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IMPLEMENTING DESIGN FEATURES IN EXISTING CANDU PLANTS FOR DESIGN EXTENSION CONDITIONS

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INTRODUCTION

In addressing lessons learned and recommendations from the 2011 earthquake at Fukushima, Japan, IAEA and many national regulators such as Canadian Nuclear Safety Commission have extended the plant design basis envelope to include 'Design Extension Conditions' or DECs, [IAEA's SSR-2/1 and CNSC's INFO-0824 & -0828]. The European Utility Requirements (EUR) in addressing safety during incidents and accident conditions expect accident condition outside the design basis conditions to be considered in the context of achieving defence-in-depth and risk reduction. 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 are defined to maintain safety functions during events leading to DECs. 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 are 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

While there is "high confidence" in the ability of the structures, systems and components (SSCs) to perform as designed during DBAs, SSCs are required to perform as designed with "reasonably high confidence" during DECs. Therefore, a design methodology by Saudy and Elgohary (2015) has been proposed 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 a more relaxed acceptance criteria.

This paper provides 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 (permanent or portable).

A REVIEW OF PROPOSED 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' 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 design features as assigned during DECs.

On one hand, safety related civil structures have to perform basic safety functions in the design against the demands developed during DECs. The basic safety functions for civil structures include:

- Structural integrity; i.e. overall stability, no collapse,
- 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 by the safety-related civil structures of the nuclear power plant, when subjected to design basis conditions, because the structures are ensured to experience no damage; i.e. quasi-elastic behaviour. However, for DECs, limited non-linear (plastic) response may be accepted; i.e. plastic behaviour. Leak tightness of structures containing radionuclide materials such as the containment structure and the spent fuel pools are usually fulfilled by demonstrating that specified release limits are met.

On the other hand, safety related mechanical systems and components, and safety-related electrical, instrumentation and control components have to perform the following basic safety functions:

- Safe shutdown of the reactor,
- Decay heat removal,
- Containment and confinement of radioactive material, and
- Control and maintain 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 and 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 tests. The assessment of stability and integrity of passive safety related 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 points.

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.

The proposed approach in evaluating adequacy of the design features assigned for DECs is based on determining both the demands due to DECs and the capacities of such features to resist these demands. The demands are determined deterministically due to the identified DECs. The capacities are determined deterministically considering all sources of overstrength attained by the design features during their regular design, construction, and procurement processes. In addition, 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 DECs.

Table 2 summarizes the design approach for the four groups of design features assigned for DECs. The proposed design philosophy is based on:

(a) For complementary design features, code-based design approach; i.e. nuclear design standards, are followed, and
(b) For upgrading or re-evaluating existing design features, a best-estimate capacity design approach is adopted for civil structures and passive mechanical and electrical components. For active mechanical and electrical components, an experience-based approach is adopted to demonstrate

seismic ruggedness and capability to perform in harsh accident conditions versus the demand due to DECs.

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

	Function	Design Basis Events	Design Extension Conditions
Civil structures, and passive mechanical, electrical and control systems, components & instruments	• Structural Integrity	Essentially elastic	Limited non-linearity
	• Protection & housing of systems and components		
	• Leak Tightness	DBE’s release limits	DEC’s release limits
Active mechanical, electrical & control systems, components & instruments	• Containment of radioactive material	Plant’s Technical Specifications for Design Basis	Plant’s Technical Specifications for DECs*
	• Safe shutdown of the reactor		
	• Decay heat removal		
	• Control & maintain safety functions		

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

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

** At least reasonably high confidence is achieved when national design codes are used. High confidence is achieved in case of nuclear codes are used.

The design philosophy for SSCs assigned for DECs is based on adopting the capacity design approach and the experience-based seismic and environmental qualification approaches to upgrade or re-evaluate the unmodified existing design features, as well as to SSCs of the complementary design features. The DEC-specific load combination are similar to the design code-based abnormal load combination; however, in the DEC-based load combination, realistic normal-condition sustained loadings (other than the perturbing DEC effects) rather than the nominal design loadings are considered. In addition, since the complementary design features are dedicated only to perform in case of events representing the DECs, their performance is ensured via applying the nuclear code-based limit-state design approach rather than the capacity design approach. At the same time, complementary design features are still 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.

Civil Structures & Passive Mechanical & Electrical Components

For both 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 of structures, systems and components to the imposed loads would be measured primarily in terms of the structural strength. The structural strength is determined at different levels: overall structure, structural members and cross section of the structural member. The parameters defining the structural strength are the material properties, cross sectional mechanical properties and structural configurations and layout.

To determine the responses of the structures to the demands induced by DECs, the concept of 'overstrength' factor introduced in the capacity design of structures (Pauley and Priestley) is used as a best-estimate design approach. The overstrength factor links the ideal strength to meet the required demand and the probable strength or actual capacity to be actually supplied to the structure to resist the demands. Ideal strength is normally based on nominal material properties and exact required dimensions/sizing for sections of different structural parts. Thus, for such nominal resistance to exceed the required demand, strength reduction factors are normally applied in the code-based design process. However, in reality, the probable actual strength would exceed that ideal strength due to the fact that actual material strength are normally higher than the nominal specified material strength. In addition, it is quite typical in the design process to select higher dimensions, larger rebar sizes and/or bigger section areas/inertias. The combination of the ideal strength and probable actual strength results in the overstrength in the structural design that accounts for all possible contributors to strength exceeding the required demand. Examples of such contributors include structural steel and rebars experiencing strain hardening at large deformations, and aging of concrete material. Therefore, a best-estimate capacity; i.e. the ability of the structure to resist the required demand, could be evaluated.

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 the DECs. Therefore, 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 is based on:

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

Active Mechanical, Electrical & Control Components & Instrument

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 developed scenario of events leading to the 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/checking test, no additional margin other than code-based margin (already in place for DBEs) is applied.

Experience-based seismic qualification methods or seismic qualification by similarity have been used in the design of nuclear power plants at the DBE level. In addition, experience-based methods have been applied recently to evaluate sufficiency of built-in design margins vis-à-vis new insights for seismic hazard at the plant site. These methods provide a means of quantifying the built-in margin that exists due to conservatism in current seismic 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 seismic capacity to withstand demands induced by a specified seismic input. One form of the seismic capacity for each safety-related SSC is either an independent deterministic estimate of the ability to resist a potential mode of failure during the seismic event. Alternatively, the seismic 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 earthquake.

Operating experience is an important data source establishing qualification for existing equipment during harsh environment conditions. Equipment performance information from the plant's pre-operational tests, periodic surveillance tests and continuous operation under normal conditions are used in establishing qualification for equipment exposed to similar service conditions. In some cases, these operating experience data can be analytically extrapolated to qualify for more severe service conditions. Operating experience from non-nuclear facilities can also be used.

APPLICATION to OPERATING CANDU NPPs

The Canadian industry has developed guidelines on the design, procurement, installation, operation, and maintenance of design features assigned to perform safety functions during DECs. The guidelines follows a classification system of the design features similar to the CNSC's classification described above. The classification of design features ensures functionality during DECs is not compromised while allowing alternative process for the complementary design features. The industry guidelines address the use of 'commercial-grade' equipment as permanent or portable complementary design features in order to provide a flexible strategy to prevent and mitigate DECs and severe accident.

Some examples of design features recently installed in nuclear power plants, according to G. Balog of Candu Owner Group, are shown in Figure 1. The figure illustrates implemented modifications to existing Canadian nuclear power plants 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. Both modifications to existing design features in the plant and installation of complementary features have been implemented.

In this section, three examples are presented to present the application of the proposed methodology in the design of SSCs to include the demand of a seismic RLC condition that exceed the DBE.

Example of Civil Structures

An annex to an existing safety-related structure is being constructed at one of the existing nuclear power plants to store and process heavy water. The existing structure is categorized as seismically qualified, therefore, the additional annex is also categorized as seismically qualified. The safety function associated with the structure and its annex is to maintain its structural form under seismic events, thus containing any discharge from any failed systems/components and preventing the release of heavy water to the environment.

To assess the risk to the station due to seismic events exceeding the design basis earthquake; i.e. seismic DECs, in addition to seismic qualification requirements for the annex, its seismic capacity to withstand the demands of seismic events is evaluated.

a) Modified exsiting feature

b) Modified exsiting feature

c) Permenant complementaryfaeature

d) Portable complementary feature

Figure 1: Examples of Implemented Design Features at Canadian Nuclear Power Plants

For this task, the design calculations and structural drawings of the annex are reviewed for evaluating its seismic capacity. The detailed design of the reinforced concrete substructure of the annex and the structural steel super-structure is carried out using Canadian design codes for safety-related structure; i.e. CSA N291-15 and CSA N289.1-08. Load combinations per these design code were applied for the DBE condition. DEC-specific load combinations is applied for a seismic RLC condition that exceed the DBE. Table 3 presents a summary of the approach followed in applying the DEC-based design methodology in designing the annex.

Table 3: Summary of DEC-based design of a civil structure

Category	Modified existing design feature
Acceptance Criteria	Non-linear behaviour is permitted
Demand	RLC is a site seismic hazard defined as 10^{-4}/year UHRS
Load Combination	Sustained loads (dead load only) + seismic load
Approach	Capacity design
Confidence	Reasonably high

The seismic capacity of the annex is evaluated after identifying a set of potential failure modes, including that of its rock anchors, and applying EPRI's screening criteria. Based on the seismic evaluation of the annex, 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.

Example of Mechanical Components

Improvements to plant safety and reliability are considered as part of the continued operation of nuclear power plants. One of the safety improvements recently introduced to one of the existing plants is to implement an alternative emergency heat sink supply to the primary heat transport system. This engineering modification to the existing plant is intended to address nuclear safety concerns regarding make-up capability to the primary heat transport system in the event of a Beyond Design Basis Accident.

The existing primary heat transport system and emergency cooling injection system are fully capable of performing their safety functions for Design Basis Accidents. However, emergency cooling functions need to be further enhanced in order to provide additional defence-in-depth during Beyond Design Basis Accidents to ensure sustained ability for fuel cooling. The modification is to provide a permanent pipe connection from the emergency service water system to the primary heat transport system to inject emergency water in case of specific accident scenarios. Such Beyond Design basis Accident scenarios may be treated as DECs.

In the detailed engineering design of the modification, the requirements of ASME BPV code are applied to all service levels including the service level C condition addressing the seismic load induced to the system due to the design basis earthquake. In addition, the engineering of the planned modification to the primary heat transport system and the emergency cooling injection system includes applying the demands due to a seismic RLC for the station; i.e. DECs, in the design. Service level D was applied to check the stresses developed due to loading condition of the seismic RLC. The seismic load is considered in conjunction with all applicable static and thermal loading during this event. Applicable sustained loading conditions include own weight of the integrated piping system, peak internal pressures and accident temperatures. In addition to inertia induced seismic loads during DBE and seismic DEC, seismic anchor movement of the planned modification is also applied in the design of the planned modification. Table 4 presents a summary of the approach followed in applying the DEC-based design methodology in designing the modification; i.e. the permanent piping connecting the primary heat transport system and the emergency cooling system.

Table 4: Summary of DEC-based design of a piping system

Category	Modified existing design feature & Permanent complementary design feature
Acceptance Criteria	Non-linear behaviour is permitted (Service Level D)
Demand	RLC is a site seismic hazard defined as 10^{-4}/year UHRS
Load Combination	Sustained loads (dead, pressure and thermal load) + seismic load
Approach	Capacity design
Confidence	Reasonably high

Based on the seismic evaluation of the modification, it was concluded that the planned emergency heat sink modifications meet the seismic demands of the seismic RLC representing the seismic DECs.

Example of Electrical & Control Instrument

During the regular maintenance of an existing station, temperature controllers and sensors associated with various heating & ventilation system were found to have various issues and needed to be replaced. The existing components are obsolete and exact item equivalency is not possible. The existing components were required to be seismically qualified during and after a seismic event ensure guaranteed functionality.

The new replacement of the temperature controller have to be seismically qualified to the design basis earthquake. In addition, an evaluation of the new replacement to the demands induced by seismic RLC which exceeds the DBE level; i.e. seismic DEC, is required. Therefore, a systematic approach into qualifying the replacement instruments for the DBE and to demonstrate adequacy for seismic DECs was carried out.

The systematic approach include, as applied to the seismic ruggedness evaluation of the temperature controllers, includes:

(a) Determine the in-structure-response spectrum for the floor slab supporting the panels due to the seismic RLC loading. The in-structure response spectra for the supporting floor of the panels are determined for the seismic RLC condition by scaling the DBE response spectra.
(b) Determining the mass ratio of replacement instrument to that of existing instrument. If the ratio exceed a specific criterion (10%), an evaluation to the supporting panels would be required. The mass ratio of the replacement controllers are found to be more than 10%. The replacement controllers are lighter than existing ones.
(c) Determine whether the experience-based documentation such as SQUG's Generic Implementation Procedures (GIP) provides evidence of seismic ruggedness of similar instrument/component. SQUG's GIP is found to be applicable in evaluating the temperature controllers.
(d) Review the tested panel including all the investigated instrument and other mounted instrument. The test response spectra is found to envelope the in-structure response spectra at the supporting floor level.
(e) Evaluate the required response spectra in the case of the seismic input representing the seismic RLC. The panel would have been considered unsatisfactory if the required response spectra for the seismic RLC is found to exceed the response spectra used in the original test of the panel housing the controllers. Upon review of the testing documentation, the test response spectra was found to envelope the required response spectra.

Table 5 presents a summary of the approach followed in applying the DEC-based design methodology in designing the replacement temperature controllers.

Table 5: Summary of DEC-based design of an electrical instrument

Category	Permanent complementary design feature
Acceptance Criteria	Checking adequacy to meet in-cabinet seismic response
Demand	RLC is a site seismic hazard defined as 10^{-4}/year UHRS
Load Combination	Seismic load only
Approach	Checking ruggedness by comparing against experience-based databases
Confidence	Reasonably high

Based on the implemented systematic approach, it was concluded that the replacement temperature controllers meet the seismic demands of the seismic RLC representing the DECs.

SUMMARY & CONCLUSIONS

This paper provides a review of a proposed design methodology to be followed in addressing the higher demands of design extension conditions or DECs on safety related structures, systems and components. 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 nuclear power plants. 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 design methodology 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 implementation of the proposed design methodology is presented in this paper. The paper provides 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. 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 design methodology is found to provide the needed substantiation the adequacy of both existing design features and complementary design features assigned to perform safety functions during DECs. In all three examples, seismic ruggedness of investigated safety-related items to meet DECs are demonstrated via the application of the proposed methodology.

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