GUIDELINES FOR IMPLEMENTING DESIGN EXTENSION CONDITIONS DUE TO SEISMIC HAZARDS IN CANDU NUCLEAR POWER PLANTS

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Abstract

One of the recent developments in defining safety requirements for the design of nuclear power plants, stemming from the lessons learned and recommendations from the 2011 earthquake at Fukushima, Japan, is the inclusion of 'Design Extension Conditions' or DECs in the design. Design extension conditions represent one of the categories used to define the different plant states on the basis of their frequency of occurrence, [1]. One of the main objectives for defining a set of design extension conditions is enhancing the plant's capabilities to withstand, without unacceptable radiological consequences, accidents that are more severe than design basis accidents. 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.

The Canadian Nuclear Safety Commission (CNSC) adopted the guidelines of International Atomic Energy Agency (IAEA) in extending the plant design envelope to include DECs, [1, 2 & 3]. In addition, the CNSC expects operating nuclear power plants to be seismically evaluated using updated site-specific seismic hazard. From a safety analysis prospective, the updated seismic hazard at the site of a nuclear power plant exceeding its original design basis level could be considered a design extension condition that would have potential to damage SSCs important to safety.

This paper provides a review of the Canadian regulatory requirements as well as a proposed design methodology to be followed in addressing the higher demands of seismic design extension conditions for existing CANDU nuclear power plants. The proposed design methodology builds on the current guidelines and requirements of applicable codes and standards for structures, systems and components (SSCs) but at the same time recommends more relaxed acceptance criteria and application of material and sectional overstrength factors, ensuring that the safety requirements for the design extension condition are met.

1. Introduction

Recent seismic events such as the March 2011 earthquake at Fukushima, Japan [4] and the North Anna earthquake in the eastern United States [5], where the design basis earthquake was exceeded, have heightened the public concern regarding the safety of the nuclear power plants worldwide. Such events led the nuclear regulators and the industry to re-assess the safety of existing and new power plants. During the March 2011 seismic induced tsunami event, safety systems were inundated and ability to shutdown in the Fukushima Daiichi units faced grave challenges, [6]. A nearby plant at Onagawa, that is much closer to the epicentre, experienced even higher seismic motion and survived mostly undamaged [7]. The North Anna earthquake, the largest seen to date in the eastern United States exceeded the 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 CNSC and the IAEA have stipulated the inclusion of DECs in the design, analysis and operation of these plants, see Figure 1.

According to IAEA guidance, [1], design extension conditions represent one of the categories used to define the different plant states on the basis of their frequency of occurrence. DECs has been addressed in Canadian regulatory guidance and documentation, [8]. According to CNSC’s guidance, 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, [9]. On the other hand, it has not been fully developed in the code and standards governing a range of subject areas, including design, analysis, construction, operation, procedures and radiation protection of nuclear power plants.

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 more severe than design basis accidents. 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><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 States, [9]

This paper provides a review of the Canadian regulatory requirements as well as a design methodology to be followed in addressing the higher demands of seismic design extension conditions for existing CANDU nuclear power plants. The proposed design methodology builds on the current guidelines and requirements of applicable codes and standards for SSCs but at the same time recommends more relaxed acceptance criteria compared to those for design basis conditions and material and sectional overstrength factors, ensuring that the safety requirements for the design extension condition are met.

2. A REVIEW of REGULATORY REQUIREMENTS for DECs

The Canadian Nuclear Safety Commission (CNSC) has recently recommended strengthening each layer of defence built in the Canadian nuclear power plant design and licensing philosophy, [3]. In particular, certain design enhancements for severe accident management – such as containment performance to prevent unfiltered releases of radioactive products, control capabilities for hydrogen and other combustible gases, and adequacy and survivability of equipment and instrumentation – need to be evaluated and implemented wherever practicable.

According to CNSC's guidance [8 and 9], BDBAs are grouped into two broad consequence categories based on the outcomes of deterministic analyses and the impact on regulatory safety goals:

a) Events where no severe fuel degradation occurs, and
b) Events where severe fuel damage occurs.

The former group of events is fully covered by the DECs while the latter group of events represents severe accidents that are considered practically eliminated conditions. It should be noted that DECs could include severe accident conditions. The spectrum of initiating events that can lead to a BDBA that would be extended in the design includes:

- internal initiating events caused by random component failures and human error;
- internal hazards; or
- external hazards, both natural and human-induced, but non-malevolent.

By extending the DECs to the plant design envelope of the broad range of accidents considered in the design in order to meet dose acceptance criteria and probabilistic safety goals, the safety systems, safety support systems, and complementary design features are required to fulfil their functions during the DECs. Therefore, the DECs encompass plant states, conditions and events, including external events, as well as those involving the reactor, or the handling and storage of the irradiated fuel.

From the CNSC guidance [8 and 9], it is understood that the consideration of DECs in the design process of the plant would be carried out in accordance with 'best estimate' methodology. Therefore, a best estimate approach may be used when designing the features assigned to meet the safety objectives during DECs. The best estimate approach should consider the following:

- the probable plant conditions existing prior to the BDBA;
- the severity of the DEC, and the consequential impact on plant SSCs and response capability;
- the treatment of uncertainties consistent with "reasonable confidence"; and
- the application of Review Level Conditions when external hazards are possible.

While for DBAs, there is "high confidence" in the ability of the SSCs to perform as designed, in the DECs, the SSCs are required to perform as designed with "reasonably high confidence." To achieve that reasonably high confidence through the best estimate approach, both DECs and the rules stipulating the design, inspection, maintenance of SSCs intended for use during DECs should be adequately selected.

3. DESIGN RULES for DECs

In addressing challenges and for restoring and maintaining safety functions, the overall strategy for DECs needs to be clearly defined, including the roles of plant assigned design features to reduce the risks. The strategy should be based on deterministic and probabilistic methods, operational experience, and engineering judgment, [9]. The design features considered in the prevention or mitigation of DECs should include the following:

i. capability to delay or arrest the progression of an accident;
ii. provisions to ensure integrity of containment and containment systems;
iii. shielding provisions to support mitigation strategies; and
iv. provision of equipment or instrumentation used in Severe Accident Management.

3.1 Design Features for DECs:

The design features for DECs would belong to either: (i) the existing plant design features that are assigned to address design basis accident (DBA) conditions, or (ii) a set of complementary design features dedicated to the challenges due 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, [9]. The complementary design features would be one or more of the following design measures:

- modifications and/or enhancement to existing design features,
- permanently engineered systems, and
- portable equipment.

Therefore, there are four groups of design features that are assigned to meet the safety objectives during DECs:

i. Existing SSCs,
ii. Upgraded existing SSCs,
iii. New permanently installed SSCs, and
iv. New portable equipment to be interconnected to SSCs.

3.2 Design Acceptance Criteria:

While for DBAs, the design requirements for safety systems are very conservative to ensure “high confidence” in performing their safety functions, the primary principle in meeting the safety objectives during DECs is to provide “reasonably high confidence” that SSCs will operate as intended. In turn, proportional design objectives should be established for the SSCs that may be used during DECs; i.e. the design features for DECs. In other words, the normal criteria and rigour applied for DBAs might not be appropriate when considering DECs. As an exception to this rule, it is paramount to emphasize that the integrity of the plant design basis is maintained and never to be compromised by any modification to the plant in implementing such design features.

Since the guiding principle for DECs is to provide "reasonably high confidence" that SSCs are capable of operation as intended, the normal criteria and rigour applied in designing SSCs for DBAs would not be applicable when considering DECs. Therefore, in addressing challenges due to DECs, engineering judgment should be used to apply an adequate degree of conservatism to provide reasonable confidence in case available knowledge is insufficient.

3.3 Design Rules for Structures, Systems & Components:

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 and do not specify any acceptance criteria for their performance during DECs. The question facing designers of new nuclear power plants and reviewers of existing nuclear power plants would be whether these codes could still be used in designing the four groups of the design features assigned to meet the safety objectives during DECs. To methodologically address the demands developed and 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 reasonable confidence that the intended safety functions would be performed by the design features as assigned during DECs.

On one hand, safety related structures have to perform basic safety functions in the protective design against the demands developed during DECs:

- Structural integrity; i.e. overall stability, no collapse.

- Containment of radioactive material or leak tightness;
- Protection of housed-in safety related systems and components from induced harmful effects;

These safety functions are generally fulfilled by the safety-related 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, structural damage, short of structural collapse, may be accepted; i.e. plastic behaviour. A summary of the acceptance criteria for fulfilling the safety functions assigned to Civil structures is presented in Table 1.

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 of a nuclear power plant:

- Safe shutdown of the reactor,
- Decay heat removal, and
- Containment and confinement of radioactive material,
- Control and maintain containment, cooling, and shutdown functions.

Therefore, safety related systems and components, even when protected by properly designed structures, need to be checked regarding their stability and functionality, considering the vibrations and pressure and thermal transients developed during DECs. To fulfil their safety requirements, the checking of the level of their transient responses; i.e. acceleration, velocity, displacement or stress, must be performed for the whole frequency range of interest. For many types of systems and components; especially instrumentation and control components, qualification is generally carried out by means of tests. The assessment of stability and integrity of 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. The acceptance criteria for fulfilling the safety functions assigned to Mechanical, Electrical, Instrumentation and Control systems and components is summarized in Table 1.

Table 1: Acceptance Criteria for Safety related Structures, Systems & Components

Function	DBEs	DECs
Structural Integrity	Elastic	Plastic
Protection of safety related systems and components	Elastic	Plastic
Containment of radioactive material	Qualified	Checked
Safe shutdown of the reactor	Qualified	Checked
Decay heat removal	Qualified	Checked
Control, monitor & maintain safety functions	Qualified	Checked

4. PROPOSED DESIGN METHODOLGY for DECs

The proposed approach to be followed in evaluating the adequacy of the design features assigned to fulfil safety functions during the DECs is based on determining both the different demands due to the DECs imposed on the design features and the capacities of such features to resist these demands. The demands are evaluated deterministically in terms of the parameters defining the identified DECs. The capacities are determined considering all sources of overstrength attained by the design features during the regular design, construction, and procurement processes.

The demand on safety related SSCs 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. For Civil structures and 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 design basis events, likely to occur during the structure's economic life, in order to avoid development of the full resistance capacity under design loads. 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 reasonable confidence in performing the safety function.

For checking the ability of the 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 from assessment of the developed scenario of events. 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. No amplification factor is applied in defining the required response input to the component qualification/checking test.

The capacity or resistance of SSCs to the imposed loads would be measured in terms of primarily 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 the DECs, the concept of 'overstrength' factor introduced in the capacity design of structures, [10], is used as part of the 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 section design. Thus, for such nominal resistance to exceed the required demand, strength reduction factors are normally applied. 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 proposed for 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 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 undergo their ductile deformations.
c) Design remaining regions with sufficient strength to remain elastic while inelastic/ductility responses is fully activated in the identified regions.

The proposed design philosophy for the SSCs assigned safety functions during DECs is based on adopting the capacity design approach to upgrade or re-evaluate the 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.

With regard to checking for the ability of the mechanical, electrical, instrumentation and control components to perform the assigned safety functions during DECs, records of the components testing should envelope the required response parameters. As in the case of seismic qualification for the design basis conditions, results of similarity with past performed tests and experience-based seismic qualifications can be used to ensure the success of SSCs functionality during DECs.

5. CASE OF SEISMIC INDUCED DECs:

The seismic design and analysis of safety-related SSCs need the definition of a set of design parameters and criteria. This set of parameters include level (frequency) of seismic hazard, ground response spectra representing such seismic hazard, material damping ratios, and the acceptance stress level. The definitions for these parameters for the design basis earthquake (DBE) level follow the regular nuclear design codes and standards; e.g. CSA N289, ASCE-4, EUR, etc. In order to consider seismically induced DECs in the design, a similar set of parameters needs to be defined in light of the expected confidence level per the design rules explained earlier. Table 2 provides the design parameters for the DBE and DECs.

Table 2: Seismic Design Parameters for DBE and DECs

	DBE	DECs
Earthquake Level Frequency	Design Basis Earthquake[1] (10^{-3}-10^{-4}/year)	Review Level Condition[2] (10^{-4}-10^{-5}/year)
Ground Response Spectra	Standard Design GRS[1]	Site-Specific UHRS[2]
Foundation Conditions	Standard-based[1]	Site-Specific-based[2]
Damping	Standard-based[1]	Capacity-based[3]
Stress Level	Level C[1]	Level D
Confidence	High	Reasonably high

[1] Per CSA N289 standards for seismic qualification of nuclear SSCs
[2] Site-specific and plant specific parameter
[3] Damping ratios as defined in EPRI NP-6041 [11] and SQUG's GIP [12] for seismic capacity evaluation

6. CONCLUSIONS

This paper provides a review of the regulatory requirements as well as a proposed design methodology to be followed in addressing the higher demands on safety related structures, systems and components of 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. The review of the Canadian regulatory requirements covers recently issued guidance and the expectations of the regulatory body in implementing design modifications to increase the robustness of existing nuclear power plants. 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.

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