CONSIDERATIONS AT BEYOND DESIGN-BASIS PHENOMENON DESIGN FOR NEW NUCLEAR POWER PLANT
Seismic and Tsunami

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ABSTRACT

Even though in the past 30 years, Beyond Design-Basis Phenomenon Design (BDPD) for a nuclear power plant (NPP) has been considered as one of the design commitments for the safety and function goals, a compromise inevitably takes place on BDPD during the detail engineering design. There are several factors that lead to this situation: (1) the need for more clear and specific regulatory requirements, (2) the lack of thorough investigation and research on this subject, (3) the need for clarity of industrial codes and standards and (4) economic considerations. From a technical and design practice point of view, this paper analyzes the essential part of BDPD for a new NPP in present time, and attempts to give insights on the following aspects: (1) new considerations of BDPD on current new NPP projects – lessons learned from the Fukushima accident, (2) a systematic re-thinking of BDPD by re-examining the basic philosophy and methodology used in the old design and (3) recommendations for a new approach to BDPD design practice that is more reliable, reasonable and economic.

INTRODUCTION

Consideration of Beyond Design-Basis Phenomenon Design (BDPD) is not a new topic; it was treated as part of the Beyond Design-Basis Accidents consideration and mitigation design throughout the history of the nuclear power industry[4], [5], [6]. From this standpoint, BDPD in the past was more focused on equipment and system design, which in fact dominated the old design approach. The Indian Ocean tsunami (Dec. 26, 2004) and the Fukushima earthquake and tsunami (March 11, 2011) followed by the Fukushima Daiichi accident illustrated the hidden potential vulnerability in existing NPP design. In any new NPP design and existing NPP service work, fundamental design requirements of the essential parts of any structure and its related civil scope needs to be designed to comply with a commitment focused on safety for nuclear power plants, and the protection of people and the environment[1], [2], [11]. This paper is a preliminary research summary on BDPD, primarily focused on the BDPD aspects of seismic events and the related tsunami impact on nuclear power plants. The summary is based on an investigation of the beyond design basis seismic event and tsunami loadings and their impact to safety-related nuclear shielding structures of the NPP, and how failure of such structures impact the safety features of the plant and the safety functions of the systems and equipment. In addition, this paper covers ways to reduce the impact and mitigate the consequences of a certain accident by pre-incorporated measures in the structural design.

10CFR Part 50 Appendix A [3] General Design Criteria 2 – Design bases for protection against natural phenomena states: “Structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) appropriate consideration of the most severe of the
natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena and (3) the importance of the safety functions to be performed”. Regulatory Guide 1.53[4] describes the application of the single-failure criterion to safety system in NPP based on the requirements presented in IEEE Standards. Regulatory Guide 1.203[5] describes transient and accident analysis methods which are set forth to deal with design basis accident conditions. NUREG-0800 SRP 3.11[6] gives details on how to cope with environmental qualification of mechanical and electrical equipment. In a U.S. Department of Energy (DOE) Report to the Secretary of Energy - “Review of Requirements and Capabilities for Analyzing and Responding to Beyond Design Basis Events” (Aug. 2011)[2] states DOE has detailed criteria and guidance supporting implementation of requirements for design basis accidents, but it does not have similarly detailed design criteria and guidance for beyond design basis events. American Nuclear Society (ANS) and IAEA published a series of standards and requirements which covered areas from the design basis accident design analysis to post accident management measures. ASME code[7] and IEEE standards set forth detailed provisions and criteria on critical structures, systems and components design under design basis accident conditions which are designated as seismic design category I (SDC-I), but no further detailed requirements are set forth for SDC-I SSCs design and qualification under BDPD conditions.

CONSIDERATIONS ON BDPD – Lesson learned from Fukushima Accident

• A Review of Fukushima Accident

On March 11, 2011, a 9.0 magnitude earthquake occurred at Tōhoku Fukushima, with the epicenter near the island of Honshu. It resulted in maximum ground accelerations of 0.56, 0.52, 0.56 g (5.50, 5.07 and 5.48 m/s²) at Fukushima Daiichi Units 2, 3 and 5. These values are above their designed tolerances of 0.45, 0.45 and 0.46 g (4.38, 4.41 and 4.52 m/s²) respectively, but are within the design tolerances for Units 1, 4 and 6. When the earthquake occurred, reactors Units 1, 2 and 3 were operating, while Units 4, 5 and 6 had already been shut down for periodic inspections. Units 1, 2 and 3 underwent a successful automatic shutdown (called SCRAM) when the earthquake struck[14],[15].

When the reactors shut down, the plant stopped generating electricity, which is the normal source of power for the plant. Tokyo Electric Power Company, Incorporated (TEPCO) reported that one of the two connections to off-site power for Reactors 1 to 3 also failed so one to three on-site emergency diesel generators began powering the plant's cooling and control systems. There are two emergency diesel generators for each of the Units 1–5 and three for Unit 6[14].

The earthquake was followed by a 13–15 m (43–49 ft) maximum height tsunami arriving approximately 50 minutes later which topped the plant’s 5.7 m (19 ft) seawall, flooding the basement of the turbine buildings and disabling the emergency diesel generators located there at approximately 15:41. At this point, TEPCO notified authorities, as required by law, of a “first level emergency”[14].

• Accident root cause analysis

From the consequence point of view, the Fukushima NPP event is considered a typical nuclear accident. The real reasons – also called “root causes” that led to this accident are fundamentally different.

(1) Actual Earthquake vs. Design Basis earthquake (SSE)
Based on the historical records, the Northeast Japan Fukushima earthquake was rated as the fourth strongest earthquake in history. It was a mega-thrust type earthquake with a Richter magnitude of M9.0. The total energy released was 9.32 Tiga-tons of TNT, and which lasted almost six minutes. The accompanied ground peak acceleration was 3.0g. Table 1 provides the comparisons between the design seismic criteria for Fukushima NPP and the actual values resulting from the Northeast Japan Fukushima earthquake\[14\].

Table 1 Comparison of seismic design values to actual values from the earthquake

<table>
<thead>
<tr>
<th></th>
<th>(1) Fukushima Design SSE</th>
<th>(2) Actual Value</th>
<th>Comparison = (2)/(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Earthquake (Magnitude)</td>
<td>8.6</td>
<td>9.0</td>
<td>$10^9/10^8.6 = 2.512$</td>
</tr>
<tr>
<td>Energy Released (Unit: Joules)</td>
<td>$10^{1.5\times8.6}$</td>
<td>$10^{1.5\times9.0}$</td>
<td>$10^{1.5\times9.0}/10^{1.5\times8.6} = 4.0$</td>
</tr>
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From the above table, we can conclude that the original Fukushima seismic design – SSE value M8.6 is almost adequate if measured from the scale of the Richter magnitude; the 2.5 difference in magnitude can be justified by cumulative multi-conservatism in the engineering design process, which range from material strength determination, design load evaluation and load combination, to analysis and detail design, etc.

Hence, it is concluded that the damages sustained at Fukushima Daiichi were primarily related to energy releasing, transferring and dissipation among the structures, systems and components (SSCs), because there is a four times energy absorbing difference between actual demand and the design capacity. Further investigations are needed to address the interaction among SSCs on the aspects of energy releasing, absorbing and dissipation. As is well known, current structural codes primarily focused on addressing the nature of structural energy from releasing to dissipation; while mechanical and system codes mainly focused on addressing the same matter of component and system.

(2) The immediate emergency response of reactor and systems

When the earthquake occurred, the operating reactors Units 1, 2 and 3 of Fukushima Daiichi underwent successful automatic shutdowns\[14\]. Therefore, the design feature and function of safety-related systems and equipment responded promptly and appropriately, and the reactors smoothly experienced a beyond design basis SSE event.

Due to the loss of off-site power supply, the Daiichi Units 1 to 3 reactors’ on-site emergency diesel generators began powering the plant’s cooling and control systems (there are two emergency diesel generators for each of the Units 1 to 3). The emergency core cooling system backup power source functioned properly.

(3) Response due to tsunami caused by earthquake
Up to this point all the designed safety functions for emergency responses were performed successfully. When the systems reached a stabilized state, all affected reactors would have undergone a controlled safe shutdown condition, and Fukushima Daiichi would have survived a beyond design basis earthquake. However, the evolvement of the Fukushima event was totally changed by the subsequent tsunami. As previously stated, the earthquake was followed by a 13–15 m (43–49 ft.) maximum height tsunami arriving approximately 50 minutes after the quake that topped the plant’s 5.7 m (19 ft.) seawall, flooding the basement of the turbine buildings and disabling the emergency diesel generators located there.

(4) Subsequent emergency response of equipment and systems

As a result of the huge wave run-up height (initial impact from tsunami), all external emergency equipment and systems were flooded. The post impact due to high level inundation (height and depth), destroyed all the facilities and disabled all external and internal equipment and systems. At this point, a "first level emergency" was declared. The following was a comparison of design values to recorded data:

| Design Site Ground Level: +10 m |
| Design (Predicted) Maximum Water level caused by Tsunami: 5.7 m |
| Actual Inundation Height: +15 m |
| Actual Inundation Depth: +5 m |
| Wave Run-up Height at Fukushima Daiichi NPP: 14 – 15 m |
| Maximum Wave Run-up Height of Tsunami event: 40 m or 133 ft (in Miyako, Iwate and Tōhoku) |

(5) Root cause analysis and lesson learned

**Background**

Fundamentally different from the Chernobyl and TMI accidents, Fukushima Daiichi was an accident caused by extremely infrequent powerful events of the nature (we categorize this type of external loading conditions on NPP as Beyond Design-basis Phenomenon loadings). Due to the unexpected magnitude of power, these very infrequent nature phenomenons are always named disasters. Even though urban and commercial structures/facilities design do not consider resisting such type of disasters, NPP designs have to take them into account. A natural disaster must not lead to another disaster which potentially could be even worse.

Relying on the advance of technology, design/analysis approaches, tools, and the experiences/lessons learned in the past half century, nuclear reactors and their related systems and equipment are currently being designed and fabricated in highly reliable quality standards. Most of these systems and equipment such as indoor-machines are shielded by structures or structural systems, which perform the following essential safety-related functions: (1) to provide appropriate internal ambient conditions, (2) to provide a reliable anchorage baseline, and (3) to protect them from any possible impact internally and externally due to environmental or human-induced influences.

This paper points out that for a NPP, the well-designed reactors, systems and equipment with high reliability do not certainly ensure that the whole NPP is absolutely safe. In fact, the plant shielding structure’s design (the layout, design analysis, installation and construction) and its safety-related functions all play their parts to determine the ultimate safety features of the NPP. The Fukushima Daiichi accident revealed this hidden root cause embedded in old codes and approaches, and caused us to consider new standards and methods which will include the BDPD, and re-define the design safety roles.
of structural and civil related scopes to achieve a comprehensive higher standard for NPPs under the beyond design-basis loading and accident condition.

Lesson learned from Fukushima Accident

- Fukushima Daiichi was a beyond design-basis accident. The beyond design-basis earthquake, and subsequent high level tsunami led to the accident conditions.
- The concept of the existing NPP design based on design-basis accident conditions needs to be reconsidered to integrate BDPD philosophy.
- BDPD may not only deal with one phenomena at a time. It is highly possible that two disasters may occur at very close intervals.
- For coastal NPPs, the emergency power source and emergency make-up cooling systems should be located and protected from the potential impact of a tsunami and subsequent flooding.
- Aside from the improvement of the primary containment design, the secondary containment or reactor overall building design should be improved to retain the released radioactive gases and contained hydrogen explorations.

The Fukushima II plant, which was also struck by the tsunami, had incorporated design changes that improved its resistance to flooding and to consequently sustain less damage. Generators and related electrical distribution equipment were located in the watertight reactor building, so that power from the grid was generated by midnight. Seawater pumps for cooling were also given protection from flooding.

RE-THINKING OF BDPD

- A review of philosophy and principle rules (NPP structural)

Even though in reality the BDPD covers a relatively wide area, the primary reason for conducting a BDPD is to determine the maximum magnitude (the severity) of impacting natural phenomenon (which is defined as beyond design phenomenon in this paper.) In the old design philosophy, maximum design seismic input and tsunami criteria are all defined by using a conventional method called “deterministic methodology.” In this method the maximum design input values that served as the “design basis” are determined based on an evaluation of local/regional historical records. A credibility study is performed for determining the maximum values, but it is just an application of simple sampling and a statistics method. Thus, the resulting design input data are highly independent, and with inherent random nature. This is why such design basis values can be exceeded even during 40 years of NPP service life.

To mitigate this issue, probabilistic methodology was recommended in the past decades. Much research was conducted in this area starting from addressing the probabilistic safety assessment (PSA) on reactors, equipment and systems, etc. The application of PSA on structural systems, components and civil facilities was adopted later and evolved in probabilistic risk assessment and probabilistic seismic hazard assessment (PHSA) to address the improved determination of a control earthquake (maximum earthquake for using as design basis input as mentioned above). However, due to the complexity of the PSA application in structural and civil areas, most of the cases are dealing with issues of seismic margin assessment (SMA) for existing NPPs (such as the IPEEE program for U.S. domestic NPPs requested by NRC in the 1990s.)

Consideration of economic issues is related to regulations and regulatory requirements.

- Compliance among codes/standards
It is well known that the key codes/standards design philosophy for NPP design are largely classified into elastic design (working stress method) and strength design (plastic method). As one of the main stream design codes for NPP, the ASME code [7] is based on working stress methods for all of its design practices; meanwhile current ACI-318 and ACI-349 codes for NPP are based on strength design methodology. Even though ACI-359 reconciled ACI-349 to ASME code, and set forth design criteria, standards for nuclear concrete structures, there is not complete compliance and reconciliation of these two codes. Load determination and combination in both codes are still rooted from the deterministic method. Mitigating the cracking state of concrete in nuclear structures, especially when it is composited or integrated with mechanical structures/systems is still not well known. Recent ASCE codes (such as ASCE-43[9]) tend to make the transition from the deterministic method to the probabilistic approach, and some provisions are well-worthy of being used as examples for other nuclear codes/standards transition to unified nuclear power codes/standards. When such standards/codes are established and agreed on as common practices for NPP design, BDPD for NPP will be found as the best approach in new plant design.

- **The transition from deterministic method to probabilistic method for BDPD**

BDPD, due to its highly improbable nature, from a practical and economic point of view, the fully adoption of probabilistic methodology is the best way to address and present almost all types of issues for beyond design basis considerations. The transition from deterministic method to probabilistic could be in a stepped approach, i.e., from a safety margin based analysis, then a probabilistic risk assessment (PRA), to an incorporation of probabilistic seismic hazard assessment (PSHA) and lastly a complete probabilistic safety analysis and assessment (PSAA) which is appropriate, valid and reliable for new NPP design.

**CONCLUSIONS and RECOMMENDED APPROACH FOR BDPD - STRUCTURAL PRACTICES**

- **Consideration of BDPD under current codes and standards provisions (downstream approach)**

Since from a structural design point of view, BDPD is essential to evaluate the input loadings and valid load combinations. These are appropriate to size and design of the NPP structures, systems and components to survive beyond design basis loading conditions. BDPD design for NPP can be considered by a means of up-scaling the design basis loading conditions (i.e. increasing the design basis loadings by a certain percent - such as 50%) to increase the existing design margins defined for design basis loading/or design basis accident condition. In this way, the plant SSCs obtained an extra capability to resist BDPD loadings. Since this capacity is acquired by a simple way of scaling to increase the design margin, the total target performance goal (often defined as an annual frequency) of the SSCs to resist beyond-design basis loading might remain unimproved, and in many cases a design validation check is required.

- **Consideration of BDPD by means of design verification (quasi-approach)**

BDPD design verification is an improved or quasi-BDPD approach by the way of using current cutting-edge techniques to address BDPD. As stated previously, before the fulfillment of the full transition of current code from deterministic method to probabilistic approach, the most economic way to perform a BDPD design is to indirectly apply the PRA and PSHA method in the determination of beyond-design basis input loadings conditions. In another words, first determine the design-basis loading condition or design accident loading condition by the PRA or PHA method, then scale these results based on the target annual exceedance frequency of acceptable performance to get beyond design basis inputs. This two-step approach is fully based on well-established techniques (PSA, SMA, SPHA and PSHA) for
basic probabilistic method application, while still using the current code’s requirements and design criteria to accomplish BDPD. Further information can be found in many BDPD-related literatures and references.

- **A realistic BDPD approach (upstream approach/source approach)**

  A realistic BDPD approach means a comprehensive and fully integrated probabilistic methodology for BDPD. The reason to describe it as an upstream approach is that this method is recommended in order to resolve the issue by returning to its source. Fundamentally speaking, BDPD is the same as that of design-basis phenomenon design (DPD); since beyond design-basis phenomenon design actually is an engineer-defined design loading limit to cope with engineering design challenges and economic issues. It keeps changing with the advancing of (1) material technology, (2) engineering analysis and design philosophy, and (3) construction techniques. So a realistic BDPD approach from the authors’ point of view is a method in which all previously stated aspects (1), (2) and (3) are coming together under the comprehensive and fully integrated probabilistic principles.

**REFERENCES**

[6] NUREG-0800, Standard Review Plan (SRP), Section 3.11
[7] ASME Boiler and Pressure Vessel Code Section III
[10] NRC Regulatory Guide RG 1.29 “Seismic Design Classification”
[11] NUREG-0800, Standard Review Plan (SRP), Section 2.4.6