Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division VII

PROBABILISTIC SURVIVABILITY EVALUATION OF STRUCTURES & COMPONENTS ASSIGNED FOR DESIGN EXTENSION CONDITIONS

Ayman Saudy[1] and Medhat Elgohary[2]

[1] Senior Technical Expert, Civil & Seismic Eng., Kinectrics, Canada (ayman.saudy@kinectrics.com)
[2] Principal Consultant, Civil & Seismic Eng., Kinectrics, Canada (medhat.elgohary@kinectrics.com)

ABSTRACT

International Atomic Energy Agency (IAEA) and many national regulators such as Canadian Nuclear Safety Commission (CNSC) have extended the plant design basis envelope to include 'Design Extension Conditions' or DECs. DECs represent accidents that are more severe than design basis accidents (DBAs). A spectrum of initiating events including random failure of systems or components, internal and external hazards is used in defining scenarios leading to DECs. A set of plant-assigned design features should be defined to maintain safety functions during events leading to DECs. These design features would be either existing design features already assigned for DBAs, or complementary design features dedicated to DECs.

While for DBAs, there is “high confidence” in the ability of the structures, systems and components (SSCs) to perform as designed, for DECs, SSCs are required to perform as designed with “reasonably high confidence.” A deterministic design methodology has been proposed to address DECs’ higher demands on the design features in new and existing CANDU NPPs (Saudy and Elgohary, 2015). The proposed design methodology builds on the current requirements of applicable codes and standards and recommends more relaxed acceptance criteria. Sample cases for design features that were implemented in existing CANDU NPPs to address DECs were later presented (Saudy and Elgohary, 2017). The deterministic design methodology was applied to three cases of Civil structures, passive components as well as active control & instrumentation. A means to probabilistically evaluate the built-in margin at the demand induced by a seismic DEC would provide a measure of the confidence level in a DEC-assigned structure or component performing its function.

A methodology based on estimating the probability of survivability of a safety-related structure or component at the demand induced by a seismic DEC is proposed. In this methodology, the fragility function normally developed for evaluation of seismic PRA is used. The mean, 5-percentile, and 95-percentile fragility functions are typically developed to determine the High-Confidence-Low-Probability-of -Failure (HCLPF) value associated with the contribution of a structure or component to the overall plant seismic risk. The survivability function of a structure or component, at a specific confidence level, may be defined as 1.0 minus the fragility function for the same confidence level. Reversing the process applied on the fragility to determine the HCLPF, the peak ground acceleration for the DEC can be used to determine either the probability of survivability at a specific confidence or the confidence level for a pre-set probability of survivability. The method maybe used as well to indicate whether there is a need for applying design modification to existing design features to address demands of seismic DEC.

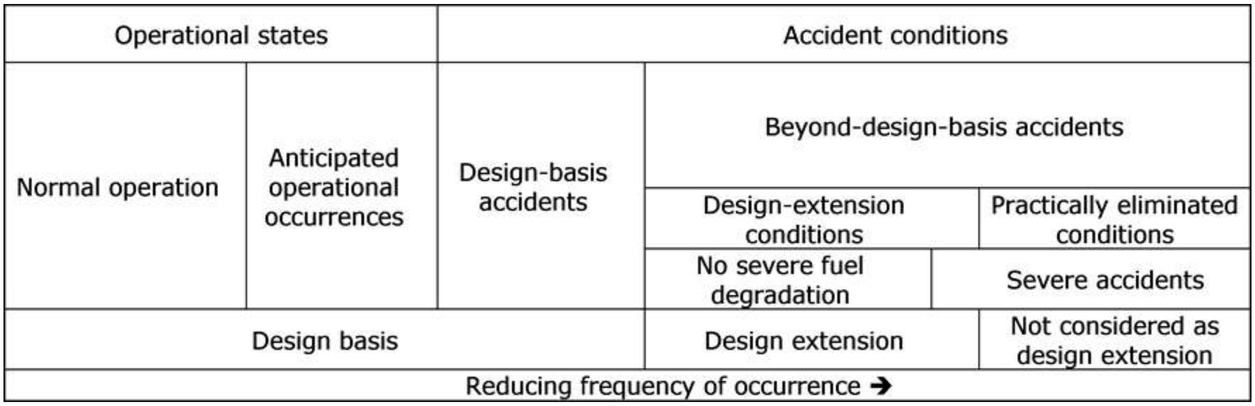
This paper provides a summary of the proposed methodology to probabilistically evaluate the confidence in the survivability of a structure or component at the demand induced by a seismic DEC. The three examples used, previously, in demonstrating the deterministic design methodology are used again to demonstrate the application of the proposed probabilistic methodology.

INTRODUCTION

Seismic events such as the March 2011 earthquake at Fukushima, Japan (IAEA, 2011) and the Virginia earthquake in the eastern United States (Grecheck, 2013), where the design basis earthquake was exceeded, have heightened the public concern regarding the safety of nuclear power plants worldwide. Such events led the nuclear regulators and the industry to re-assess the safety of existing and new power plants. The March 2011 seismic induced tsunami event inundated the safety systems and posed grave challenge to achieve cold shutdown in the Fukushima Daiichi units, (NISA, 2011). A nearby plant at Onagawa, that is much closer to the epicentre, experienced even higher seismic motion and survived mostly undamaged (IAEA, 2013). The August 2011 Virginia earthquake, the largest seen to date in the eastern United States exceeded the nearby North Anna plant design basis. Extensive review and inspections showed that the plant did not suffer any damage.

The ongoing international investigation of the Fukushima accident has resulted in increased effort in developing strategies for preventing and mitigating accident situations and scenarios beyond those considered during the initial design of nuclear facilities. These accident scenarios are termed 'Design Extension Conditions' or DECs and their consideration is becoming increasingly prevalent within the international nuclear community. In defining safety requirements for nuclear power plants, the IAEA and many national regulatory agencies have stipulated the inclusion of DECs in the design, analysis and operation of these plants, Figure 1 (IAEA, 2012 and CNSC, 2011, 2012 & 2014). Design extension conditions represent one of the categories used to define the different plant states based on their frequency of occurrence. The European Utility Requirements in addressing safety during incidents and accident conditions (EUR, 2012) expect accident condition outside the design basis conditions to be considered in the context of achieving defence-in-depth and risk reduction

One of the main objectives for defining a set of DECs is enhancing the plant's capabilities to withstand, without unacceptable radiological consequences, accidents that are either more severe than design basis accidents or that involve additional failures. The set of DECs are derived based on engineering judgement, deterministic assessments and probabilistic assessments of the plant and are considered a subset of the Beyond Design Basis Accident (BDBA) conditions.



<table>
<tr><th colspan="2">Operational states</th><th colspan="4">Accident conditions</th></tr>
<tr><td rowspan="3">Normal operation</td><td rowspan="3">Anticipated operational occurrences</td><td rowspan="3">Design-basis accidents</td><td colspan="3">Beyond-design-basis accidents</td></tr>
<tr><td colspan="2">Design-extension conditions</td><td>Practically eliminated conditions</td></tr>
<tr><td>No severe fuel degradation</td><td colspan="2">Severe accidents</td></tr>
<tr><td colspan="3">Design basis</td><td colspan="2">Design extension</td><td>Not considered as design extension</td></tr>
<tr><td colspan="6">Reducing frequency of occurrence ➔</td></tr>
</table>

Figure 1. DECs in relation to other Plant State Conditions

In Canada, while the concept of DECs has been addressed in CNSC's regulatory document REGDOC 2.5.2 (CNSC, 2014a), according to the discussion paper DIS-14-01 (CNSC, 2014b), DECs do not associate with the "high confidence" associated with other plant states guaranteed through conservative design. Instead, the principle of "reasonably high confidence" in the success of activities associated with DECs is applied.

This principle has not been fully developed in the codes and standards governing areas such as design, analysis, construction, and operation of nuclear power plants.

To maintain safety functions during events leading to DECs, the approach is to define a set of plant-assigned design features. These design features would be either existing plant design features already assigned to address DBAs, or complementary design features dedicated to DECs. Only when the existing design features are not sufficiently capable to meet the safety objectives during DECs, then, complementary design features are introduced to provide the additional capability needed to meet the safety objectives. Therefore, there are four groups of design features that could be assigned to meet the safety objectives during DECs:

- Unmodified existing SSCs,
- Upgraded existing SSCs,
- Permanently new installed SSCs, and
- Portable new equipment to be connected to existing systems

A design methodology has been proposed by Saudy and Elgohary (2015) and presented in SMiRT 23 to address DECs' higher demands on the design features in new and existing CANDU NPPs. The proposed design methodology for DECs builds on the current requirements of applicable codes and standards and proposes more relaxed acceptance criteria. In SMiRT 24, Saudy and Elgohary (2017) presented examples for design features that were implemented in existing CANDU NPPs to meet CNSC's recommendations based on lessons learned from Fukushima accident. The proposed methodology for DECs is applied in each example. The examples include two different groups of design features in addressing DECs: (a) existing design features (either as-is or after being upgraded), and (b) complementary design features (either permanent or portable). The deterministic design methodology was applied to three cases of Civil structures, passive components as well as active control & instrumentation. A means to probabilistically evaluate the built-in margin at the demand induced by a seismic DEC would provide a measure of the confidence level in a DEC-assigned structure or component performing its function.

This paper provides a methodology based on estimating the probability of survivability of a safety-related structure or component at the demand induced by a seismic DEC. In this methodology, the fragility function normally developed to represents the failure frequency for evaluation of seismic PRA is used. "Failure" is defined in terms of the performance level for that component or structure. The survivability function of a structure or component, with various confidence levels, may be defined as 1.0 minus the fragility function. Reversing the process applied for the fragility, the peak ground acceleration for the DEC can be used to determine either the probability of survivability with a specific confidence or the confidence level for a pre-set probability of survivability. The method maybe used as well to indicate whether there is a need for applying design modification to existing design features to address demands of seismic DEC.

In the following sections, first, a summary of the design methodology to address DECs' higher demands in existing CANDU NPPs is presented followed by a summary of the proposed methodology to probabilistically evaluate the confidence in the survivability of a structure or component at the demand induced by a seismic DEC. Finally, the three examples used, previously, in demonstrating the deterministic design methodology before are used again to demonstrate the application of the proposed probabilistic methodology.

SUMMARY OF DESIGN METHODOLGY

Current codes and standards used in the design of safety related SSCs of nuclear power plants do not address the engineering demands due to DECs nor do they specify any acceptance criteria for their performance. The question facing designers of nuclear power plants would be whether these codes could still be used in designing the features assigned for DECs. To methodologically address the developed demands imposed on safety related SSCs during DECs, a design-based approach that defines such demands and states the relevant acceptance criteria is proposed by Saudy and Elgohary (2015 & 2017). The primary objective was to have reasonably high confidence that the intended safety functions would be performed by the design features as assigned during DECs. A summary of the acceptance criteria for fulfilling the safety functions assigned to civil structures as well as to mechanical, electrical, instrumentation and control systems and components is presented in Table 1 (Saudy and Elgohary, 2015 & 2017).

Table 1: Acceptance criteria for safety related structures, systems & components

Item		Safety Function	Design Basis Events	Design Extension Conditions
Category	Type			
Civil Structures	General	Housing systems & components Shielding systems & components Structural integrity	Essentially elastic	Limited non-linearity
	Containments Pools & Tanks	Leak tightness Containment of radionuclides	Strain-controlled Design	No through-wall cracks
Mechanical & Electrical Components & Control Instrument	Passive	Structural integrity Leak tightness & pressure boundary Safe reactor shutdown Decay heat removal Control & maintain safety functions Containment of radionuclides	Essentially elastic	Limited non-linearity
	Active	Containment of radionuclides Safe reactor shutdown Decay heat removal Control & maintain safety functions	Plant’s Technical Specifications & Release Limits for DBEs	Plant’s Technical Specifications & Release Limits for DECs*

* The built-in margin in case of DECs would be less than that for design basis events.

As proposed, the design methodology deterministically ensures the adequate performance expected or credited to the design features assigned for DECs. Whether these features are existing or complementary, their design will bring about reasonably high confidence in their performance during postulated DECs. However, the methodology does not shed any light on the confidence level in the design of those features implemented specifically for DECs. Evaluating that confidence level could be beneficial on two fronts: design-assist and risk-assist, via establishing the probability of survivability of a structure or a component that is dedicated to performing specific safety functions during DECs. Probabilistically evaluating the built-in margin and quantifying it in terms of the seismic load parameters such as the peak ground acceleration would provide the means to establish its probability of survivability for a specific confidence level.

On the design-assist front, the probability of survivability of that structure or component would substantiate its required adequacy; thus, meeting the acceptance criteria normally stated in any nuclear design codes. Especially, in case of existing design features (whether as-is or upgraded), the seismic margins are typically already calculated for the purposes of many rounds of probabilistic risk evaluations. Therefore, if the probability of survivability of an item is established for the imposed demands of DECs, many detailed systematic design calculations needed to deterministically substantiate the item’s adequacy may be avoided. The evaluated probability of survivability maybe used as well to indicate whether there is a need for applying design modification to existing design features to address demands of seismic DEC.

On the risk-assist front, the overall plant risk evaluations are typically performed for a hazard-specific review levels with a different probability of occurrence from that for DECs. Nevertheless, the survivability of that structure or component could still be used in sensitivity studies of the plant-logic model; i.e. event fault-trees. It should be noted that the probability of survivability may be determined for existing design features as well as the complementary design features.

PROPOSED PROBABILISTIC EVALUATION METHODOLGY

A methodology based on estimating the probability of survivability of a safety-related structure or component at the demand induced by a seismic DEC is proposed. The seismic DEC is defined via a site-specific ground motion that is typically defined at a lower non-exceedance probability than that for the design basis earthquake and using the results of the probabilistic seismic hazard assessment conducted for the site. The probability of survivability of a structure or component, with various confidence levels, may be defined as the complementary to (1.0 minus) the fragility function. Reversing the process applied on the fragility to determine the HCLPF, the peak ground acceleration for the DEC can be used to determine either the probability of survivability for a specific confidence or the confidence level in a pre-set probability of survivability.

Two main input parameters need to be determined and/or calculated for the structure or component under consideration prior to the implementation of the proposed evaluation methodology. These are:

1. Seismic Demand. The demand takes the form of developed internal design forces in structural members or stresses (directional or averaged) in mechanical components or its anchorages that are normally obtained using dynamic structural analyses. Several factors contribute to the conservativism in the evaluated demands. The demands, including the built-in conservatism, would be evaluated at the same level of non-exceedance at which the site-specific ground motion for the seismic DEC is defined.
2. Seismic Capacity. The capacity may take the form of the mean, median, 5th-percentile and 95th percentile fragility functions normally developed for evaluation of the plant's seismic PRA. Therefore, either the median capacity or the HCLPF capacity may be used. Both capacities are typically calculated for items in the plant's safe shutdown list.

Figure 2 illustrates the probability of failure (or the complementary to survivability) considering the two main input parameters. The general relative relation between the seismic demand and capacity of a safety-related structure or component is presented. It should be noted that both the demand and capacity are normally expressed in terms of a parameter used in defining the ground motion such as the peak ground acceleration or the spectral acceleration at a specific structural frequency.

Two distinct seismic demands (each is represented by a normal distribution curve of the seismic response) can be seen to the left of the plot in Figure 2: one for the DBE level and the other for the DEC level. It should be noted that the seismic demand nominally used in the design is at the 84% non-exceedance probability (mean demand + 1.0 times standard deviation). Therefore, the demand for the DBE is at point (D_1) and that for the DEC level is at point (D_2). The mean or best-estimate structural response for the DBE and DEC levels can be seen at points ($D_1^{'}$) and ($D_2^{'}$); respectively. It should be noted that the scattering of the probability distributions for the demand to DBE and DEC are assumed identical; however, the scattering associated with the demand distribution due to DEC is expected to be greater than that associated with the demand distribution due to DBE.

To the right of the plot in Figure 2, the fragility function representing the structure's or component's seismic capacity is seen, demonstrating the case of its robust design. If the demand curve falls ahead of the fragility curve, then the design of the structure or component would be inadequate. The single mean fragility curve is considered a "composite" function as it includes both randomness and uncertainty associated with the evaluated capacity. When randomness and uncertainty are segregated, the fragility of the component or structure is represented by three percentile curves; i.e. the 5th, 50th (median), and 95th percentiles curves.

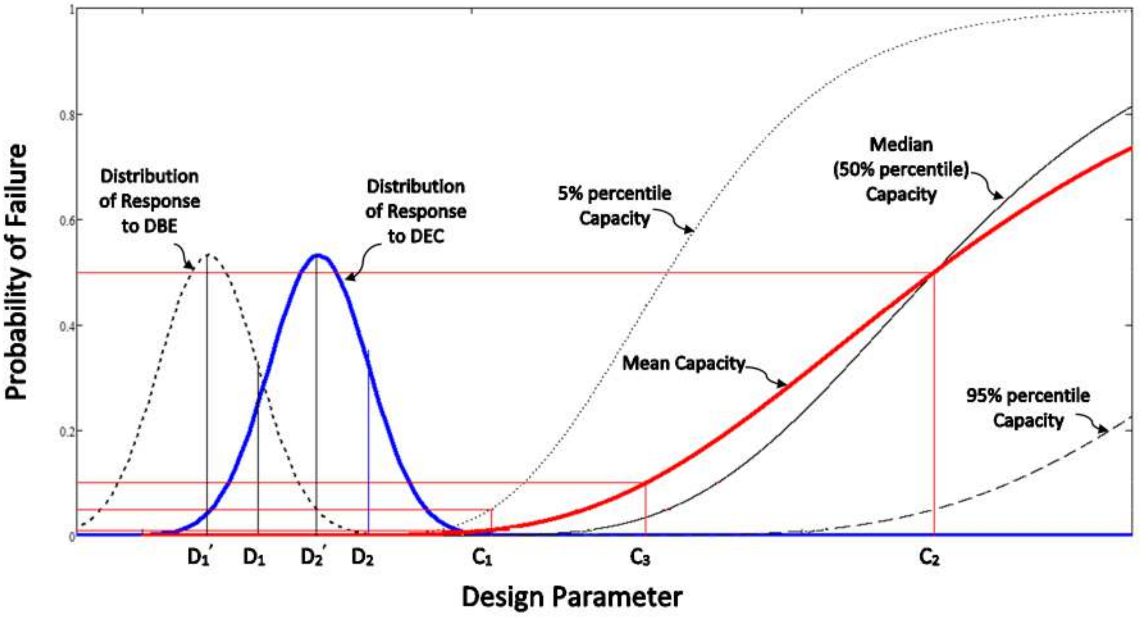


Figure 2. Frequency of Failure (or Survivability): Demand vs. Capacity

Several points on the mean fragility curve of Figure 2 are identified:

- CAP_{01} is indicated as point (C_1) at which there is a 1% frequency of failure for the given demand,
- CAP_{50} is indicated as point (C_2) at which there is 50% frequency of failure, and
- CAP_{10} is indicated as point (C_3) at which there is 10% frequency of failure.

The HCLPF point on the 95th percentile fragility curve is a convenient point at which the design capacity of a structure or a component is specified. The HCLPF corresponds to a 95% confidence (over uncertainty) of less than a 5% (over randomness) frequency of failure. It should be noted that the HCLPF corresponds very closely to a 1% frequency of failure (C_1) given the demand as obtained from the composite mean fragility curve.

According to NUREG/CR-6728 (NRC, 2001), the capacity ratio C_2/C_1 ranges typically between 2.0 and 4.0, based on uncertainties associated with the median capacity. According to many studies and established seismic risk evaluations (Kennedy 1999), the composite variability accounting for randomness and uncertainties in evaluating the capacity ranges from 0.3 (for structures) to 0.6 (for components). In the meantime, the demand ratio D_1/D_1' (or D_2/D_2') is approximately 1.25, based on relatively less variability in evaluating the nominal demand (or seismic response). It should be noted that for ensuring adequate margins in the design of nuclear power plants, a ratio of 1.67 is typically observed between the HCLPF capacity, or point (C_1), of a design feature credited in the plant's risk evaluation, and the nominal demand due to the design basis condition, or point (D_1), per NUREG/CR-6728, and CNSC's REGDOC 2.5.2.

The mean fragility function of a structure or component once established via the three capacity parameters above (Points C_1, C_2, and C_3), provides its capacity in terms of a ground motion parameter for a specific probability of failure. Inversely, the mean fragility function provides the probability of failure for a structure or component may be determined for a specific capacity that could be achieved by design (EPRI, 1994).

For the case of design extension conditions, several capacity/demand ratios can be derived from the parameters shown in Figure 2. The proposed probabilistic methodology is primarily based on evaluating these key parameters. The parameters are the ratios between the CAP_{01} (or HCLPF), CAP_{50} and CAP_{10} and the nominal demand imposed by DECs (D_2) and are defined as follows:

$$R_1 = \frac{C_1}{D_2}\,, R_2 = \frac{C_2}{D_2} \;\&\; R_3 = \frac{C_3}{D_2} \tag{1}$$

Assessment of Existing Design Features

The existing design feature selected to be credited in performing specific safety-related function(s) and in resisting that demands imposed during DECs, might be already included in the plant logic model associated with evaluating the seismic risk of the nuclear plant. In this case, both CAP_{50} (mean fragility) and HCLPF (or CAP_{01}; i.e. 1% probability of failure) are already determined. In case the existing design feature is not included in the plant logic model, then, calculating its CAP_{50} and HCLPF capacity parameters is a pre-required step in the proposed methodology.

As one of two scenarios may occur, the adequacy of the selected existing design feature to sustain the demand imposed by DECs would be determined. The two scenarios are:

(a) The HCLPF capacity of that feature is sufficiently greater than the nominal demand imposed by DECs. In other words, when $R_1 > 1.0$, then, in this case, the adequacy of the credited feature is established. The survivability of that design feature is substantiated with high confidence with a probability greater than or equal to 99%.

(b) The nominal demand imposed by DECs exceeds the HCLPF capacity of that feature. In other words, when $R_1 < 1.0$, then, adequacy of the credited feature will need to be assessed. Based on the assessment, the design feature could potentially be modified and/or upgraded to enhance its capacity. Depending on that exceedance of the nominal demand beyond the HCLPF capacity, or on where point (D_2) lies to the right of point (C_1) in Figure 2, one of three cases may arise:
    1. The nominal demand imposed by DECs might exceed HCLPF but at the same time, it might be less than the CAP_{10} capacity; i.e. $R_3 > 1.0$. In this case, the design features may be considered adequate since its survivability would be about 90% which may be permitted based on the relaxed 'reasonable confidence' of performance allowed by regulators.
    2. The permitted 'reasonable confidence' of performance could not be extended to scenarios of both R_1 & $R_3 < 1.0$; i.e. the nominal demand is greater than the CAP_{10} capacity. In this case, the design features would certainly need to be modified or upgraded to ensure its adequacy to perform intended functions during DECs, therefore enhancing its survivability.
    3. The nominal demand imposed by DECs might even exceed CAP_{50}, i.e. the median capacity of the design features. In this case, major modification of the design features would be expected, if it would be relied on to perform during DECs. An alternative design option could be either selecting a different design feature or installing a complementary design feature.

The assessment of the existing design feature in question, from design engineering perspective, will conclude with a design feature adequate to perform its credited safety functions during DECs. Subsequently, the probability of survivability of that feature can be estimated using the ratios, R_1, R_2, and R_3 defined above. Nevertheless, according to the lognormal distribution assumed in representing the fragility function (EPRI, 1994), the combined variability in the fragility function (β) accounting for both randomness and uncertainty can be estimated as follows:

$$\beta = \frac{-1}{2.33}\ln\left(\frac{C_1}{C_2}\right) \tag{2}$$

For a specific demand level of a design parameter (X), the probability of failure (P_f) may be evaluated as follows:

$$P_f = \Phi\left[\frac{\ln\left(\frac{X}{C_1}\right)}{\beta}\right] \tag{3}$$

As the probability of survivability (P_s) of the design feature is the complementary probability of its failure (P_f). Then, the survivability of the design feature is as follows:

$$P_s = 1 - \Phi\left[\frac{\ln\left(\frac{X}{C_1}\right)}{\beta}\right] \tag{4}$$

Assessment of Complementary Design Features

Since the complementary design features, whether permanently installed or portable, are designed specifically for the nominal demands of DECs, using the nuclear design codes, then the confidence level in their performance would be as high as any confidence level achieved in designing for the nominal demands due to design basis conditions. Therefore, the survivability of these complementary design features will not be in question. Both HCLPF and CAP_{50} (median) capacities can be evaluated, if the survivability of a complementary design feature is needed. In this case, the probability of survivability is evaluated using the method described in Equations (2), (3) and (4) above.

APPLICATION to OPERATING CANDU NPPs

Three examples of candidate design features that could be credited in postulated DECs are considered. Each of the design features belongs to a plant logic model used in evaluating the plant's risk to seismic events. Therefore, the mean capacity of each feature and its associated combined uncertainty are already calculated. Table 2 provides a summary of the three features and the capacity parameters. The failure mode governing the design feature's capacity is included as well. The peak ground acceleration is selected as the design parameter for the nominal demand and calculated capacity. The nominal demand for the seismic DECs is 0.20g. It should be noted that the nominal demand for the design basis earthquake is 0.08g. Figure 3 illustrates the mean fragility functions for the three design features along with the nominal demand imposed by the seismic DEC.

As can be seen, the Civil structure is considered adequate to be credited in meeting the demand imposed by the seismic DEC since its HCLPF is greater than 0.20g. And, its probability of survivability would be exceeding 99%. In the case of the heat exchanger, the demand exceeds the HCLPF capacity but is less than the CAP_{10} capacity. Therefore, the heat exchanger is considered adequate. As for the switchgear, however, it would need to be modified and/or upgraded to enhance its survivability. Engineering a modification to the switchgear and its anchorage would aim to increasing its capacity parameters and shifting its fragility function to the right in Figure 3. The HCLPF, CAP_{10} and CAP_{50} capacities for the upgraded switchgear are evaluated as 0.27g, 0.39g, and 0.61g; respectively. Table 3 provides the evaluated survivability of each of the three features and for the case of modified switchgear.

Therefore, the proposed probabilistic evaluation methodology establishes the adequacy of existing design features credited for DECs, flags the need for implementing any design modifications, and estimates the probability of survivability in sustaining the demand of postulated DECs.

Table 2: Capacity Parameters of The Design Features

Feature	Failure Mode	HCLPF (g)	CAP$_{10}$ (g)	CAP$_{50}$ (g)	β_c
Civil Structure	Uplift due to Breaking of Rock anchors	1.37	1.90	2.87	0.32
Heat exchanger	Buckling of saddle support	0.17	0.22	0.32	0.28
Switchgear	In adequate anchorage	0.08	0.11	0.17	0.35

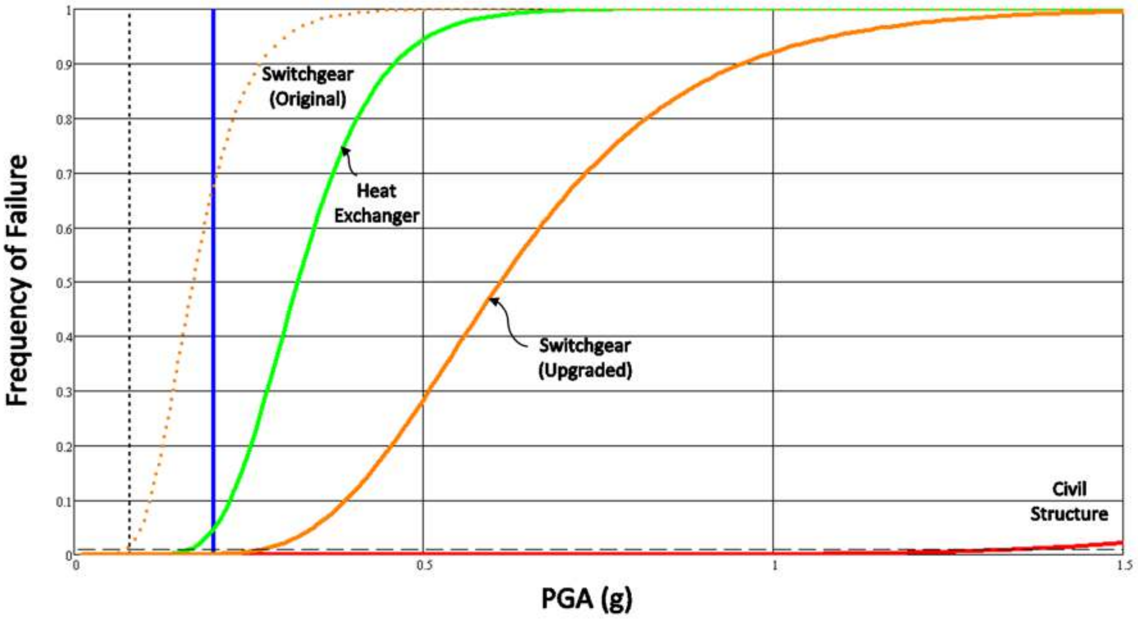


Figure 3. Frequency of Failure (or Survivability) for The Design Features

Table 3: Survivability Evaluation for The Design Features

Feature	R$_1$	R$_3$	R$_2$	Survivability
Civil Structure	6.83	9.52	14.35	99.6%
Heat exchanger	0.84	1.12	1.60	68.0%
Switchgear (original)	0.38	0.54	0.85	43.5%
Switchgear (upgraded)	1.35	1.95	3.05	86.8%

SUMMARY & CONCLUSION

This paper provides a review of a proposed methodology based on estimating the probability of survivability of a safety-related structure or component at the demand induced by a seismic DEC. In this methodology, the fragility function normally developed for evaluation of seismic PRA is used. The mean, 5-percentile, and 95-percentile fragility functions are typically developed to determine the HCLPF value associated with the contribution of a structure or component to the overall plant seismic risk. The survivability of a structure or component, for a specific confidence level, is defined as 1.0 minus the fragility function for the same confidence level. Reversing the process applied on the fragility to determine the HCLPF, the peak ground acceleration for the DEC can be used to determine either the probability of survivability with a specific confidence or the confidence level for a pre-set probability of survivability. The method maybe used as well to indicate whether there is a need for applying design modification to existing design features to address demands of seismic DEC. For the design and evaluation of a structure or component credited to perform during design extension conditions, several capacity/demand ratios are derived. The proposed probabilistic methodology is primarily based on evaluating the ratios between the HCLPF and mean capacities and the nominal demand imposed by DECs.

The implementation of the proposed probabilistic methodology is presented in the paper and is demonstrated, as well, via three examples of candidate design features that could be credited in postulated DECs. The proposed probabilistic evaluation methodology establishes the adequacy of existing design features credited for DECs, flags the need for implementing any design modifications, and estimates the survivability in sustaining the demand of postulated DECs.

REFERENCES

Canadian Nuclear Safety Commission (2011). INFO-0824, CNSC Fukushima Task Force Report.

Canadian Nuclear Safety Commission (2012). INFO-0828, CNSC Staff Action Plan on the CNSC Fukushima Task Force Recommendations.

Canadian Nuclear Safety Commission (2014a). REGDOC -2.5.2, Design of Reactor Facilities: Nuclear Power Plants.

Canadian Nuclear Safety Commission (2014b). DIS-14-01, Design Extension Conditions for Nuclear Power Plants.

Electric Power Research Institute (1994). TR-103959 Methodology for Developing Seismic Fragilities.

European Utility Requirements for Light Water Reactor Nuclear Power Plants (2012). Volume 2, Revision D, Generic Nuclear Island Requirements, Chapter 4, Design Basis.

Grecheck, E.S. (2013). “North Anna Earthquake Event, Response, DBE Exceedance and Restart,” *8th Nuclear Plants Current Issues Symposium*, January 23-25, 2013, Orlando Florida.

International Atomic Energy Agency, (2011). IAEA International Fact-Finding Expert Mission of the Fukushima Dai-Ichi NPP Accident following the Great East Japan Earthquake and Tsunami.

International Atomic Energy Agency (2012). Specific Safety Requirements No. SSR-2/1, Safety of Nuclear Power Plants: Design.

International Atomic Energy Agency (2013). IAEA Mission to Onagawa Nuclear Power Station to Examine the Performance of Systems, Structures, and Components Following the Great East Japanese Earthquake and Tsunami – Onagawa and Tokyo, Japan.

Kennedy, R.P. (1999). “Overview of Methods for Seismic PRA and Margin Analysis Including Recent Innovations” Paper in OECD’s Report # NEA/CSNI/R(99)28.

Nuclear & Industrial Safety Agency (2011). The Accident at TEPCO's Fukushima Nuclear Power Stations, Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety.

Saudy, A. and Elgohary, M. (2015). “Proposed Design Guidelines for Implementing DECs due to Seismic Hazards in CANDU Nuclear Power Plants” *Proc., Structural mechanics in Reactor Technology 23rd Conference,* SMiRT 23, Manchester, United Kingdom.

Saudy, A. and Elgohary, M. (2017). “Implementing Design Features in Existing CANDU Plants for Design Extension Conditions” *Proc., Structural mechanics in Reactor Technology 24th Conference,* SMiRT 24, Bosan, South Korea.

US Nuclear regulatory Commission (2001). NUREG/CR-6728, Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk- Consistent Ground Motion Spectra Guidelines, Accession Number: ML013100232.