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DESIGN BASIS VS. BEYOND DESIGN BASIS CONSIDERATIONS FOR OPERATING PLANTS

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ABSTRACT

Based on the lessons learned from the Fukushima Accident (2011), U.S.NRC has issued various information requests requiring plant licensees to evaluate the current design to evaluate and cope with beyond design basis external events (BDBEE) (seismic, flooding, tsunami, etc.), provide mitigation strategies (FLEX) for responding to loss of offsite power, enhance emergency preparedness, etc. In response to the U.S.NRC orders, nuclear plants are having to make improvements/modifications to plant structures, systems, and components (SSC's). Since these modifications are being implemented in response to BDBEE, the design criteria may be different than those required for the plant design basis events (DBE).

In this paper, typical examples of BDBEE would be presented highlighting the differences in the design/evaluation criteria between DBE and BDBEE. The examples include beyond design basis seismic and flooding events. The treatment of these two events are quite different given that the available plant margins in resisting these events are different. In the case of earthquake loading, plant structures, systems, and components typically have redundant load paths and margins are substantial. However, flooding may pose a possible "cliff edge" effect, meaning a small increase in postulated flood height could cause a dis-proportionate increase in plant equipment failure.

The paper also addresses the different criteria used in evaluating plant SSC's to perform their intended safety functions following a BDBEE, and those features of the plant deployed for mitigating the effects of a BDBEE.

INTRODUCTION

Design Basis (U.S.NRC 2014b) means that information which identifies the specific functions to be performed by a structure, system, or component (SSC) of a facility, and the specific values or ranges of values chosen for controlling parameters as reference bounds for design. The reference values may be based on the state-of-art of the subject matter. They could also be based on analysis of the consequences of the postulated design basis accident for which the plant must remain functional. *Design Basis Events* (DBE) are defined (U.S.NRC 2014a) as conditions of normal operation, including operational occurrences, design basis accidents, external events, and natural phenomena for which the plant must be designed to ensure safety functions.

The regulatory philosophy in the US has been to hypothesize certain maximum credible events/accidents and their consequences and then require defense-in-depth measures to guard against them. The maximum credible accidents were then used to define design basis events and in turn used to determine parameters for the design of Systems, Structures, and Components (SSC's). Following accidents at TMI and Chernobyl, the U.S.NRC and other regulatory agencies in the world started to address plant events and occurrences beyond the plant's design basis. That was the genesis of beyond design basis which simply stated refers to any event that either exceeds the bounds of the original design basis or was not previously considered. Beyond design event could be either an internal event or an external event. The focus of this paper is on beyond design basis external events (BDBEE).

A BDBEE has characteristics that could challenge the design of SSC's and lead to potential loss of critical safety functions. The exceedance (over design basis values) could be minor or major. An example of a minor exceedance is the Mineral, Virginia, USA earthquake that affected North Anna Nuclear Plant (August 2011). The tsunami that followed the Great East Japanese (GEJ) Earthquake of March 2011 is an example of a major (significant) increase over the design basis.

There are several reasons why we are having to deal with BDBEE. Firstly, we have lot more data now than when the plant was designed several decades ago. This is certainly the case with earthquakes. Improvements in the state-of-art of performing hazard analysis (probabilistic as opposed to the traditional deterministic approach) has enabled us to better account for uncertainties in the various parameters affecting the definition of the event. Advances in numerical simulation and super computers have made it possible to solve more complex algorithms.

This paper describes the commonly used approaches in dealing with BDBEE and includes two specific examples, seismic and flooding and another example of a general mitigation approach intended to deal with any BDBEE.

PROTECTION VS. MITIGATION

Any BDBEE evaluation typically would involve the following basic steps:

- Hazard Analysis
- Plant Response Analysis
- Evaluation of Plant Capability
- Enhance Plant Capability (if required)

The BDBEE evaluation could be performed using either deterministic or probabilistic methods. The current trend in the industry is to use probabilistic methods and guidelines and standards (ASME/ANS 2013) that exist to perform them.

The approaches to enhance plant capability to deal with BDBEE involve protection, mitigation or a combination of the two. There is also the option of doing nothing and decommission a plant, based on economic and political considerations.

Protection involves ensuring the SSC's that are required for safe cold shutdown of the plant are adequately designed for the consequences of a BDBEE. This does not, however, mean that the same design criteria used for the DBEE also need to be used for BDBEE. Typically, High Confidence Low Probability of Failure (HCLPF) capacity values would be used for BDBEE as opposed to code allowable values used for DBEE.

Mitigation is based on the philosophy that not all of the plant SSC's required for cold shutdown would remain functional following a BDBEE, and thus other compensatory measures would be required to ensure the integrity of the reactor core and spent fuel.

Independent of specific BDBEE evaluation, all plants in the US are mandated to develop mitigation strategies to cope with extended loss of AC power and loss of ultimate heat sink following a BDBEE.

This requirement resulted from Recommendation 4.2 (U.S.NRC 2011), one of the twelve recommendations made by the U.S.NRC's Near Term Task Force (NTTF) based on the lessons learned from the 2011 Fukushima Accident. In response to this requirement, the US nuclear industry proposed the "FLEX" mitigation strategy (NEI 2012). This approach acknowledges the inherent uncertainties involved in hazard analysis, and take credit for equipment provided per the FLEX mitigation strategy. An example of the FLEX mitigation strategy is described in this paper.

CHANGES TO DESIGN BASIS

As stated in the introduction, the exceedance of a BDBEE over the DBEE may be minor or major. A minor exceedance may only require an evaluation of the plant's SSC's to cope with the BDBEE and provide any additional protection or mitigation or both. However, for those BDBEE where the exceedances are significant, the U.S.NRC has stated that they may consider potential changes to the plant's design basis. This action would be taken in Phase 2 of the NTTF Recommendation 2.1 program. At this time, no quantitative criteria have been established as to what constitutes a "significant" exceedance.

Aside from the Fukushima lessons learned programs, U.S.NRC has required a few plants to perform supplemental (BDBEE) evaluations in addition to the design basis considerations. For example, in the case of the North Anna plant, any future modification to the plant's SSC's need to consider the effects of the 2011 Mineral, VA earthquake in addition to the design basis earthquake (Virginia Electric Power Co. 2011). However, the acceptance criteria for the BDBEE are not necessarily the same as those used for DBE. HCLPF capacity values were used in evaluating for the Mineral earthquake effects.

BDBEE EXAMPLE 1 – SEISMIC

The design basis earthquake (also known as the safe shutdown earthquake or SSE) for current operating plants in the US (all designed and constructed prior to 1990) was established deterministically. The shape of the ground motion response spectra (GMRS) was based only on a few recorded ground motions from the western US. Based on subsequent recorded ground motions in other regions, it became evident that the characteristics of earthquake ground motion in the Central and Eastern United States (CEUS) are distinctly different from the earthquakes of the western US. This finding coupled with the lessons learned from Fukushima event has led to the performance of Probabilistic Hazard Seismic Analysis (PSHA) for CEUS plants (EPRI 2012). The U.S.NRC is requiring detailed seismic evaluations for those plants whose new GMRS exceeds the original design basis earthquake in the 1 to 10 Hz spectral range (represents the most damage causing frequency range of an earthquake). Typically a Seismic Probabilistic Risk Assessment (SPRA) is required, unless if the exceedances are minor (< 30%) in which case a deterministic Seismic Margin Assessment (SMA) is sufficient.

Figure 1 shows a comparison of the DBEE (Seismic) and BDBEE (Seismic) spectra for the Watts Bar Nuclear Plant located in Tennessee, USA. The design basis earthquake (SSE) for this plant is characterized by a broad band spectrum in the 2 to 7 Hz range with a peak spectral acceleration of 0.46g and a peak ground acceleration (PGA) of 0.18g. A BDBEE (Seismic) evaluation as part of the U.S. NRC Individual Plant Examination of External Events (IPEEE) was initially performed in 1998 using a review level ground motion spectrum (NUREG/CR 0098) with a PGA of 0.3g (Tennessee Valley Authority 1998). More recently an IPEEE was performed for Watts Bar for a PGA of 0.5g. The higher capacity was made possible with more refined calculations and a minor modification to the anchorage of equipment (Tennessee Valley Authority 2015). The IPEEE evaluations were performed using a Seismic Margin Assessment (SMA) methodology.

The CEUS GMRS for this plant is also shown in Figure 1. The CEUS based GMRS has a PGA of 0.37g and is dominated by high frequency content (above 10 Hz) with a peak spectral acceleration of 0.76g in the 15 to 25 Hz range. It is seen that at frequencies below 4.7 Hz, the design basis SSE is greater than the GMRS. A Seismic PRA for the plant is currently underway and is scheduled to be completed by June 2017. The figure also shows 2xSSE spectrum that was used in an interim evaluation (Expedited Seismic Evaluation Process or ESEP) of the plant as part of U.S. NRC NTTF 2.1 Seismic Program (Tennessee Valley Authority 2014). It is seen that the 2xSSE and 0.5g IPEEE spectra envelop the new GMRS in the 1 to 10 Hz range.

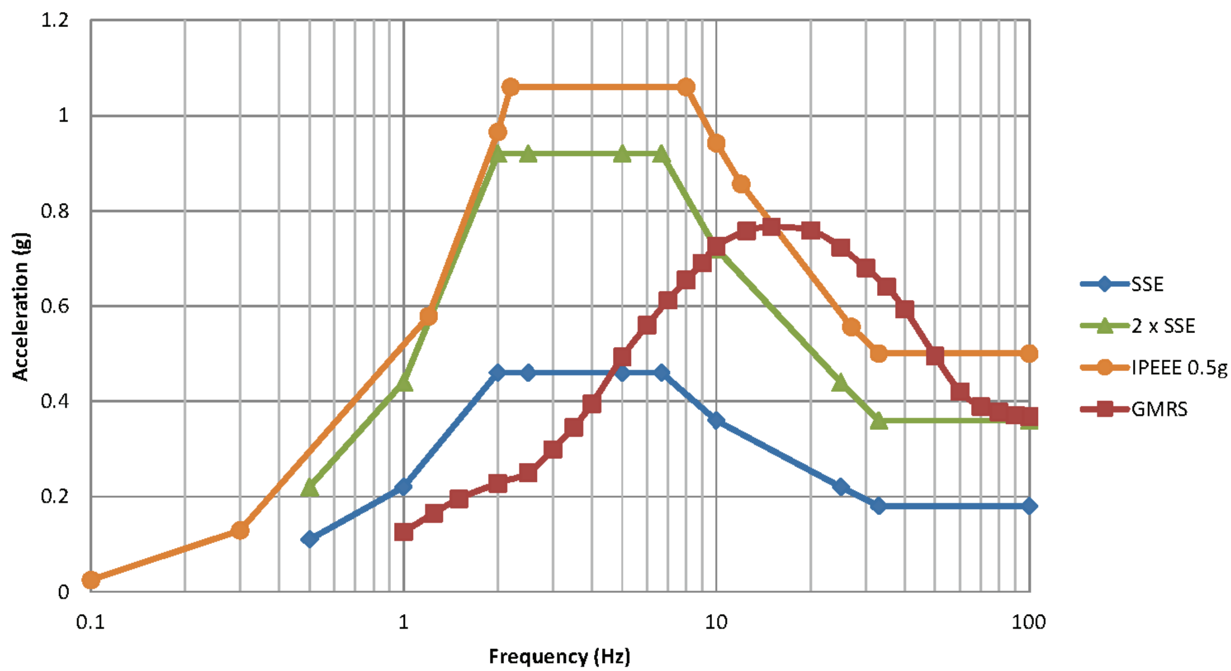

Figure 1 – Comparison of DBE and BDBEE (Seismic) for Watts Bar Nuclear Plant
(Source: TVA 2014)

There are several examples of recorded seismic BDBEE, notably the 2007 Chuetsu-oki Earthquake (Kashiwazaki-Kariwa Plant), 2011 Great East Japanese Earthquake (Fukushima and Onagawa Plants), and the 2011 Mineral Earthquake (North Anna Plant). A summary of the DBE peak ground motion acceleration (PGA) values and those recorded during the earthquake events (BDBEE) are provided in Table 1.

Table 1 – DBEE vs. BDBEE Horizontal Peak Ground Accelerations

DBE/BDBEE	K-K (Unit 1)	Fukushima Daiichi (Unit 2)	Onagawa (Unit 2)	North Anna (Unit 1)
Original Design Basis	0.28	0.18	0.38	0.18
Updated Design Basis	---	0.45	0.61	--
Observed (BDBEE)	0.69	0.56	0.62	0.27

(Acceleration values reported in units of "g")

It is worth noting that the Japanese plants were initially designed for a lower ground motion acceleration, comparable to many plants in the US. Starting in 2006, the design basis of the plants were increased to higher magnitudes, mandated by the regulatory authorities. The updated design basis values are also shown in Table 1. It is seen that the recorded PGA values (BDBEE) were significantly greater than the original design basis values but when compared to the updated DBEE values, the increases were relatively minor.

In response to the revised seismic requirements, many of the Japanese plants started to make extensive modifications to plant systems and equipment anchorages. The Onagawa plant made several modifications (as reported in IAEA 2012) to the piping, cable trays, and instrumentation. Additional protection and mitigation were either planned or already implemented following the GEJ Earthquake of March 2011. Similarly, the Kashiwazaki-Kariwa plants made extensive reinforcements (see Yamashita 2010) to plant systems and equipment following the 2007 Chuetsu-oki Earthquake and in response to the increased DBEE requirements. The updated seismic requirements corresponded to a PGA of nearly 1g (Yamashita 2010).

In contrast to the Japanese plants that experienced significant increases resulting from actual earthquake events to the original design basis seismic requirements, the Mineral, VA Earthquake of August 2011 only resulted in minor increases over the design basis at the North Anna Plant (Virginia Electric Power Co. 2011). No functional damage to any of the SSC's was reported. The plant had to make detailed evaluations and committed to providing additional seismic instrumentation to record the free-field ground motions and also committed to perform evaluation of any future plant modifications to the effects of the 2011 Mineral, VA earthquake.

Protection vs. Mitigation

From the above examples, it is seen that protection to guard against BDBEE that are significantly greater than the DBEE could involve extensive modifications. Alternatively, several mitigation strategies (that would be less costly) listed below may be pursued subject to regulatory acceptance:

- Perform a probabilistic risk analysis (PRA) coupled with a cost-benefit analysis to determine which modifications would be prudent
- Improve the seismic instrumentation systems (use of digital instruments and provision for free-field instruments even for hard rock sites)
- Early warning systems (being considered in Japan and elsewhere)
- Seismic isolation systems

For beyond design basis earthquakes, protection or mitigation alone may not be the solution, but a combination of protection and mitigation may be prudent, considering the uncertainty in the prediction of future earthquake ground motions at a site.

BDBEE EXAMPLE 2 - FLOODING

The basic hazard mechanisms considered in the determination of (original) design basis and the (current) beyond design basis floods for nuclear power plants have not changed. These include: precipitation, river flooding, storm surge, seiche, tsunami, dam failure, etc. Though the hazard mechanisms have not changed, the state-of-art of the hazard analysis and the analytical tools have significantly improved and we now have a better understanding of the flooding mechanisms and certainly more data.

The best example of a beyond design basis flooding event is the tsunami that followed the GEJ earthquake of March 2011. In the original design basis of the Fukushima Daiichi plant the tsunami height was estimated to be 3.1 m. Based on a re-evaluation the design basis tsunami wave height was revised to be 5.7 m. However, the GEJ earthquake induced tsunami resulted in wave heights of 14 to 15 m at the plant site. It has been reported that both the original and the revised design basis tsunami did not account for the historic tsunami that hit coastal Japan in 889 AD. The following lessons were learned from the Fukushima accident relative to BDBEE (flooding):

1. DBEE (or BDBEE) should not be limited to select historic events in the vicinity of the plant; it should include the entire region that could potentially impact the site.
2. Plant design should incorporate defense-in-depth features to mitigate the “Cliff Edge” effects.

In the US, a major flooding event occurred at Fort Calhoun plant in June 2011. The flooding was caused by a combination of record snowfall (> 200%) in the Rocky Mountains and record rainfall (one year worth of rainfall occurred in 2.5 weeks in May 2011). US Corps of Engineers had to release twice the normal amount of water from five dams on the Missouri River, upstream of the plant. The water level (1004 ft. or 308.5 m) at the plant was below the licensing basis (1014 ft. or 309.1 m). Thus, this event was not a BDBEE, but it did challenge some of the safety systems. Some water entered through a manhole into the intake structure and threatened the raw water pumps. Plant workers initiated several mitigating action to prevent water from impacting electrical transformers and other vital equipment (see Figure 2).

Figure 2 – Flooding at Fort Calhoun Plant (June 2011**)**
(Source: U.S.NRC 2012a)

Based on the lessons learned from the Fukushima accident, the flooding event at Fort Calhoun plant and the new plant applications, U.S.NRC required all operating plants to perform a flooding evaluation using the current regulatory guidance and standards, similar to those used by new plant applicants. If the re-evaluated flooding hazard is not bounded by the current licensing basis, those plants are required develop an integrated assessment (U.S.NRC 2012b). Figure 3 shows a schematic of the Flooding Integrated Assessment Process.

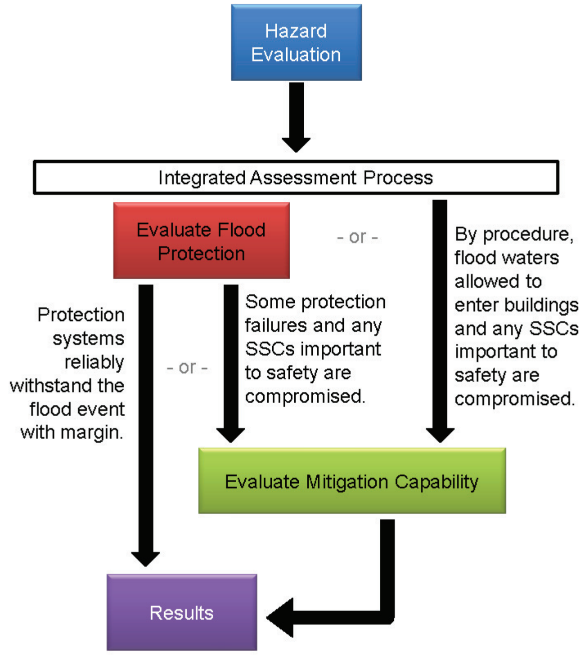

Figure 3 – Flooding Integrated Assessment Process
(Source: U.S.NRC 2012b)

The scope of the integrated assessment report includes the following elements:

1. Description of the integrated procedure used to evaluate the integrity of the plant
2. Controlling flood mechanisms and their effects on the plant, including available or planned mitigation features
3. Additional flood protection or mitigation features installed or planned
4. Any other actions taken or planned to address plant specific vulnerabilities

Integrated assessments are due two years after the submittal of the hazard evaluations.

BDBEE EXAMPLE 3 – FLEX MITIGATION STRATEGY

As stated earlier, all plants in the US have to develop a mitigation strategy to address potential loss of extended off-site power and ultimate cooling sources, so called "FLEX" strategy. The FLEX strategy supplements the protection and/or mitigation features provided to address specific BDBEE, such as seismic, flooding, etc. NEI 12-06 (NEI 2012) provides guidelines (endorsed by the U.S.NRC) for the implementation of the FLEX strategy.

In essence, the FLEX strategy consists of utilizing portable equipment that provides means of obtaining power and water to maintain or restore key safety functions for the reactors. The equipment could be either already installed equipment in the plant (Phase 1), spare equipment stored in a separate facility in the plant (Phase 2), or stored at a remote off-site facility (Phase 3). Typical mechanical equipment for a boiling water reactor (BWR) might include reactor core isolation cooling (RCIC) pumps, valves, and condenser, safety relief valves (SRV) and accumulators, RPV injection valves, etc. For a pressurized water reactor (PWR), they may include turbine driven auxiliary feedwater pump (AFW), steam generator power operated relief valves (PORV), condensate storage tank (CST), etc. The electrical equipment for BWR or PWR might include batteries, inverters, motor control centers, DC distribution panels, switchgears, relays, transmitters, etc.

The FLEX equipment needs to be evaluated for the various site-specific external hazards, including seismic, floods, high winds, etc. However, per NEI 12-06, *equipment relied upon to support FLEX implementation does not need to be qualified to all extreme environments that may be posed, but some basis should be provided for the capability of the equipment to continue to function*. The FLEX equipment (permanently installed or stored) at the plant site needs to be protected in an enclosure building that could be either an existing Seismic Category I structure, a new structure that is designed to the requirements of ASCE 7-10 (ASCE 2010), or outside a structure, evaluated for the potential adverse interaction due to failure of seismically non-rugged equipment or structure.

Figure 4 shows the FLEX Equipment Storage Building (FESB) at the Watts Bar Nuclear Plant in Tennessee, USA. The FESB houses equipment that would be used in Phase 2 of the plant's FLEX strategy. It includes: diesel generators, portable pumps, hose couplers, tow vehicles, light stands, debris removal equipment, etc. The structure is designed to with stand postulated external events, including tornado wind and tornado-generated missiles, seismic, flooding, etc.

Figure 4 – FLEX Storage Building at Watts Bar Nuclear Plant
(Source: TVA)

The FESB measures 100 ft. x 100 ft. (30.5 m x 30.5 m) and 30 ft. (9.1 m) tall. It is built of reinforced concrete with walls being 18 in. (46 cm) thick and a 16 in. (41 cm) roof. The walls and roof slabs are governed by the tornado missiles spectrum defined in U.S.NRC Regulatory Guide 1.76 (U.S.NRC 2007). A tornado rotational speed of 360 mph (580 km/hr.) was used. The building was evaluated for seismic forces corresponding to 2 times the SSE, though it did not control the design. The foundation slab measures 117 ft. x 100 ft. (35.7 m x 30.5 m) and is 3.5 ft. (1.1 m) thick. The foundation slab in turn is supported on 147 micro-piles that are embedded in bed rock at a depth of roughly 30 ft. (9.1 m) from the foundation slab. The FESB was also evaluated for the IPEEE with a PGA of 0.5g.

Equipment can be moved in and out of the FESB through a 14 ft. x 16 ft. (4.3 m x 4.9 m) opening. The opening is protected by a reinforced concrete door which rolls on two wheels on a railroad track. The door is operated by an electric motor and can be moved manually with a chain fall if electric power is lost.

To provide feed water to the reactor in case of loss of the ultimate heat sink during a BDBEE, an auxiliary feedwater supply tank (AFWST) has been constructed at the site. The AFWST (Figure 5) measures 48 ft. (14.6 m) in diameter and is 42 ft. (12.8 m) tall with a capacity of 500,000 (US) gallons (1,892,700 litres). The tank is designed for all postulated external events, similar to the FESB.

Figure 5 – FLEX Auxiliary Feedwater Storage Tank at Watts Bar Nuclear Plant
(Source: TVA)

CONCLUSIONS

1. The Chuetsu-oki Earthquake (2007) and the Great East Japanese Earthquake (2011) remind us that external events such as earthquakes and tsunamis are difficult to predict with any certainty. Thus, nuclear plants needs to have a strategy to cope with such events.
2. Beyond Design Basis External Events (BDBEE) can be coped with protection, mitigation, or a combination of the two.
3. Protection may not be practical in all instances and thus mitigation should be considered in such instances.
4. The FLEX strategy being implemented (in addition to BDBEE seismic and flooding assessments) in the US is a practical mitigation approach that addresses uncertainty associated with the magnitude of the BDBEE.

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