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DETERMINISTIC & PROBABILISTIC EVALUATIONS OF STRUCTURES & COMPONENTS CREDITED FOR SEISMIC DESIGN EXTENSION CONDITIONS

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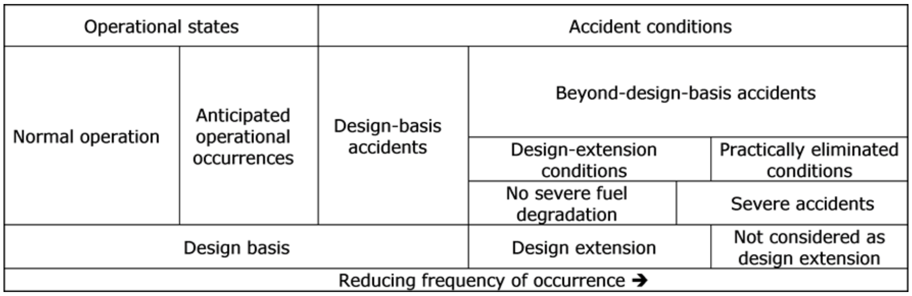
ABSTRACT

There is “high confidence” in the ability of the structures, systems, and components (SSCs) of Nuclear Power Plants (NPPs) to perform as designed for Design Basis Accidents (DBAs). For Design Extension Conditions (DECs), the SSCs are required to perform as designed with “reasonably high confidence.” DECs represent scenarios or accidents that are more severe than DBAs. Typically, a spectrum of initiating events including random failure of systems or components, internal and external hazards is used in defining scenarios leading to the DECs. Seismic events that exceed the Design Basis Earthquake (DBE) of a station could be considered a seismic DECs. A deterministic design method is proposed to address higher demands of seismic DECs in new and existing CANDU NPPs. The deterministic method builds on the current requirements of applicable codes and standards and recommends more relaxed acceptance criteria. Nevertheless, a means to probabilistically evaluate margins that are built-in during the design process for the DBE demands would provide a measure of the confidence in a DEC-assigned structure or component performing its function. Therefore, a probabilistic method that estimates the probability of survivability for a structure or component when subjected to the demand induced by a seismic DEC is proposed. The probabilistic method could be used to indicate whether there is a need for applying design modification to existing design features to address demands of seismic DEC. The mean, 5-percentile, and 95-percentile fragility functions of these SSCs are used in this method. These 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. Sample cases for design features that were implemented in existing CANDU NPPs to address seismic DECs are presented. The application of the deterministic and probabilistic methods to Civil structures, passive Mechanical & Electrical components as well as active Control & Instrumentation components is described.

INTRODUCTION

Seismic events such as the March 2011 earthquake at Fukushima, Japan, and the Virginia earthquake in the eastern United States, where the design basis earthquake for the nuclear power plant was exceeded, have heightened the public concern regarding their safety 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 related systems and posed grave challenge to achieve cold shutdown in the Fukushima Daiichi units, (IAEA & TEPCO, 2011). The August 2011 Virginia earthquake, the largest seen to date in the eastern United States exceeded the North Anna plant design basis, (Grecheck, 2011).

The 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 and their consideration in the design of new NPPs and in the evaluation of existing NPPs is becoming increasingly prevalent within the international nuclear community. Therefore, the International Atomic Energy Agency (IAEA) and many national regulators such as the Canadian Nuclear Safety Commission (CNSC) have extended the plant design basis envelope to include 'Design Extension Conditions' or DECs that represent accidents that are more severe than DBAs. DECs represent one of the categories used to define the different plant states based on their frequency of occurrence, Figure 1, (IAEA & CNSC, 2012). 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.



<table>
<tr><td colspan="2">Operational states</td><td colspan="4">Accident conditions</td></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>
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Figure 1. DECs in relation to other plant state conditions

A spectrum of initiating events including random failure of safety related SSCs, internal and external hazards is used in defining scenarios leading to DECs. 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 DBAs or that involve additional failures. The set of DECs are derived based on engineering judgement, deterministic and probabilistic assessments of the plant and are considered a subset of the Beyond Design Basis Accident conditions. To maintain safety functions during events represented by the DECs, a set of plant-assigned design features is defined. These design features would be either existing plant features already assigned to address DBAs, or complementary features dedicated to DECs. Only when the existing features are not sufficiently capable to meet the safety objectives during DECs, then, complementary features are introduced to provide the additional capability needed to meet the safety objectives. The existing features could be either credited unmodified or after being upgraded SSCs. The complementary features could be either permanently installed or portable new SSCs.

In Canada, the concept of DECs has been addressed in CNSC's regulatory document REGDOC 2.5.2, according to the discussion paper DIS-14-01. However, the principle of "high confidence" in successful performance of safety functions associated with design basis plant states guaranteed through conservative design does not apply for DECs. 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 NPPs.

This paper provides two methods to address the higher demands of seismic events that exceed the DBE, i.e., seismic DECs, for new and existing CANDU NPPs: a deterministic design method and a probabilistic evaluation method. To demonstrate the application of the deterministic and probabilistic methods, three examples of design features implemented in existing CANDU NPPs are presented.

CONSIDERATION OF A SEISMIC DEC in DESIGN PROCESS & SAFETY EVALUATION

Current codes and standards used in the design of safety related SSCs do not address the engineering demands due to DECs nor do they specify any acceptance criteria for their performance. The question facing designers would be whether these codes could still be used in designing the DECs-assigned features. To methodologically address the demands imposed on these features in case of a seismic DEC, a ‘design’ approach that defines such demands and states the relevant acceptance criteria is proposed. The primary objective is to have reasonably high confidence that the intended safety functions would be performed by the assigned design features.

On one hand, the basic safety functions for civil structures include structural integrity, containment of radioactive material or leak tightness, and protection of housed-in safety related systems and components from induced harmful effects. These safety functions are generally fulfilled, because the structures are ensured to experience no damage, i.e., quasi-elastic behaviour. However, when subjected to DECs, limited non-linear (plastic) response may be accepted, i.e., plastic behaviour. Leak tightness of structures, such as the containment structure and the spent fuel pools, containing radionuclide materials are usually fulfilled by demonstrating that specified release limits are met.

On the other hand, the basic safety functions for mechanical, electrical, instrumentation and control systems and components include safe shutdown of the reactor, decay heat removal, containment of radioactive material, and control and maintenance of containment, cooling, and shutdown functions. Therefore, safety related systems and components, even when protected by properly designed civil structures, need to be checked regarding their stability and functionality, considering the vibrations, pressure and thermal transients developed during DECs. For many types of active mechanical and electrical systems and components; especially instrumentation and control components, qualification is generally carried out by means of testing. The assessment of stability and integrity of passive mechanical systems is usually carried out by means of analytical procedures, based on appropriate mathematical models and using the applicable transients on the systems and its supporting anchor points.

A summary of the acceptance criteria for fulfilling the safety functions assigned to civil structures and to mechanical, electrical, instrumentation and control systems and components is presented in Table 1.

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	Release Limits for DBEs	Release Limits for DECs [*]

[*] Built-in margins in case of DECs would be less than those for DBEs.

DETERMINISTIC DESIGN METHOD

The proposed deterministic method in designing of the assigned design features is based on determining (a) the demands due to a seismic DEC and (b) the seismic capacities of the design features to resist such demands. Both the demands and capacities are determined deterministically. The demand on safety related structures, systems and components should be defined via appropriate load combinations reflecting the normal operating loading conditions in addition to the perturbing effects (pressure, deformation, temperature) imposed by the seismic DEC. All sources of overstrength attained during regular design, construction, and procurement processes are considered in determining the capacities of the design features.

Table 2 summarizes the design approach for the design features assigned to DECs. The proposed design philosophy to demonstrate seismic ruggedness and capability of those design features to perform in harsh accident conditions due to seismic DECs is as follows:

a) For complementary design features, code-based design approach, i.e., nuclear design standards, are followed, and
b) For designing and evaluating existing civil structures and passive mechanical and electrical components, a best-estimate capacity design approach is followed.
c) For designing and evaluating existing active mechanical and electrical components, an experience-based approach is followed.

Table 2: Design philosophy for SSCs assigned safety functions during seismic DECs

	Existing Design Features		Complementary Design Features	
	Unmodified	Upgraded	Permanent	Portable
Demand	RLC*	RLC*	RLC*	RLC*
Load Combination	DEC-specific	DEC-specific	DEC-specific	DEC-specific
Approach - Structures - Components	 Capacity design Experience-based	 Capacity design Experience-based	 Code-based design Experience-based	 Code-based design Experience-based
Confidence	Reasonably high	Reasonably high	Reasonably high†	Reasonably high†

* Review Level Condition: code-based design parameters representing seismic DECs
† At least reasonably high confidence is achieved when national design codes are used. High confidence is achieved in case nuclear codes are used.

The design philosophy is based on adopting the capacity design approach and the experience-based seismic and environmental qualification approaches to upgrade or evaluate the existing features, as well as the complementary features. The DEC-specific load combinations are similar to the design code-based abnormal load combination; however, in the DEC-specific load combination, realistic normal-condition sustained loadings (other than the perturbing DEC effects) rather than the nominal design loadings are considered. Since the complementary design features are dedicated only to perform in case of DECs, their performance is ensured via applying the nuclear code-based limit-state design approach rather than the capacity design approach. In addition, the complementary features still need to be designed to demands due to the design basis conditions to perform their function with the expected high confidence normally achieved by following the applicable design codes.

For civil structures and passive mechanical and electrical components, design load combinations are defined in terms of the load effects multiplied by load factors. Greater-than-unity load factors are applied in the design process for sustained loads and normal operation conditions, likely to occur during the structure's economic life, in order to avoid development of the full resistance capacity under design basis events. However, unity load factors are assigned for all loading effects in case of the design process for DECs considering their lower probability of occurrence and the expectation of reasonably high confidence in performing the safety function.

The capacity or resistance to the imposed loads would be measured primarily in terms of the structural strength. The structural strength is typically determined at different levels: overall structure, structural members, and structural member's cross section. The parameters defining the structural strength are the material properties, cross sectional mechanical properties and structural configurations and layout. In the capacity design approach proposed for civil structures and supports of mechanical and electrical components, distinct elements or regions are designed and detailed for energy dissipation under severe imposed deformations induced by DECs. Such regions would undergo inelastic responses in the dominant failure mode such as flexure and shear. Introducing ductility in flexural failure mode is recommended and easier to achieve than in shear failure mode. All other regions of the structure are designed to undergo elastic behaviour, i.e., with greater strength than that induced in the inelastic regions. In summary, the proposed approach consists of:

a) Defining potential regions or elements in the structure to undergo inelastic response in case of DECs, if possible.
b) Inhibiting undesirable failure modes such as shear failure, anchorage failure or instability before the identified inelastic regions or elements undergo their ductile deformations.
c) Designing remaining regions or elements with sufficient strength to remain elastic while inelastic/ductility responses is fully activated in the identified regions.

For checking the ability of active mechanical, electrical, instrumentation and control components to perform the assigned safety functions during DECs, the required response parameters due to the perturbing effects are evaluated based on assessment of the events leading to DECs. Examples of the required response parameters include acceleration and displacement responses at the component anchor points due to natural hazard such as earthquakes or tornadoes, and temperature and pressure transient due to internal events. In defining the required response input to the component qualification tests, no additional margin other than code-based margins that are already considered for Design Basis Events (DBEs) is applied.

Experience-based qualification methods or qualification by similarity have been used in the design basis of NPPs, (EPRI, 1991). In addition, experience-based methods have been applied recently to evaluate sufficiency of built-in design margins vis-à-vis new insights for evaluated hazards. These methods provide a means of quantifying the built-in margin attributed to conservatism in current design practices. The basis for these methods is the observed performance of SSCs of heavy industrial plants in major earthquakes as well as in generic seismic test data of various equipment and components. The built-in design margin is quantified as the capacity to withstand demands induced by a specified hazard level. One form of the capacity is an independent deterministic estimate of the ability to resist a potential mode of failure during the event. Alternatively, the capacity may be represented by a probabilistic parameter, i.e., High Confidence Low Probability of Failure (HCLPF), that is evaluated in terms of a specified review level condition.

PROBABILISTIC EVALUATION METHODOLGY

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

The seismic demand and seismic capacity need to be determined for the structure or component that is assigned for seismic DECs prior to the implementation of the proposed probabilistic evaluation method. Figure 2 illustrates the probability of failure (or the complementary to survivability) considering the two main 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.

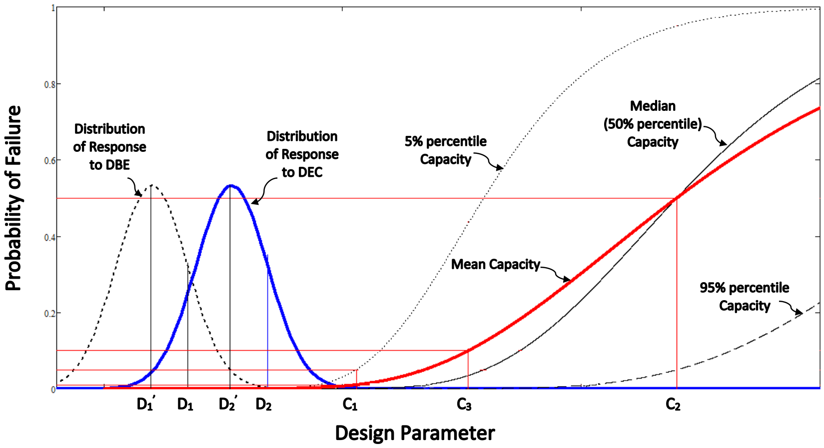

Figure 2. Frequency of failure (or survivability): demand vs. capacity

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 seismic DEC level. Two points are identified on the distribution curves:

- Point (D_1) indicates the nominal demand for the DBE (D_{DBE}), and
- Point (D_2) indicates the nominal demand for the seismic DEC (D_{DEC}).

It should be noted that the seismic demand nominally used in the design is at the 84% non-exceedance probability (mean + 1.0 * standard deviation). The mean or best-estimate demand for the DBE and seismic DEC can be seen at points (D_1') and (D_2'); respectively. The scattering of the probability distributions for the DBE and seismic DEC demands are assumed identical, although the scattering associated with the seismic DEC demand distribution is expected to be greater than that associated with the DBE demand.

To the right of the plot in Figure 2, the mean (composite) fragility function representing the seismic capacity of the structure or component is seen, demonstrating 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 mean (composite) fragility function includes both randomness and uncertainty associated with the evaluated capacity. When randomness and uncertainty are segregated, the fragility of the component or structure could be represented multiple functions such as the 5th, 50th (median), and 95th-percentiles curves.

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

- Point (C_1) indicates the capacity at which there is a 1% frequency of failure (CAP_{01}),
- Point (C_2) indicates the capacity at which there is 50% frequency of failure (CAP_{50}), and
- Point (C_3) indicates the capacity at which there is 10% frequency of failure (CAP_{10})

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) as obtained from the composite mean fragility function. The mean composite fragility function of a structure or component provides its capacity for a specific probability of failure in terms of a ground motion parameter. Inversely, the probability of failure for a structure or component may be determined for a specific capacity that could be achieved by design using its mean fragility function, (EPRI, 1994).

For evaluating the structure or components for the seismic DEC, several capacity/demand ratios can be derived from the parameters shown in Figure 2. The proposed probabilistic method is primarily based on evaluating the ratios between the CAP_{01} (or HCLPF), CAP_{50} and CAP_{10} and the nominal demand imposed by the seismic DEC (D_2). The existing design feature might be already included in the plant logic model developed for evaluating the seismic risk of the nuclear plant. In this case, both CAP_{50} (median capacity) and CAP_{01} (HCLPF) 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 method.

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

- The HCLPF capacity is sufficiently greater than the nominal demand imposed by seismic DECs. In other words, when $C_1 > D_2$, 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 $\geq 99\%$.
- The nominal demand imposed by seismic DECs (D_2) exceeds the HCLPF capacity of that feature (C_1). Then, the adequacy of the credited feature will need to be assessed. Based on this assessment, the design feature could potentially be modified and/or upgraded to enhance its capacity. Depending 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 seismic DECs might exceed HCLPF but at the same time, it might be less than the CAP_{10} capacity, i.e., $C_3 > D_2$. 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 accepted 'reasonable confidence' of performance could not be extended to scenarios of both C_1 & $C_3 < D_2$. In this case, the design features would certainly need to be modified or upgraded.
    3. The nominal demand imposed by seismic 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.

From design process perspective, the assessment of the candidate existing design feature will conclude with an adequate selected feature to perform the credited safety functions during DECs. Subsequently, the probability of survivability of that feature can be estimated using the ratios defined above. According to the lognormal distribution assumed in representing the fragility function, (EPRI, 1994), the combined variability in the fragility function accounting for both randomness and uncertainty would be estimated. For a specific demand level, the probability of failure and that of survivability could be evaluated.

Since the complementary design features, whether permanently installed or portable, are designed specifically for the nominal demands of seismic 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 above.

APPLICATION TO OPERATING CANDU PLANTS

The Canadian industry has developed guidelines on the design, procurement, installation, operation, and maintenance of design features assigned to perform safety functions during DECs, (IAEA, 2015). The guidelines follow a classification system of the design features similar to the CNSC's classification in REGDOC 2.5.2 & DIS-14-01. The classification of design features ensures functionality is not compromised during DECs while allowing alternative process for the complementary features. The industry guidelines address the use of 'commercial-grade' equipment as permanent or portable complementary design features to provide a flexible strategy to prevent and mitigate DECs and severe accident. Canadian utilities implemented modifications to existing design features and installed complementary features have been implemented to ensure provision of emergency make-up water to safety-related systems such as the primary heat transport, moderator, shield tank, steam generators, and irradiated fuel bays.

The two proposed methods were applied in the design and evaluation of three different types of SSCs to confirm their adequacy to the demands of a seismic DEC or a seismic Review Level Condition (RLC). The three SSCs are typical safety-related Civil Structures, Mechanical Components and Electrical & Control Instrumentation. The seismic RLC was defined to assess the risk due to seismic events exceeding the design basis earthquake. The peak ground acceleration of the DBE and seismic RLC defined for the existing station is 0.08g and 0.20g; respectively. The three examples represent the following situations:

(a) Construction of a new annex building to an existing safety-related structure that stores and processes heavy water.
(b) Implementing an alternative emergency heat sink supply to the primary heat transport system that altered the seismic responses of key components such heat exchanger and valves.
(c) Replacement of a switchgear hosting electrical and control instrumentation for the safety-related shutdown system.

For the annex building, the detailed design of the reinforced concrete substructure and the structural steel super-structure is carried out using Canadian design codes for safety-related structure, i.e., CSA N291 and CSA N289.1. Code-based load combinations including the DBE condition per both codes were applied. DEC-specific load combination is applied to determine the seismic demand due to the seismic RLC. Based on the deterministic design, it was concluded that the structure of the annex meets the acceptance criteria for DECs, i.e., achieving reasonably high confidence, indicating its seismic ruggedness. Applying the probabilistic evaluation method, the governing failure mode is a breakage of the foundation's rock anchors, and its HCLPF capacity is determined as 1.37g exceeding the nominal demand for the seismic RLC, i.e., 0.2g. Therefore, the annex building, is considered adequate to be credited in meeting the demand imposed by the seismic RLC, and its probability of survivability of the annex building exceeds 99%.

For the detailed design of the heat exchanger, ASME BPV code requirements are applied to all service levels including the service level C condition addressing the seismic load induced to the system due to the DBE, per Canadian design code CSA N289.3. Service level D was applied to check the stresses developed due to loading condition of the seismic DEC. The seismic load is considered in conjunction with all applicable sustained static and thermal loading conditions during this seismic event. Applying the probabilistic evaluation method, the governing failure mode is buckling of the exchanger's saddle supports. The HCLPF capacity of the heat exchanger is determined as 0.17g which is less than the nominal demand for the seismic RLC. However, the nominal seismic RLC demand is less than the heat exchanger's CAP_{10} capacity, i.e., 0.22g. Therefore, the heat exchanger is considered adequate, and its probability of survivability would be 68% in case of the seismic RLC.

Canadian design codes for safety-related structure, i.e., CSA N291 and CSA N289.1 were used to demonstrate that the anchorage of the replacement switchgear meets the demands of the DBE level. The switchgear was included in the logic model used in evaluating the plant's risk to seismic events. Therefore, the mean capacity of the switchgear and its associated combined uncertainty were already determined. Inadequate anchorage was identified as the governing failure mode of the switchgear. The HCLPF capacity of the switchgear was 0.08g, i.e., significantly less than the nominal demand of the seismic RLC. The switchgear needed to be modified and/or upgraded to enhance its survivability since even its CAP_{10} (= 0.11g) capacity is less than the demand for the seismic RLC. Engineering a modification to the switchgear and its anchorage would aim to increasing its capacity parameters. Upgrading the switchgear anchorage to the supporting floor was implemented considering the seismic RLC. The nuclear design code CSA N291 was followed in designing the upgraded anchorage. The capacity parameters, i.e., HCLPF, CAP_{10} and CAP_{50}, of the upgraded switchgear were re-evaluated. Based on the evaluated capacities, the upgraded switchgear is considered adequate, and it would have 86% probability of survivability (rather than 43%) in case of the seismic RLC.

Table 3 presents a summary of the parameters used in applying the deterministic method in designing the three investigated SSCs. Table 3 presents, as well, the parameters used in applying the probabilistic method in evaluating the three SSCs. These parameters are the HCLPF, CAP_{10}, and mean capacities for the three SSCs along with the associated combined uncertainty. All capacity parameters are evaluated in terms of the peak ground acceleration of the seismic event.

Table 3: Design & evaluation of three SSCs assigned for seismic DECs

		The Annex Building	The Heat Exchanger	The Switchgear
Deterministic design	Category	Modified existing design feature	Modified existing & Permanent complementary design features	Permanent complementary design feature
	Acceptance Criteria	Non-linear behaviour is permitted	Non-linear behaviour is permitted (Service Level D)	Checking adequacy to meet in-cabinet seismic response
	Demand	RLC is a site seismic hazard defined as 10^{-4}/year UHRS		
	Load Combination	Sustained loads (dead load only) + seismic load	Sustained loads (dead, pressure, and thermal loads) + seismic load	Seismic load only
	Approach	Capacity design	Design by analysis	Experience-based databases
	Confidence	Reasonably high	Reasonably high	Reasonably high
Probabilistic evaluation	Failure Mode	Breaking of rock anchors	Buckling of saddle support	Inadequate anchorage
	HCLPF (g)	1.37	0.17	0.08 (0.27g)*
	CAP_{10} (g)	1.90	0.22	0.11 (0.39g)*
	CAP_{50} (g)	2.87	0.32	0.17 (0.61g)*
	β_c	0.32	0.28	0.35 (0.27)*
	Probability of Survivability	99.6%	68.0%	43.5% (86.8)*

Figure 3 illustrates the mean fragility functions for three design features along with the nominal demand imposed by the seismic DEC. As can be seen, the adequacy of the annex building, the heat exchanger and the upgraded switchgear is demonstrated by comparing the HCLPF and CAP_{10} capacities to the nominal demand of the seismic RLC.

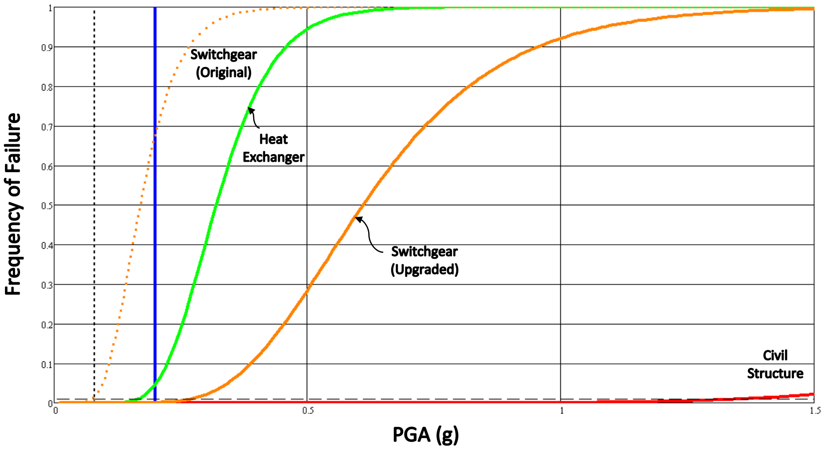

Figure 3. Frequency of failure (or survivability) for the design features

SUMMARY & CONCLUSIONS

This paper provides two methods for the design and evaluation of safety related structures, systems, and components in existing and new nuclear power plants. The deterministic design and probabilistic evaluation methods proposed to be followed in addressing the higher demands of design extension conditions are presented. The design extension conditions represent conditions and scenarios induced by accidents and natural hazards that are less probable than those considered in the design basis of CANDU NPPs. These conditions and scenarios form an extension to the conditions and scenarios defining the design basis.

To ensure the safety requirements for the design extension condition are met, the proposed deterministic design method builds on current guidelines and requirements of applicable codes and standards but at the same time recommends more relaxed acceptance criteria and application of overstrength factors based on material and sectional properties. The proposed probabilistic evaluation method is based on estimating the probability of survivability of a safety-related structure or component at the demand induced by a seismic DEC. In the probabilistic method, the fragility functions normally developed for evaluation of seismic PRA is used. 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.

Three examples for design features that were implemented in existing CANDU NPPs to meet CNSC's recommendations and action plan based on lessons learned from Fukushima accident are presented. The examples include a new civil structure, replacement of electrical and control instrumentation, and construction of a piping runs connecting two safety-related piping system to ensure continued capability for emergency heat sink during Beyond Design Basis Events. The proposed methods demonstrated the seismic ruggedness of investigated safety-related items.

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