicability
Core Damage Frequency (CDF)	Level 1 Single-unit PSA
Large Early Release Frequency (LERF)	Limited scope Single-unit Level 2 PSA
Site Core Damage Frequency (SCDF)	Level 1 MUS PSA
Single Unit Core Damage Frequency (SUCDF)	
Multi-Unit Core Damage Frequency (MUCDF)	
Conditional Probability of Multi-Unit Accident (CPMA)	
Site Large Early Release Frequency (SLERF)	Limited scope Multi-unit Level 2 PSA
Release Category Frequency (RCF)	Full Scope Level 2 Single Unit PSA
Site Release Category Frequency (SRCF)	Full Scope Level 2 MUS PSA
Complementary Cumulative Distribution Function (CCDF)	Level 3 Single Unit PSA
Site CCDF (SCCDF)	Level 3 Multi-unit or Multi-facility PSA
Quantitative Health Objectives (QHOs)	

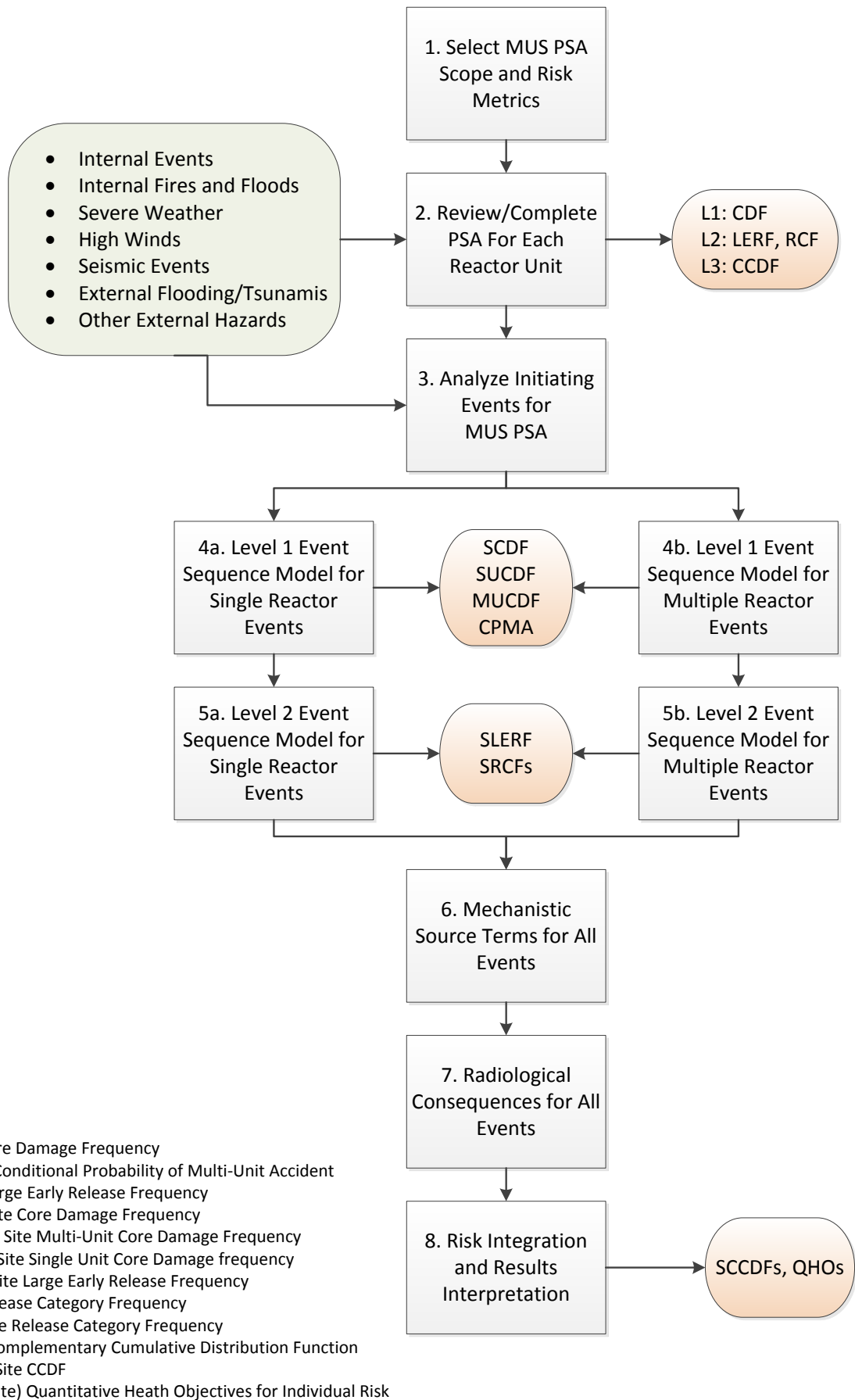


Fig. 2: Framework for Probabilistic Safety Assessment of Multiunit Sites against External Events

The relationships between CDF and SCDF can be seen in the following equations.

$$CDF = CDF_1 + CDF_2 \quad (1)$$

$$SCDF = SUCDF + MUCDF \quad (2)$$

$$SUCDF = 2CDF_1 \quad (3)$$

$$MUCDF = CDF_2 \quad (4)$$

$$SCDF = 2CDF_1 + CDF_2 = 2CDF - CDF_2 \quad (5)$$

Where:

<i>CDF</i> :	Reactor CDF, frequency of core damage involving a specific reactor, per reactor year
<i>SCDF</i> :	Site CDF, frequency of core damage on one or more reactors at the site, per site year
<i>SUCDF</i> :	Site single unit CDF, frequency of an accident involving core damage involving a single reactor unit, per site year
<i>MUCDF</i> :	Site Multi-unit CDF, frequency of an accident involving core damage involving multiple reactor units, per site year
<i>CDF₁</i> :	Single unit core damage frequency, frequency of core damage on one reactor, per reactor year
<i>CDF₂</i> :	Dual unit core damage frequency, frequency of core damage on two reactors concurrently, per site (pair of reactors) year

3.3 Screening

For Fukushima serious questions have been raised on the inability to protect the plant against internal and external hazards. This could to a great extent be contributed to the optimistic screening of hazards and the exclusion of hazards combinations that have a higher potential of occurring than could be supported in developing a “deterministic” design basis. It appears that the frequency of events that would exceed the design basis protection against tsunamis, earthquakes and floods are much more likely than assumed in the original design and licensing. So the screening of hazards for multiunit sites need to be more carefully evaluated than previously practiced. Thus careful screening of hazards is an essential ingredient for the safety assessment of multiunit site against multiple hazards.

3.4 Human Reliability

In current PSA models credit is taken for operator recovery actions and accident management for the recovery of the plant from a degraded state or core damage condition. As demonstrated in the Fukushima accident these activities can be severely restricted by releases at other installations. The human reliability analysis for single units does not take such a scenario into consideration. For multiunit site the human reliability analysis needs to account for condition where the site is contaminated with radioactive material and accident management action need to be executed in this environment, adding another level of complexity to the safety assessment of multiunit sites.

3.5 Infrastructure

For sever accident management it is usually anticipated that the infrastructure of the site is unaffected by the demands made by the hazard. The toil on the infrastructure during the Fukushima accident was significant and many of the resources that would have played a role in the mitigational actions during the severe accident management were render unusable by the tsunami. In response to this, the industry has undertaken actions to deploy additional resources that can be quickly bought into play to offset

damaged infrastructure. In the site safety assessment the role and sequence of such deployment of alternate resources need to be included in establishing a reasonable quantification of the risk profile for the site.

4. LOSS OF OFFSITE POWER EXAMPLE

To illustrate the steps in estimating the initiating event frequencies for a multi-unit PRA, consider the case of loss of offsite power (LOOP) at a site with two identical reactor units. In traditional PRAs that are performed on each reactor separately, the initiating event frequencies are analyzed on a reactor basis and for a multi-unit site, each unit is analyzed separately. In a multi-unit PRA it is necessary to resolve which events impact each reactor separately and independently and which impact both units concurrently. This requires careful analysis of the industry data which may come from a mixture of sites with different numbers of reactors on each site.

The example is quantified using data that has been recently developed for U.S. nuclear plant PRAs. The event tree for this example is shown in. This event tree models the occurrence of both multi-unit and single unit loss of offsite power events at a two unit site, and the response of the emergency diesel generators (EDGs) at each unit in a manner that is similar to the Seabrook PRA that was discussed in the previous section.

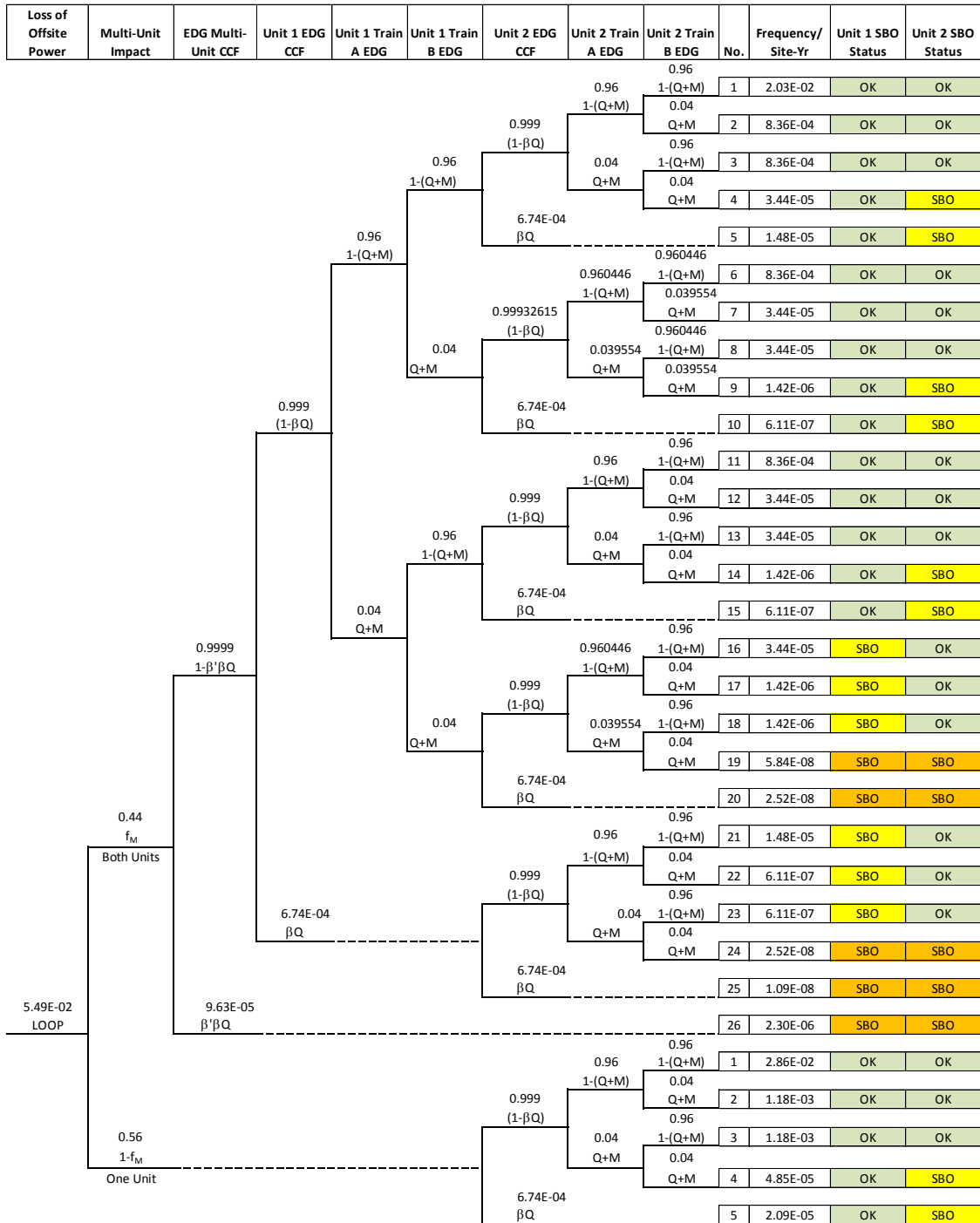
When comparing these results against those of typical existing PRAs there are two key differences. One is that the frequency of a single unit LOOP is increased to reflect this is a site based frequency. The other is that there are different results for LOOP events and SBO events involving single units and both units on this example two unit site. While the frequency of the dual unit SBO is significantly smaller than that for a single unit, it is sufficiently high to avoid screening out of a multi-unit PRA. Note that this example did not include the probability of non-recovery of offsite or onsite power, nor did it include other components such as breakers, fuel transfer pumps, and other components whose failure or unavailability could contribute to an SBO sequence at one or multiple units.

The purpose of the simplified example is to illustrate the process of modelling initiating events and accident sequences in a multi-unit risk analysis and to provide some insights into the relative frequencies of single unit and multiple unit LOOP and SBO events.

Table 2 Parameter Data for LOOP/SBO Example

Model Parameter	Assumed Value	Basis
F_M = Frequency of site and region based events involving loss of offsite power at both units at a two unit site	2.39E-02 per site-year	“LOOP Event and Exposure Data” for region based and site based LOOP events
F_S = Frequency of reactor based events involving loss of offsite power	1.55E-02 per reactor-year	“LOOP Event and Exposure Data” for reactor based LOOP events
F_{Site} = Frequency of loss of offsite power at two unit site	5.49E-02 per site-year	$F_{Site} = F_M + 2F_S$ and above values
f_M = Fraction of loss of offsite power events at a two unit site involving loss of offsite power at both units	0.435	$f_M = \frac{F_M}{F_M + F_S}$ and above values
Q , EDG failure probability	$Q = \lambda_s + \lambda_r T$	Standard model for standby component
λ_s = EDG Failure rate for failure to Start or to load and run for 1hr	7.45E-03 per demand	NUREG/CR-6928 based on U.S. NPP service data
λ_r =EDG failure to run after first hour	8.48E-04 per hour	NUREG/CR-6928 based on U.S. NPP service data
T = mission time	23 hours after first hour	Model assumption
M = EDG maintenance unavailability	1.26E-02	NUREG/CR-6928 based on U.S.

Model Parameter	Assumed Value	Basis
		NPP service data
β = Fraction of EDG failures involving common cause failures shared with another EDG	.025	
β' = Fraction of EDG common cause failures involving failure of all 4 EDGs on both units	$\beta' = \frac{4n_4}{4n_4 + 2n_2}$	MGL model equation for non-staggered testing per NUREG/CR-4780
n_2 , number of EDG common cause events with two component failures on one site	6	Seabrook PRA, one out of 7 common cause events of EDGs would impact all 4 EDGs on a multi-unit site
n_4 , number of EDG common cause events with four component failures on two sites	1	



5. CONCLUSIONS

In summary, it can be said that the site safety assessment for a multiunit site will be quite complex and need to start with individual unit risk assessments, these need to be combined considering the interactions between units and their responses, and the fragilities of the installations established considering the combined demands from all interactions. Using newly established risk metric the risk can then be integrated for the overall site. Fig. 2 shows schematically such a proposal. Much work has to done and the IAEA has established a working group that is systematically establishing the structure and process to incorporate the many issues that are a part of a multiunit site safety assessment.

6 ACKNOWLEDGMENTS

The authors thank the Karl Fleming as the main contributor to the draft IAEA Safety Report [3] which provides the basis of this paper.

7 REFERENCES

- [1] ANS Special Committee on Fukushima Daiichi, (2012), "Fukushima Daiichi: ANS Special Committee Report", LaGrange Park, IL, USA
- [2] United States Nuclear Regulatory Commission, Recommendations for Enhancing Reactor safety in the 21st Century, The Near-Term Task Force, Review of insights from the Fukushima Dai-ichi Accident, USNRC. Washington DC (July 2012)
- [3] IAEA Draft Safety Report on "Technical approach to Multi-Unit Site Probabilistic Safety Assessment (Draft 2, Jan. 2014).