STRESS TESTS FOR NUCLEAR POWER PLANT SITES

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INTRODUCTION

As part of a typical Safety Analysis Report (SAR) Investigation for a nuclear power plant (NPP) site, Design Basis Events (DBEs) are defined. These events are determined on the basis of the International Atomic Energy Agency (IAEA) Safety Guides such as SSG-9 and U.S. Nuclear Regulatory Commission (USNRC) Regulatory Guidelines such as RG 1.208, each for earthquake events. All of the DBEs are determined in a highly conservative methodology, taking into account the epistemic and aleatory uncertainties in the input parameters and analytical steps – all in accordance with an intense quality assurance program that meets or exceeds the requirements of an ASME NQA-1 Program or an ISO-9001 Program. The writers of the Safety Guides and the Regulatory Guidelines, as well as the implementing analysts, believed that the Design Basis Parameters as determined with this type of guidance would not be exceeded during the life of the NPP.

Then on March 11, 2011 a Beyond Design Basis Event (BDBE) occurred at Fukushima. Specifically the Design Basis Tsunami was exceeded, followed immediately by the Loss of Offsite Power. The resulting partial core melt, spent fuel degradation, hydrogen explosions, and radioactive releases to the air, groundwater, surrounding soils, and Sea of Japan forever changed the nuclear industry. The consequence of exceeding a Design Basis Event demands the consideration of Beyond Design Basis Events, not as a design basis parameter, but as a consequence analysis.

More specifically, if a DBE is exceeded, these questions should be addressed:

- What is the potential consequence to public health and safety?
- Can the plant’s Structures, Systems, and Components protect the reactor?
- Can the event be mitigated?
- Is the plant’s Emergency Preparedness Program capable of managing the consequences of such an event?
We contend that the first question above should be asked when a new site is being selected. BDBEs should be considered before the site is judged to be a candidate site for a new NPP, practically independent of the technologies being considered. Consideration of BDBEs should be a factor in the site selection process and contribute to the ranking, including possible exclusion, in the very early stages of the site selection protocol.

**STRESS TESTS FOR SITES**

We propose that a nuclear site be subjected to a Stress Test, much like the Stress Test that the Western European Nuclear Regulator’s Association (WENRA) has specified for operating plants in the European Community – an assessment of the safety margins for hypothetical extreme naturally occurring BDBEs that could challenge the safety functions of an NPP at the site.

A Stress Test for a site should consist of:

- An evaluation of the response of a site subjected to a naturally-occurring extreme event (a BDBE); and

- A verification of the preventative measures, if any, chosen for the proposed NPP site following a defense-in-depth logic, i.e., a breakwater.

**ESTABLISHING BDBES FOR SITES**

DBEs are determined with a highly conservative methodology, taking into account the uncertainties in the input parameters and analytical steps. IAEA Safety Guides and USNRC Regulatory Guidelines, as well as other national site safety approaches and protocols for Safety Cases provide for reasonable, conservative, and implementable guidance for establishing DBEs. Establishing BDBEs for a Stress Test for a site requires more of an “out-of-the-box” approach, one that is arguably comparable to the approach taken by AREVA with the EPR where they construct a core catcher under the Reactor Vessel to essentially catch the melting fluidized core during a meltdown. Westinghouse Electric’s AP1000 also provides for in-vessel retention of molten core debris via external cooling of the Reactor Vessel, which mitigates core-concrete interaction and ex-vessel steam explosion. Such changes by AREVA, Westinghouse Electric, and other GEN-3 designs were driven by the post-Three Mile Island licensing environment.
The first step in a Stress Test for a site involves establishing a set of BDBEs for the site, such as:

- **Beyond Design Basis Earthquake**
  - Potential for fault rupture, liquefaction, and slope failure, and
  - Volcano, lava flows, ash fallout.

- **Beyond Design Basis Tsunami**
  - **Beyond Design Basis Flood**
    - Probable Maximum Flood (PMF) and Probable Maximum Precipitation (PMP) of nearby water bodies;
    - Dam Break and wave run-up;
    - Storm Surge, and
    - Sieche.

- **Beyond Design Basis Tornado/Cyclone**

- **Beyond Design Basis Loss of Offsite Power:**
  - Redundancy and reliability of power sources and lines, and
  - Reliability of switchyards and substations.

- **Beyond Design Basis Industrial Accidents**
  - Associated with nearby facilities such as pipelines, highways, and shipping channels.

- **Beyond Design Basis Spills of Radioactive Fluids**

- **Vulnerability of Safety Class Components to BDBEs**
  - Onsite Emergency Power Systems;
  - Diesel Generators;
  - Fuel Supplies;
  - Switchgear;
  - Transformers; and
The Stress Test for a site should focus on measures that can be taken after a loss or degradation of safety systems that protect against the set of regulatory-defined design accidents. It is assumed, a priori, that the safety systems (1) have been assessed in connection with the Site and Plant Licensing; (2) are part of the existing Licensing Design Bases; and (3) are not re-assessed in the Stress Test. It is recognized that all measures taken to protect the site constitute an essential part of the defense-in-depth concept.

**Beyond Design Basis Earthquake**

To establish a Beyond Design Basis (BDB) Earthquake for a site, one has available the guidance in SSG-9 by the IAEA as well as USNRC Regulatory Guide 1.208. The guidance from the IAEA is to conduct a comprehensive Probabilistic Seismic Hazard Analysis (PSHA), including provisions to account for epistemic and aleatory uncertainty. Such uncertainties exist in the basic earthquake catalog, such as the definition of the seismic sources as either faults or zones of seismicity. For example, a typical BDB Earthquake Methodology would include the following steps:

- Start with Probabilistic Seismic Hazard Analysis (PSHA) Hazard Curve such as shown on *Figure 1* and confirm its validity out to $10^{-8}$.

![Figure 1](image-url)
• Check the probability of DB Earthquake, say at $10^{-4}$; if the PSHA is based on USNRC Regulatory Guide 1.208, it is likely that the probability of the DB Earthquake is somewhere between $10^{-4}$ and $10^{-5}$

• De-aggregate the Hazard Curve at $10^{-4}$, $10^{-5}$, $10^{-6}$, and $10^{-7}$ for each of the Seismic Source Zones and faults as applicable, as typically shown on Figure 2.

![Figure 2: Hazard by Source Zone](image)

**FIGURE 2**
HAZARD BY SOURCE ZONE

• Determine the “Driving” Seismic Source Zone (SSZ), Magnitude (M), and Depth (D) at the high frequency spectral responses; and

• Assess the “Drivers” in terms of the following:
  o Is there a Driving SSZ that always governs at high spectral frequency?
  o Does the Driving SSZ change with lower probability?
For the example shown on Figure 2, such an assessment leads to the following typical results:

**TABLE 1**

**DE-AGGREGATION RESULTS – TYPICAL “DRIVERS”**

<table>
<thead>
<tr>
<th>Probability</th>
<th>Seismic Source Zone</th>
<th>Magnitude</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-4}$</td>
<td>SSZ -1</td>
<td>7.0</td>
<td>150 km</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>SSZ -1 &amp; SSZ -6</td>
<td>7.5</td>
<td>150 km</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>SSZ -6</td>
<td>6.0</td>
<td>25 km</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>SSZ -6</td>
<td>6.5</td>
<td>20 km</td>
</tr>
</tbody>
</table>

The results on Table 1 indicate that a close event in the range of 20 km, having a magnitude in the range of 7.0, is driving the seismic hazard at this particular site. The next step is to postulate the occurrence of such an event and to assess the effect at the site with a Deterministic Seismic Hazard Analysis (DSHA). In the process, one should especially consider the epistemic and aleatory uncertainty in Ground Motion Prediction Equations (GMPEs). This is a necessary step particularly for the GMPEs, as the commonly used GMPEs range of validity, generally have limitation.

With this approach, one is using the results of a PSHA to determine the most likely type of earthquake from a distance and magnitude perspective that would exceed the DB Earthquake. Then, given such an event, one relies on a deterministic approach to characterize the ground motion at the site associated with the BDB Earthquake. Such an event could then be compared with a Review Level Earthquake (RLE) if one has been used previously in a Seismic Margin Analysis (SMA).

**Beyond Design Basis Tsunami**

A BDB Tsunami is somewhat more complex and computationally demanding than a Beyond Design Basis Earthquake. We consider here only tsunamis caused by earthquakes/fault ruptures but in reality, one has to also consider tsunamis caused by landslides, ice falls, and volcanoes, which, in fact, may pose a greater threat. Here again, for the earthquake/fault rupture case, we propose a multistep process, as follows:
• Start with an existing PSHA Hazard Curve for earthquakes within 300km of a site – the normal area of consideration of a PSHA for a site. If necessary extend the hazard curves to $10^{-8}$. This initial step allows for the earthquakes in the region of the site to be considered directly.

• Secondly, one follows the same steps as for BDB Earthquake, except that one is now concerned with fault sources in the offshore. Onshore fault ruptures and earthquakes that are not tied to specific faults are generally not considered.

• In the third step, one needs to consider tsunami sources that are beyond 300 km as these can be significant and possibly controlling. We cite by way of example the impact of a source in Indonesia on a site in the Middle East or India, or the impact of a tsunami source on the Pacific Rim on a site along the West Coast of the United States. The product of this step is a Supplemental Tsunami Source Map as shown for example on Figure 3.

![Supplemental Tsunami Source Map](image-url)
• Using the results of the PSHA for the regional earthquake and the distant tsunami sources, one can develop a Scenario Parametric Table as shown in Table 2.

### TABLE 2
TSUNAMI PARAMETRIC TABLE

<table>
<thead>
<tr>
<th>Probability</th>
<th>Tsunami Source Zone</th>
<th>Fault Rupture Offset</th>
<th>Tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^-4</td>
<td>Multiple</td>
<td>Multiple</td>
<td>Several</td>
</tr>
<tr>
<td>10^-5</td>
<td>Multiple</td>
<td>Multiple</td>
<td>Several</td>
</tr>
<tr>
<td>10^-6</td>
<td>Multiple</td>
<td>Multiple</td>
<td>Several</td>
</tr>
<tr>
<td>10^-7</td>
<td>Multiple</td>
<td>Multiple</td>
<td>Several</td>
</tr>
</tbody>
</table>

As suggested by Table 2, one may have multiple sources and multiple probability values for the tsunami-causing earthquake and associated fault rupture. Then, with this basic set of scenarios, one has to consider a suite of propagation paths for the tsunami. The paths will have various lengths, arrival times and may proceed around other land masses before reaching the site under consideration. With this approach the computational demand is increasing dramatically, possibly by orders of magnitude, and the bookkeeping requires an appropriate computer code. One must move to a logic tree analysis or a Monte Carlo Analysis scheme that can handle a large database. The end result of this step is a Probabilistic Tsunami Hazard Curve of the general form, shown on Figure 4.
The shape of the Tsunami Hazard curve is particularly important as it must be extended to the right and with lower probability such that the curve becomes closer to vertical. This is similar in concept to finding a “Characteristic Earthquake” for a fault, allowing one to place a cap on the magnitude of the causative event. Here we have the Characteristic Tsunami that will yield a maximum wave height.

To this Characteristic Tsunami, one must then add tidal effects and wave run-up deterministically to arrive at a BDB Tsunami flood level to be compared with other causes of flooding such as dam breaks, Probable Maximum Floods (PMF), Probable Maximum Precipitation (PMP) and storm surge. Our experience suggests that either the tsunami or the storm surge will govern, but all sources of flooding should be addressed.

When considering tsunami sources immediately offshore, for a susceptible site such as what occurred at Fukushima, analysts reported a similar observation to the one illustrated on Figure 5, which is that a tsunami wave may be enhanced due to rupture of the causative fault over several segments at different times.
Each fault segment can cause a mini-tsunami with different timing in such a way that the mini-tsunamis may be additive and complementary, resulting in a tsunami wave that is greater than that associated with any one rupture as shown on Figure 6. Thus a parametric analysis of possible scenarios should be considered if such a scenario is practical for the site under consideration. Generally speaking, we contend that this type of tsunami enhancement is not observed, suggesting that as the tsunami wave travels over large distances, the mini-tsunami coalesce into a single governing wave.
Beyond Design Basis Flood Level Due to Dam Breaks

The strategy recommended for establishing a flood level for a BDB Dam Break is more deterministic than the probabilistic nature of the BDB Earthquake or Tsunami. The U.S. Federal Energy Regulatory Commission (FERC) the prime regulator for hydroelectric projects uses the concept of a Potential Failure Modes Analysis for dams whereby potential failure modes are postulated as extreme events. The conventional dam break analysis postulates an abrupt removal, of a segment of a dam, without stating the cause and the level and timing of the resulting wave front is predicted downstream. Of course, the key postulation is the width of the failing segment.

For concrete dams, one usually postulates the width of the failure zone as the abrupt removal of a monolith of concrete between two adjacent construction joints. Construction joint spacing is generally...
in the range of 60 feet to 100 feet, with the latter being more appropriate for Roller Compacted Concrete with a high percentage of fly ash to control temperature rise. For an earthfill dam, the postulated width of failure is not as obvious and one should consider such related features as the foundation depth and foundation conditions, geologic features in the foundation such as offsets and faults, the proximity of concrete structures such as spillways and outlets, and abrupt changes in dam alignment that can affect the long term integrity of filters and drainage systems.

The recommended step-by-step assessment for determining the flood level associated with a Beyond BDB Dam Break involves the following steps:

- Perform a Potential Failure Modes Analysis (PFMA) in a deterministic manner. This FERC-style PFMA will result in a list of potential failure modes for the dam that could lead to a catastrophic uncontrolled release of water from the impounded reservoir. The magnitude and timing of the governing uncontrolled release is generally an abrupt failure of the type described above.

- In the process of the analysis, one must consider:
  - Coincident and complementary failure modes;
  - Coincident flooding, specifically the failure postulated to occur on a “sunny day” or during a flood caused by weather conditions;
  - The timing of peak flows from multiple dam failure scenarios; here one must consider domino failures and ask the question, does the failure of an upstream dam result in overtopping and possible catastrophic failure of a dam immediately downstream?
  - Consider common cause failures such as those postulated to occur almost simultaneously by an extreme weather event when the storage reservoirs are already at full capacity; and
  - Throughout the process, one must consider the different breach rates and breach widths to estimate a maximizing scenario to arrive at a BDB Flood due to dam break to obtain higher peak flows.

- Finally, one has to consider the possibility of blockage in the main channel potentially caused by ice or flood debris, which in turn raises the flood level at a site under extreme conditions.
Beyond Design Basis Probable Maximum Flood Level Due to Precipitation

Our experience suggests that a PMF due to a PMP event is unlikely to govern the flood level for BDBEs. Previous experience tells us the extreme water level associated with a storm surge or tsunami will govern. The general methodology for a PMF results in an extreme event. Although the methodology is deterministic, back-calculations usually indicate that a PMF has a probability of occurrence in the range of $10^{-5}$ to $10^{-6}$. Nevertheless, a Stress Test for the site should examine the PMF following the conventional practice outlined below:

- Compute a PMP and verify that it has probability of occurrence in the range of $10^{-6}$ to $10^{-8}$;
- Move the center of the PMP through a grid over the watershed;
- Compute the PMF at each PMP probability level, preferably at $10^{-6}$, $10^{-7}$ and $10^{-8}$;
- Compute water levels for each PMF/probability; including
  - Using various antecedent conditions and reservoir storage scenarios, if applicable; and
  - Incorporating coincident wind wave; and
- Establish the governing PMF.

Beyond Design Basis Storm Surge

We continue to work on a singular methodology for developing a BDB Storm Surge, working currently with two approaches as illustrated in Figure 7. Approach No. 1 considers synthetic storm tracks with associated probabilities of occurrence. The storm surge level associated with each track is estimated with a goal to approach convergence to a dominant level. To this level, one must add wave set-up and wave run-up to arrive at a BDB Storm Surge Level suitable for a Stress Test.
Approach No. 1, to some degree, avoids the need to make a judgment as to what probability is low enough. The number of tracks, wind speeds, etc. make for a large number of events to be analyzed that can be summarized as on Table 3. The large number of combinations and permutations can be analyzed with a Monte Carlo approach to derive a BDB Storm Surge Level associated with these combinations.

TABLE 3

STORM SURGE APPROACH NO. 1

<table>
<thead>
<tr>
<th>Probability</th>
<th>Tracks</th>
<th>Storm Ensembles</th>
<th>Maximum Sustained Wind Speed (m/s)</th>
<th>Maximum Surge Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-4}$</td>
<td>Several</td>
<td>Several</td>
<td>To be established</td>
<td>To be established</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>Several</td>
<td>Several</td>
<td>To be established</td>
<td>To be established</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>Several</td>
<td>Several</td>
<td>To be established</td>
<td>To be established</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>Several</td>
<td>Several</td>
<td>To be established</td>
<td>To be established</td>
</tr>
</tbody>
</table>
For Approach No. 2, one has to de-aggregate historical data to pull out the portion of the water level rise attributed to a representative observed actual storm surge event versus normal tide levels and then to develop synthetic storm surge level versus time (i.e. surge hydrograph) as broadly illustrated in Figure 8 below. One has to pull the sea level and time parameters from observed surge events to develop many synthetic surge hydrographs. The number of parameters needed to parameterize a storm surge event depends on the region under study. The example on Figure 8 shows 18 sea level parameters and six time parameters.

![Sea Level Parameters](image)

**FIGURE 8**  
STORM SURGE APPROACH NO. 2  
SOURCE: WAHL ET AL, 2010

Then the large number of combinations and permutations resulting from the parameterization of the sea level and time parameters can be analyzed with a Monte Carlo approach as illustrated in Figure 9 below.
Based on the Monte Carlo simulation results, the statistical assessment of extreme events is possible and the resulting synthetic storm surges can additionally serve as the basis for a large number of investigations.

Approach No. 2 shown in Figure 7 uses the synthetic surge curves developed from the historical data together with an extrapolation curve such as a Weibul curve to predict a low probability – high consequence event. This approach requires a judgment call that can be challenged, as to what is a “low probability.” Is $10^{-7}$ or $10^{-8}$ low enough or perhaps $10^{-9}$? The example shown on Figure 10 shows a probability as low as $10^{-5}$, but this can be extended to perhaps $10^{-9}$. Here again, one must add wave set-up and wave run-up to account for wave interaction with the shoreline and to arrive at a BDB Storm Surge Level suitable for a Stress Test.
CONCLUDING REMARKS

A Stress Test for a site will document the response of the site and the effectiveness of the preventive measures, noting any potential weak point and cliff-edge effects for each of the considered extreme situations. A cliff-edge effect could be, for instance, exceeding a point where significant flooding of the site begins or when the margin of safety against slope instability is less than unity.

The approach is to evaluate the robustness of the defense-in-depth measures credited for the site, to evaluate the adequacy of current accident management measures, and to identify the potential of safety improvements, both technical and organizational (procedural, human resources, and emergency response), and the use of external resources.
The end product of the effort is envisioned to be a site specific report describing the site and the plant technology’s response to BDBEs, and may include answers to such questions as:

- In the event of the Beyond Design Basis Earthquake, is there a potential for a core meltdown or a severe radioactive release?
- In the event of the Beyond Design Basis Tsunami, is there a potential for the site or key equipment to be inundated?
- In the event of a Loss of Off-site Power and a concurrent failure of safety-related emergency power sources to automatically start up, is there a potential for the plant to experience a core melt?
- In the event of concurrent BDB Earthquake and a related other BDBE, is there a potential for extreme structural damage?

Since Fukushima, numerous evaluations have been conducted and documents have been produced outlining current Design Basis and the need to recognize Beyond Design Basis Events utilizing Stress Tests. Électricité de France’s (EDF’s) review of the objectives of the Stress Test illustrates the need for the global nuclear community:

“to reconfirm that we have considered sufficiently severe hazards in our design safety analysis based on a review of the most up to date information available; and, even if this is the case, to consider what measures we might be able to take to increase our resilience in the extremely unlikely event that an even more severe hazard were to occur.”

Our thesis is to assess the impact of those BDBEs for a site that could lead to a core melt or radioactive release, independent of the plant technology, and to develop assurance that with the occurrence of a BDBE, the consequences can be managed, controlled, and mitigated without endangering public health and safety.
REFERENCES
