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**RECORD OF REVISION**

| <b>Rev #</b> | <b>Description</b>   |
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| 0            | Initial issue  |
| 1            | Revised to include updated results from Revision 1 FPE and FWS Seismic Fragility Calculations  |
| 2            | Revised to include resolutions to comments provided by the NRC during the North Anna 3, Combined License Application Review of Structural Design Evaluation of Seismic Category I Structures and Supporting Information Described in Final Safety Analysis Report Section 3.8 Audit No. 2 performed on March 21-25, 2016 |
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## 1.0 INTRODUCTION

A generic PRA-based seismic margins analysis (SMA) was performed for the Economic Simplified Boiling Water Reactor (ESBWR) in NEDO-33201, Revision 6 (Reference (Ref.) 1) to assess the impacts of seismic events on the safe operation of the ESBWR plant for generic sites. The SMA performed in Ref. 1 used the systems models and the fragility analysis method of Ref. 2 to calculate High Confidence of a Low Probability of Failure (HCLPF) capacities for important accident sequences and accident classes. The Seismic Margin Earthquake (SME) for this PRA-based seismic margin assessment was the ESBWR Certified Seismic Design Response Spectrum (CSDRS).

The analysis in Ref. 1 showed that the ESBWR plant is capable of withstanding an earthquake with HCLPF capacity of at least 1.67 times the Safe Shutdown Earthquake (SSE), where the SSE was the ESBWR CSDRS with 0.5g Peak Ground Acceleration (PGA). However, per 10 CFR52.79 (d) (1) and the associated Nuclear Regulatory Commission (NRC) guidance contained in ISG-20, a North Anna 3 (NA3) site-specific SMA that reflects the actual site conditions needs to be completed before the issuance of the combined license (COL) (Ref. 3).

A PRA-based NA3 site-specific update to the SMA for the ESBWR is performed in this report in accordance with ISG-20 to evaluate the impacts of changing the SSE from the ESBWR CSDRS (0.5g PGA) to the NA3 site-specific Ground Motion Response Spectra (GMRS) with 0.55g PGA to reflect actual site conditions. Additionally, site-specific seismic fragility analysis, including the use of generic data, is performed to calculate HCLPF capacities for ESBWR SSCs.

The NA3 site-specific SMA shows that the NA3 site-specific ESBWR plant is capable of withstanding an earthquake with HCLPF capacity of at least 1.67 times the SSE, where the SSE is the NA3 site-specific GMRS (0.55g PGA). Demonstration of the plant-specific plant-level HCLPF value to be equal to or greater than 1.67 times the site-specific GMRS PGA is also an ISG-20 requirement. This demonstration of a 1.67 margin is in compliance with the SECY 93-087 (Ref. 4) requirement "PRA insights will be used to support a margins-type assessment of seismic events. A PRA-based seismic margins analysis will consider sequence-level High Confidence, Low Probability of Failures (HCLPFs) and fragilities for all sequences leading to core damage or containment failures up to approximately one and two-thirds the ground motion acceleration of the Design Basis SSE."

The scope of the NA3 site-specific SMA includes both at-power and shutdown seismic-induced accident scenarios.





## 2.0 METHODOLOGY

The NA3 site-specific evaluation of the seismic risk assessment uses a SMA method based on Ref. 2 to calculate HCLPF seismic capacities for important accident sequences and accident classes leading to core damage and/or containment failure. This is the same methodology used for the SMA for the standard ESBWR design.

The PRA-based seismic margins approach used in this NA3 site-specific SMA evaluates the capability of the plant to withstand an earthquake of 1.67 times the SSE ( $1.67 \times \text{SSE}$ ). The SSE used in the NA3 site-specific SMA is the GMRS with 0.55g PGA.

The NA3 site-specific SMA involves the following two major steps:

- (1) Seismic fragilities
- (2) Accident sequence HCLPF analysis

Additionally, Interim Staff Guidance DC/COL-ISG-020, ML1004912330 (Ref. 3) provides a detailed process that a COL applicant may use to update the PRA-based SMA and includes four technical activities that are as follows:

- (1) Updating plant system and sequence analysis
- (2) Updating seismic fragility evaluation including use of generic data
- (3) Updating plant-level capacity of HCLPF
- (4) Post COL activities

The seismic fragilities of the ESBWR systems, structures, and components are based on generic industry information and ESBWR specific seismic capacity calculations for certain structures.

The MIN-MAX method (Ref. 5) is used in the determination of functional and accident sequence fragilities. Per the MIN-MAX method, the overall fragility of a group of inputs combined using OR logic (i.e., seismic event tree nodal fault tree) is determined by the lowest (minimum) HCLPF input. Conversely, per the MIN-MAX method, the overall fragility of a group of inputs combined using AND logic (i.e., seismic event tree sequence) is determined by the highest (maximum) HCLPF input.

A basic overview of seismic fragilities and accident sequence HCLPF analysis is presented in Sections 3.0 and 4.0 of this report; however, more detailed information regarding this methodology is presented in Sections 15.3 and 15.4 of Ref. 1.

Both at-power and shutdown seismic-induced accident scenarios are analyzed.

### Activities after COL Issuance

The NA3 site-specific HCLPF capacities include an as-built engineering walk-down to verify assumptions made in the SMA and a determination of whether there are components that require strengthening if the as-built SMA indicates additional capacity margin is required.



## 2.1 ASSUMPTIONS

The NA3 site-specific SMA is derived based on the following assumptions:

- Prior to detailed design information becoming available, minimum HCLPF capacities of  $1.67 \times \text{SSE}$  are assumed for NA3 site-specific components. Although the design details of the NA3 site-specific equipment are not currently available, insights from seismic capacity results at other nuclear power plants can be drawn to support this assumption. Per a review of the Lungmen Nuclear Power Plant seismic capacity results (Ref. 6), there is a high confidence that a HCLPF capacity of  $1.67 \times \text{SSE}$  is achievable for key components at NA3, as discussed in more detail in Section 3.0.



### 3.0 SEISMIC FRAGILITIES

Section 15.3 of Ref. 1 presents the methodology for the evaluation of seismic capacities for selected structures and components that have been identified as potentially important to the seismic risk analysis of the ESBWR standard plant. The seismic capabilities are first estimated in terms of seismic fragilities, from which the HCLPF capacities are then derived. The HCLPF capacities serve as input to the system analysis following the PRA-based seismic margins approach of NUREG/CR-4482 (Ref. 5).

The NA3 site-specific horizontal and vertical GMRS are presented in Figure 3-1 and Figure 3-2, respectively. Extensive NA3 site-specific soil-structure interaction (SSI) analyses of the Reactor Building/Fuel Building Complex, Control Building, and Firewater Service Complex were performed and documented in Ref. 7, Ref. 8, and Ref. 9, respectively.

For the seismic category I structures for which seismic design information is available, the seismic fragilities are evaluated using the separation-of-variable method (Ref. 2). This approach identifies various conservatisms and associated uncertainties introduced in the seismic design process (both capacity and demand sides) and provides a probabilistic estimate of the earthquake level required to fail a structure or component in a postulated failure mode by extrapolating from the design information supplemented by limited nonlinear analysis to account for building response beyond yielding.

As stated as an assumption in Section 2.1, the design details are not currently available for safety-related components such as pumps, valves, and electrical equipment; therefore, a generic HCLPF capacity of  $1.67 \times \text{SSE}$  is assigned to these components for the purpose of the NA3 site-specific SMA, with a commitment that the safety-related components will be designed with HCLPF capacities of at least  $0.92g$ . Although the design details of the NA3 site-specific equipment are not currently available, insights from seismic capacity results at other nuclear power plants can be drawn to support this assumption. Per a review of the Lungmen Nuclear Power Plant seismic capacity results (Ref. 6), the following insights can be drawn:

- Generally, instrument and control (I&C) panel boards and instrumentation panels have a HCLPF capacity greater than  $0.92g$ .
- Most electrical components have similar HCLPF capacities. Battery chargers and inverters may be vulnerable, but Lungmen-specific results show higher HCLPF capacities are achievable (i.e., batteries, switchgears, and motor control centers).
- Some vulnerable component failure modes (such as relay chattering) have been removed with newer designs.
- Lungmen-specific HCLPF capacities for pumps, valves, and other key components show that they can be greater than  $0.92g$ .
- RPV and vessel internals have lower HCLPF capacities, but these components are assumed to have been designed to meet the seismic requirements along with the fuel bundle designs; therefore, no specific concerns with regards to the NA3 site-specific seismic PRA exists.

On the basis of this assessment, there is a high confidence that a HCLPF capacity of  $1.67 \times \text{SSE}$  is achievable for key components at NA3, and thus the assumption in Section 2.1.



The structural seismic fragilities and corresponding HCLPF values of the Reactor Building/Fuel Building Complex, Reinforced Concrete Containment Vessel (RCCV), the Reactor Pressure Vessel (RPV) Pedestal, the RPV support brackets, the Control Building, and the Firewater Service Complex are summarized in Table 3-1. All have HCLPF seismic capacities greater than 1.67 times the SSE.

The HCLPF fragility information for the NA3 site-specific SMA input into each event tree node is obtained from the fragility analyses presented in Ref. 10 through Ref. 16. A detailed analysis of each of the structures/components listed in Table 3-1 is presented in Table 3-2 through Table 3-7. Additionally, the HCLPF inputs as a function of event tree node are summarized in Table 3-8.

**Table 3-1: Seismic Capacity Summary<sup>(1)</sup>**

| Structure/Component                    | Failure Mode          | Fragility                         |                                     | HCLPF (g) |
|--|-----------------------|-----------------------------------|-------------------------------------|-----------|
|  |                       | Capacity $A_m$ (g) <sup>(2)</sup> | Combined Uncertainty <sup>(3)</sup> |           |
| Reactor Building/Fuel Building Complex | Shear failure of wall | 3.64                              | 0.47                                | 1.22      |
| RCCV                                   | Shear failure of wall | 6.80                              | 0.45                                | 2.41      |
| RPV Pedestal                           | Flexural failure      | 21.22                             | 0.49                                | 6.76      |
| RPV Support Brackets                   | Yielding of bracket   | 2.22                              | 0.32                                | 1.06      |
| Control Building                       | Shear failure of wall | 5.11                              | 0.47                                | 1.71      |
| Firewater Service Complex              | Shear key failure     | 2.59                              | 0.37                                | 1.10      |

Notes to Table 3-1:

- (1) This table is a summary of the data presented in Table 3-2 through Table 3-7.
- (2) Capacities are in terms of median peak ground acceleration.
- (3) Combined uncertainties are composite logarithmic standard deviations of uncertainty and randomness.

Table 3-2: Seismic Fragility for Reactor Building Shear Walls<sup>(1)</sup>

| Component:  |                               | Reactor Building/Fuel Building Complex                           |              |           |           |
|---|-------------------------------|--|--------------|-----------|-----------|
| Failure Mode:   |                               | Shear Failure of RB/FB Shear Wall Along Column FA/FF at El. 4650 |              |           |           |
| Factor of Safety  |                               |  | Median Value | $\beta_R$ | $\beta_U$ |
| F <sub>C</sub>  | F <sub>S</sub>                | Strength   | 1.36         | 0.00      | 0.20      |
|   | F <sub><math>\mu</math></sub> | Inelastic Energy Absorption                                      | 3.09         | 0.07      | 0.14      |
| F <sub>RS</sub>   | F <sub>SA</sub>               | Spectral Shape   |              |           |           |
|   |                               | <i>Response Spectrum Shape</i>                                   | 1.00         | 0.00      | 0.00      |
|   |                               | <i>Horizontal Direction Peak Response</i>                        | 1.00         | 0.13      | 0.00      |
|   |                               | <i>Vertical Component Response</i>                               | 1.00         | 0.10      | 0.00      |
|   | F <sub>D</sub>                | Damping  | 1.58         | 0.00      | 0.18      |
|   | F <sub>M</sub>                | Modeling   | 1.00         | 0.00      | 0.25      |
|   | F <sub>MC</sub>               | Model Response Combination                                       | 1.00         | 0.15      | 0.00      |
|   | F <sub>ECC</sub>              | Earthquake Component Combination                                 | 1.00         | 0.05      | 0.00      |
|   | F <sub>SSI</sub>              | Soil Structure Interaction                                       |              |           |           |
|   |                               | <i>Ground Motion Incoherence</i>                                 | 1.00         | 0.00      | 0.00      |
|   |                               | <i>Vertical Spatial Variation</i>                                | 1.00         | 0.08      | 0.00      |
|   |                               | <i>SSI Analysis</i>  | 1.00         | 0.00      | 0.00      |
| Overall Factor of Safety  |                               |  | 6.62         | 0.25      | 0.40      |
| A <sub>d</sub> = Peak Ground Acceleration of the NA3 site-specific GMRS = 0.55g |                               |  |              |           |           |
| A <sub>m</sub> = Median Peak Ground Acceleration = F*A <sub>d</sub> = 3.64g     |                               |  |              |           |           |
| $\beta_C$ = Combined Logarithmic Standard Deviation = 0.47                      |                               |  |              |           |           |
| HCLPF = 1.22g   |                               |  |              |           |           |

Notes to Table 3-2:

- (1) This table was developed based on the data presented in Section 8 of DBR-0013327 (Ref. 10).

Table 3-3: Seismic Fragility for Containment Wall<sup>(1)</sup>

|   |                               |   |                     |                             |                             |
|---|-------------------------------|---|---------------------|-----------------------------|-----------------------------|
| <b>Component:</b>   |                               | RCCV                                      |                     |                             |                             |
| <b>Failure Mode:</b>  |                               | Shear Failure of RCCV Wall                |                     |                             |                             |
| <b>Factor of Safety</b>   |                               |   | <b>Median Value</b> | <b><math>\beta_R</math></b> | <b><math>\beta_U</math></b> |
| F <sub>C</sub>  | F <sub>S</sub>                | Strength                                  | 6.76                | 0.00                        | 0.21                        |
|   | F <sub><math>\mu</math></sub> | Inelastic Energy Absorption               | 1.16                | 0.04                        | 0.06                        |
| F <sub>RS</sub>   | F <sub>SA</sub>               | Spectral Shape                            |                     |                             |                             |
|   |                               | <i>Response Spectrum Shape</i>            | 1.00                | 0.00                        | 0.00                        |
|   |                               | <i>Horizontal Direction Peak Response</i> | 1.00                | 0.13                        | 0.00                        |
|   |                               | <i>Vertical Component Response</i>        | 1.00                | 0.10                        | 0.00                        |
|   | F <sub>D</sub>                | Damping                                   | 1.58                | 0.00                        | 0.18                        |
|   | F <sub>M</sub>                | Modeling                                  | 1.00                | 0.00                        | 0.24                        |
|   | F <sub>MC</sub>               | Model Response Combination                | 1.00                | 0.15                        | 0.00                        |
|   | F <sub>ECC</sub>              | Earthquake Component Combination          | 1.00                | 0.05                        | 0.00                        |
|   | F <sub>SSI</sub>              | Soil Structure Interaction                |                     |                             |                             |
|   |                               | <i>Ground Motion Incoherence</i>          | 1.00                | 0.00                        | 0.00                        |
|   |                               | <i>Vertical Spatial Variation</i>         | 1.00                | 0.08                        | 0.00                        |
|   |                               | <i>SSI Analysis</i>                       | 1.00                | 0.00                        | 0.00                        |
| Overall Factor of Safety  |                               |   | 12.36               | 0.24                        | 0.37                        |
| A <sub>d</sub> = Peak Ground Acceleration of the NA3 site-specific GMRS = 0.55g |                               |   |                     |                             |                             |
| A <sub>m</sub> = Median Peak Ground Acceleration = F*A <sub>d</sub> = 6.80g     |                               |   |                     |                             |                             |
| $\beta_C$ = Combined Logarithmic Standard Deviation = 0.45                      |                               |   |                     |                             |                             |
| HCLPF = 2.41g   |                               |   |                     |                             |                             |

Notes to Table 3-3:

- (1) This table was developed based on the data presented in Section 8 of DBR-0013611 (Ref. 12).

Table 3-4: Seismic Fragility for RPV Pedestal<sup>(1)</sup>

|   |                               |   |                     |                             |                             |
|---|-------------------------------|---|---------------------|-----------------------------|-----------------------------|
| <b>Component:</b>   |                               | RPV Pedestal                              |                     |                             |                             |
| <b>Failure Mode:</b>  |                               | Flexural Failure of Pedestal              |                     |                             |                             |
| <b>Factor of Safety</b>   |                               |   | <b>Median Value</b> | <b><math>\beta_R</math></b> | <b><math>\beta_U</math></b> |
| F <sub>C</sub>  | F <sub>S</sub>                | Strength                                  | 11.94               | 0.00                        | 0.25                        |
|   | F <sub><math>\mu</math></sub> | Inelastic Energy Absorption               | 2.04                | 0.06                        | 0.15                        |
| F <sub>RS</sub>   | F <sub>SA</sub>               | Spectral Shape                            |                     |                             |                             |
|   |                               | <i>Response Spectrum Shape</i>            | 1.00                | 0.00                        | 0.00                        |
|   |                               | <i>Horizontal Direction Peak Response</i> | 1.00                | 0.13                        | 0.00                        |
|   |                               | <i>Vertical Component Response</i>        | 1.00                | 0.10                        | 0.00                        |
|   | F <sub>D</sub>                | Damping                                   | 1.58                | 0.00                        | 0.18                        |
|   | F <sub>M</sub>                | Modeling                                  | 1.00                | 0.00                        | 0.24                        |
|   | F <sub>MC</sub>               | Model Response Combination                | 1.00                | 0.15                        | 0.00                        |
|   | F <sub>ECC</sub>              | Earthquake Component Combination          | 1.00                | 0.05                        | 0.00                        |
|   | F <sub>SSI</sub>              | Soil Structure Interaction                |                     |                             |                             |
|   |                               | <i>Ground Motion Incoherence</i>          | 1.00                | 0.00                        | 0.00                        |
|   |                               | <i>Vertical Spatial Variation</i>         | 1.00                | 0.08                        | 0.00                        |
|   |                               | <i>SSI Analysis</i>                       | 1.00                | 0.00                        | 0.00                        |
| Overall Factor of Safety  |                               |   | 38.59               | 0.25                        | 0.42                        |
| A <sub>d</sub> = Peak Ground Acceleration of the NA3 site-specific GMRS = 0.55g |                               |   |                     |                             |                             |
| A <sub>m</sub> = Median Peak Ground Acceleration = F*A <sub>d</sub> = 21.22g    |                               |   |                     |                             |                             |
| $\beta_C$ = Combined Logarithmic Standard Deviation = 0.49                      |                               |   |                     |                             |                             |
| HCLPF = 6.76g   |                               |   |                     |                             |                             |

Notes to Table 3-4:

- (1) This table was developed based on the data presented in Section 8 of DBR-0013613 (Ref. 13).

Table 3-5: Seismic Fragility for RPV Support Brackets<sup>(1)</sup>

| Component:  |                               | RPV Support Brackets                                       |              |           |           |
|---|-------------------------------|--|--------------|-----------|-----------|
| Failure Mode:   |                               | Yielding of 150-mm Horizontal Plate of RPV Support Bracket |              |           |           |
| Factor of Safety  |                               |  | Median Value | $\beta_R$ | $\beta_U$ |
| F <sub>C</sub>  | F <sub>S</sub>                | Strength   | 3.51         | 0.00      | 0.12      |
|   | F <sub><math>\mu</math></sub> | Inelastic Energy Absorption                                | 1.00         | 0.00      | 0.00      |
| F <sub>RS</sub>   | F <sub>SA</sub>               | Spectral Shape   |              |           |           |
|   |                               | <i>Response Spectrum Shape</i>                             | 1.00         | 0.00      | 0.00      |
|   |                               | <i>Horizontal Direction Peak Response</i>                  | 1.00         | 0.13      | 0.00      |
|   |                               | <i>Vertical Component Response</i>                         | 1.00         | 0.10      | 0.00      |
|   | F <sub>D</sub>                | Damping  | 1.00         | 0.00      | 0.00      |
|   | F <sub>M</sub>                | Modeling   | 1.00         | 0.00      | 0.15      |
|   | F <sub>MC</sub>               | Model Response Combination                                 | 1.00         | 0.15      | 0.00      |
|   | F <sub>ECC</sub>              | Earthquake Component Combination                           | 1.00         | 0.05      | 0.00      |
|   | F <sub>SSI</sub>              | Soil Structure Interaction                                 |              |           |           |
|   |                               | <i>Ground Motion Incoherence</i>                           | 1.15         | 0.00      | 0.07      |
|   |                               | <i>Vertical Spatial Variation</i>                          | 1.00         | 0.08      | 0.00      |
|   |                               | <i>SSI Analysis</i>  | 1.00         | 0.00      | 0.00      |
| Overall Factor of Safety  |                               |  | 4.03         | 0.24      | 0.21      |
| A <sub>d</sub> = Peak Ground Acceleration of the NA3 site-specific GMRS = 0.55g |                               |  |              |           |           |
| A <sub>m</sub> = Median Peak Ground Acceleration = F* A <sub>d</sub> = 2.22g    |                               |  |              |           |           |
| $\beta_C$ = Combined Logarithmic Standard Deviation = 0.32                      |                               |  |              |           |           |
| HCLPF = 1.06g   |                               |  |              |           |           |

Notes to Table 3-5:

- (1) This table was developed based on the data presented in Section 8 of DBR-0013616 (Ref. 14).



Table 3-6: Seismic Fragility for Control Building<sup>(1)</sup>

|   |                               |   |                     |                             |                             |
|---|-------------------------------|---|---------------------|-----------------------------|-----------------------------|
| <b>Component:</b>   |                               | Control Building                              |                     |                             |                             |
| <b>Failure Mode:</b>  |                               | Shear Failure of Wall Along Column Line C1/C5 |                     |                             |                             |
| <b>Factor of Safety</b>   |                               |   | <b>Median Value</b> | <b><math>\beta_R</math></b> | <b><math>\beta_U</math></b> |
| F <sub>C</sub>  | F <sub>S</sub>                | Strength                                      | 2.55                | 0.00                        | 0.20                        |
|   | F <sub><math>\mu</math></sub> | Inelastic Energy Absorption                   | 3.04                | 0.12                        | 0.23                        |
| F <sub>RS</sub>   | F <sub>SA</sub>               | Spectral Shape                                |                     |                             |                             |
|   |                               | <i>Response Spectrum Shape</i>                | 1.00                | 0.00                        | 0.00                        |
|   |                               | <i>Horizontal Direction Peak Response</i>     | 1.00                | 0.13                        | 0.00                        |
|   |                               | <i>Vertical Component Response</i>            | 1.00                | 0.10                        | 0.00                        |
|   | F <sub>D</sub>                | Damping                                       | 1.20                | 0.00                        | 0.18                        |
|   | F <sub>M</sub>                | Modeling                                      | 1.00                | 0.00                        | 0.15                        |
|   | F <sub>MC</sub>               | Model Response Combination                    | 1.00                | 0.15                        | 0.00                        |
|   | F <sub>ECC</sub>              | Earthquake Component Combination              | 1.00                | 0.05                        | 0.00                        |
|   | F <sub>SSI</sub>              | Soil Structure Interaction                    |                     |                             |                             |
|   |                               | <i>Ground Motion Incoherence</i>              | 1.00                | 0.00                        | 0.00                        |
|   |                               | <i>Vertical Spatial Variation</i>             | 1.00                | 0.08                        | 0.00                        |
|   |                               | <i>SSI Analysis</i>                           | 1.00                | 0.00                        | 0.00                        |
| Overall Factor of Safety  |                               |   | 9.29                | 0.27                        | 0.39                        |
| A <sub>d</sub> = Peak Ground Acceleration of the NA3 site-specific GMRS = 0.55g |                               |   |                     |                             |                             |
| A <sub>m</sub> = Median Peak Ground Acceleration = F*A <sub>d</sub> = 5.11g     |                               |   |                     |                             |                             |
| $\beta_C$ = Combined Logarithmic Standard Deviation = 0.47                      |                               |   |                     |                             |                             |
| HCLPF = 1.71g   |                               |   |                     |                             |                             |

Notes to Table 3-6:

- (1) This table was developed based on the data presented in Section 8 of DBR-0013328 (Ref. 11).

Table 3-7: Seismic Fragility for Firewater Service Complex<sup>(1)</sup>

|  |           |   |                     |                             |                             |
|--|-----------|---|---------------------|-----------------------------|-----------------------------|
| <b>Component:</b>  |           | Firewater Service Complex                 |                     |                             |                             |
| <b>Failure Mode:</b>   |           | Basemat Shear Key Failure                 |                     |                             |                             |
| <b>Factor of Safety</b>  |           |   | <b>Median Value</b> | <b><math>\beta_R</math></b> | <b><math>\beta_U</math></b> |
| $F_C$  | $F_S$     | Strength                                  | 3.48                | 0.00                        | 0.18                        |
|  | $F_\mu$   | Inelastic Energy Absorption               | 1.00                | 0.00                        | 0.00                        |
| $F_{RS}$   | $F_{SA}$  | Spectral Shape                            |                     |                             |                             |
|  |           | <i>Response Spectrum Shape</i>            | 1.00                | 0.00                        | 0.00                        |
|  |           | <i>Horizontal Direction Peak Response</i> | 1.00                | 0.10                        | 0.00                        |
|  |           | <i>Vertical Component Response</i>        | 1.00                | 0.10                        | 0.00                        |
|  | $F_D$     | Damping                                   | 1.20                | 0.00                        | 0.18                        |
|  | $F_M$     | Modeling                                  | 1.00                | 0.00                        | 0.15                        |
|  | $F_{MC}$  | Model Response Combination                | 1.00                | 0.15                        | 0.00                        |
|  | $F_{ECC}$ | Earthquake Component Combination          | 1.00                | 0.05                        | 0.00                        |
|  | $F_{SSI}$ | Soil Structure Interaction                |                     |                             |                             |
|  |           | <i>Ground Motion Incoherence</i>          | 1.13                | 0.00                        | 0.06                        |
|  |           | <i>Vertical Spatial Variation</i>         | 1.00                | 0.00                        | 0.00                        |
|  |           | <i>SSI Analysis</i>                       | 1.00                | 0.00                        | 0.00                        |
| Overall Factor of Safety   |           |   | 4.70                | 0.21                        | 0.30                        |
|  |           |   |                     |                             |                             |
| $A_d$ = Peak Ground Acceleration of the NA3 site-specific GMRS = 0.55g |           |   |                     |                             |                             |
| $A_m$ = Median Peak Ground Acceleration = $F \cdot A_d$ = 2.59g        |           |   |                     |                             |                             |
| $\beta_C$ = Combined Logarithmic Standard Deviation = 0.37             |           |   |                     |                             |                             |
| HCLPF = 1.10g  |           |   |                     |                             |                             |

Notes to Table 3-7:

- (1) This table was developed based on the data presented in Section 8 of DBR-0013619 (Ref. 15).

Table 3-8: ESBWR Systems and Components/Structures Fragilities<sup>(1)</sup>

| System/Component as a function of Event Tree Node                | A <sub>m</sub> (g) | β <sub>C</sub> | HCLPF(g) |
|--|--------------------|----------------|----------|
| <u>STRUCTURAL INTEGRITY (SI)</u>                                 |                    |                |          |
| - Reactor Building/Fuel Building Complex (FRBLDG) <sup>(2)</sup> | 3.64               | 0.47           | 1.22     |
| - RCCV (FCONT) <sup>(3)</sup>                                    | 6.80               | 0.45           | 2.41     |
| - RPV Pedestal (FPEDST) <sup>(4)</sup>                           | 21.22              | 0.49           | 6.76     |
| - RPV Support Brackets (FRPV) <sup>(5)</sup>                     | 2.22               | 0.32           | 1.06     |
| - Control Building (FCTRBLDG) <sup>(6)</sup>                     | 5.11               | 0.47           | 1.71     |
| - Firewater Service Complex (FFWSC) <sup>(7)</sup>               | 2.59               | 0.37           | 1.10     |
| <u>DC POWER (DC)</u>   |                    |                |          |
| - Batteries (FBTR)   |                    |                | 0.92     |
| - Cable trays (FCTRAY)   |                    |                | 0.92     |
| - Motor control centers (FMCC)                                   |                    |                | 0.92     |
| <u>REACTIVITY CONTROL SYSTEM (SCRAM)</u>                         |                    |                |          |
| - Fuel assembly (FFASSY)   |                    |                | 0.92     |
| - CRD guide tubes (FCRDGTB)                                      |                    |                | 0.92     |
| - Shroud support (FSHRSPT)                                       |                    |                | 0.92     |
| - CRD housing (FCRDHS)   |                    |                | 0.92     |
| - Hydraulic control unit (FHYLTUT)                               |                    |                | 0.92     |
| <u>SAFETY RELIEF VALVE (SRV)</u>                                 |                    |                |          |
| - SRV (FSRV)   |                    |                | 0.92     |
| <u>STANDBY LIQUID CONTROL SYSTEM (SLCS)</u>                      |                    |                |          |
| - Accumulator tank (FACCT)                                       |                    |                | 0.92     |
| - Check valve (FCHV)   |                    |                | 0.92     |
| - Squib valve (FSQUV)  |                    |                | 0.92     |
| - Piping (FPIP)  |                    |                | 0.92     |
| - Valve, air-operated (FAOV)                                     |                    |                | 0.92     |

Table 3-8: ESBWR Systems and Components/Structures Fragilities<sup>(1)</sup>

| System/Component as a function of Event Tree Node | $A_m(g)$ | $\beta_c$ | HCLPF(g) |
|---|----------|-----------|----------|
| <u>ISOLATION CONDENSER (IC)</u>                   |          |           |          |
| - Piping (FPIP)                                   |          |           | 0.92     |
| - Heat exchanger (FICHEX)                         |          |           | 0.92     |
| - Valve, motor-operated (FMOV)                    |          |           | 0.92     |
| - Valve, nitrogen-operated (FNOV)                 |          |           | 0.92     |
| <u>DEPRESSURIZATION VALVE (DPV)</u>               |          |           |          |
| - DPV (FDPV)                                      |          |           | 0.92     |
| <u>GRAVITY-DRIVEN COOLING SYSTEM (GDCCS)</u>      |          |           |          |
| - Check valve (FCHV)                              |          |           | 0.92     |
| - Squib valve (FSQUV)                             |          |           | 0.92     |
| - Piping (FPIP)                                   |          |           | 0.92     |
| <u>VACUUM BREAKERS (VB)</u>                       |          |           |          |
| - Vacuum breakers (FVBS)                          |          |           | 0.92     |
| <u>PASSIVE CONTAINMENT COOLING SYSTEM (PCCS)</u>  |          |           |          |
| - Heat exchanger (FPCCSHEX)                       |          |           | 0.92     |
| - Piping (FPIP)                                   |          |           | 0.92     |
| <u>IC/PCC POOL INTERCONNECTION (PI)</u>           |          |           |          |
| - Valve, motor-operated (FIC/PCCI)                |          |           | 0.92     |
| <u>FIRE PROTECTION WATER (FPW)</u>                |          |           |          |
| - Pump, diesel-driven (FPUMPDD)                   |          |           | 0.92     |
| - Tank (FTANK) <sup>(8)</sup>                     | 7.33     | 0.41      | 2.82     |
| - Piping (FPIP)                                   |          |           | 0.92     |
| - FWSC (FFWSC) <sup>(7)</sup>                     | 2.59     | 0.37      | 1.10     |

Table 3-8: ESBWR Systems and Components/Structures Fragilities<sup>(1)</sup>

| System/Component as a function of Event Tree Node                | $A_m(g)$ | $\beta_C$ | HCLPF(g) |
|--|----------|-----------|----------|
| <b>STRUCTURAL INTEGRITY SHUTDOWN (SIS)</b>                       |          |           |          |
| - Reactor Building/Fuel Building Complex (FRBLDG) <sup>(2)</sup> | 3.64     | 0.47      | 1.22     |
| - Control Building (FCTRBLDG) <sup>(6)</sup>                     | 5.11     | 0.47      | 1.71     |
| - RPV Support Brackets (FRPV) <sup>(5)</sup>                     | 2.22     | 0.32      | 1.06     |
| - Fuel assembly (FFASSY)   |          |           | 0.92     |
| - RPV Pedestal (FPEDST) <sup>(4)</sup>                           | 21.22    | 0.49      | 6.76     |
| - Shroud support (FSHRSPT)                                       |          |           | 0.92     |
| - Containment (FCONT) <sup>(3)</sup>                             | 6.80     | 0.45      | 2.41     |
| - CRD housing (FCRDHS)   |          |           | 0.92     |

Notes to Table 3-8:

- (1) HCLPF capacity for components that are significant contributors to overall plant level seismic margin is assumed to be 0.92g minimum which is 1.67 times SSE (see assumptions in Section 2.1 for additional information).
- (2) The data depicted for this structure is a summary of the data presented in Table 3-2.
- (3) The data depicted for this structure is a summary of the data presented in Table 3-3.
- (4) The data depicted for this structure is a summary of the data presented in Table 3-4.
- (5) The data depicted for this structure is a summary of the data presented in Table 3-5.
- (6) The data depicted for this structure is a summary of the data presented in Table 3-6.
- (7) The data depicted for this structure is a summary of the data presented in Table 3-7.
- (8) The data depicted for this structure is a summary of the data presented in Section 8 of DBR-0013618 (Ref. 16).

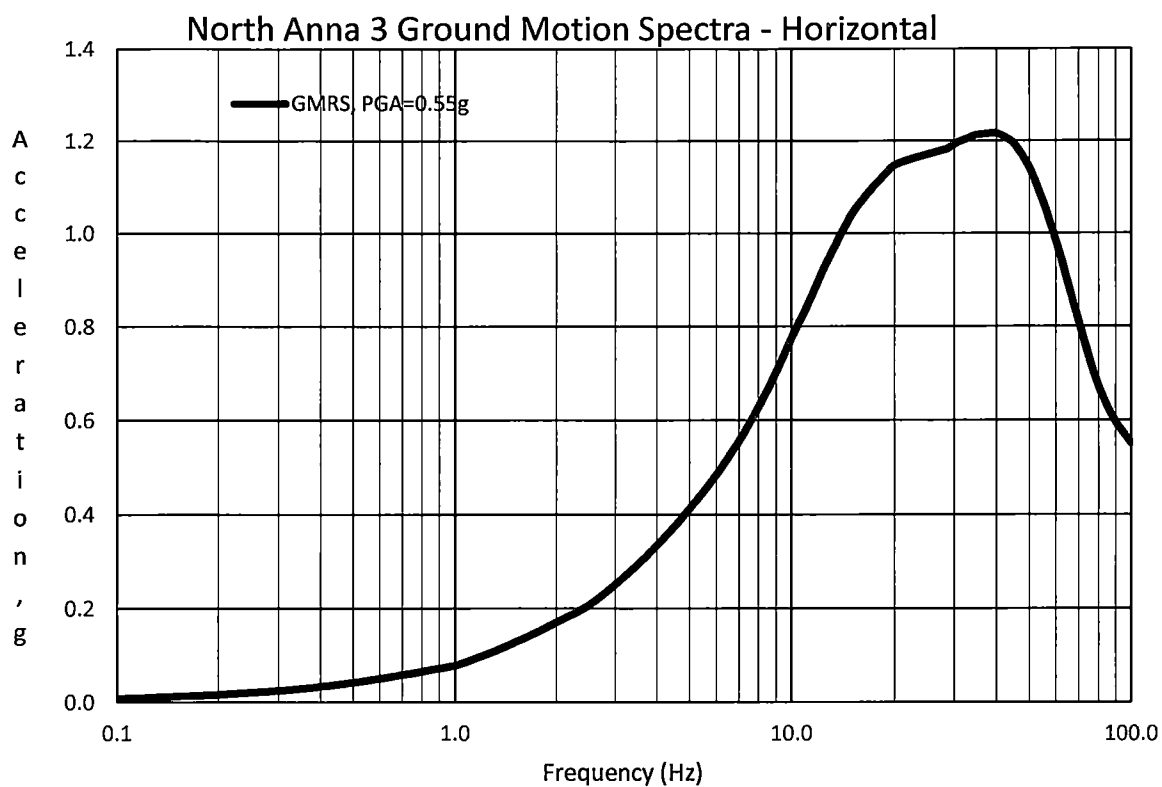


Figure 3-1: North Anna 3 Site-Specific Ground Motion Spectra – Horizontal, 5% Damped

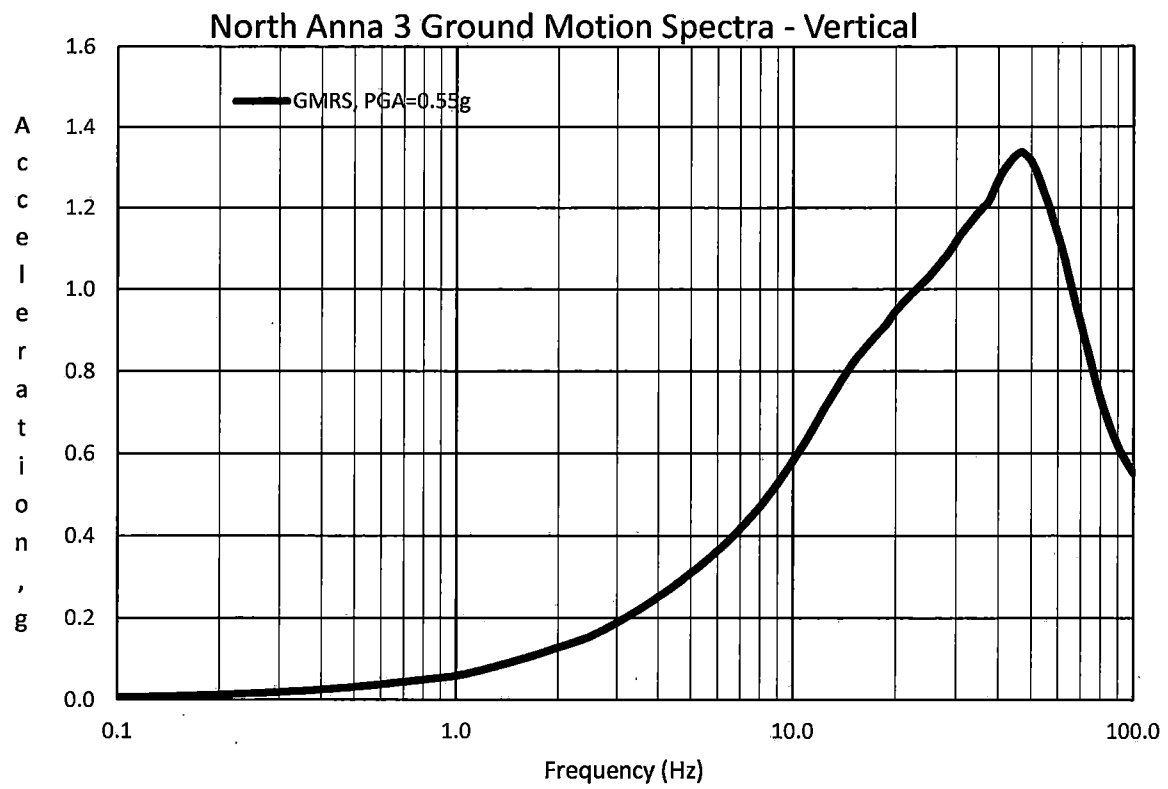


Figure 3-2: North Anna 3 Site-Specific Ground Motion Spectra – Vertical, 5% Damped



## **4.0 ACCIDENT SEQUENCE HCLPF ANALYSIS**

An event tree structure, similar to that used in the generic ESBWR SMA, is used to illustrate the accident sequences analyzed in the NA3 site-specific SMA.

The seismic event tree is used to identify those structures and components requiring seismic capacity analysis and to identify the HCLPFs of individual seismic-induced accident sequences.

If a system, S, (or sequence) contains two components (A, B) combined with OR logic, the failure of any component will fail the system ( $S = A + B$ ), and the cumulative fragility distribution of the system is governed by the fragility distribution of the weakest component. This principle is applied to the system fault trees, which generally are comprised of OR gates.

If two elements operate in AND logic, only the failure of both components will fail the system ( $S = A * B$ ), and the cumulative fragility distribution of the system is governed by the fragility distribution of the most seismically rugged component. This principle is applied to accident sequences, which are composed of AND elements.

The scope of this analysis includes both at-power and shutdown seismic-induced accident scenarios. The seismic accident analysis for the at-power condition is discussed in detail in Section 15.4.1 of Ref. 1, and the analysis for the shutdown condition is discussed in Section 15.4.2 of Ref. 1. The associated top events in the NA3 site-specific SMA are shown in Table 4-1.





Table 4-1: Seismic Event Tree Nodal HCLPF Equations

| Top Event                             | Nodal HCLPF Equations <sup>(1) (2)</sup>   |
|---------------------------------------|--|
| Structural Integrity (SI)             | $FSTRUC = FRBLDG + FCONT + FPEDST + FRPV + FCTRBLDG + FFWSC = (1.22g + 2.41g + 6.76g + 1.06g + 1.71g + 1.10g) = 1.06g$                                       |
| DC Power (DC)                         | $FDCP = FBTR + FCTRAY + FMCC = (0.92g + 0.92g + 0.92g) = 0.92g$  |
| Reactivity Control System (SCRAM)     | $FRC = FFASSY + FCRDGTB + FSHRSPT + FCRDHS + FHYLTUT = (0.92g + 0.92g + 0.92g + 0.92g + 0.92g) = 0.92g$  |
| Safety Relief Valve (SRV)             | $FSRV = FSRV = 0.92g$  |
| Standby Liquid Control System (SLCS)  | $FSLCS = FACCT + FCHV + FSQUV + FPIP + FAOV = (0.92g + 0.92g + 0.92g + 0.92g) = 0.92g$   |
| Isolation Condenser (IC)              | $FIC = FPIP + FICHEX + FMOV + FNOV = (0.92g + 0.92g + 0.92g + 0.92g) = 0.92g$  |
| Depressurization Valve (DPV)          | $FDPV = FDPV = 0.92g$  |
| Gravity-Driven Cooling System (GDSCS) | $FGDCS = FCHV + FSQUV + FPIP = (0.92g + 0.92g + 0.92g) = 0.92g$  |
| Vacuum Breakers (VB)                  | $FVB = FVBS = 0.92g$   |
| Passive Containment Cooling (PCCS)    | $FPCCS = FPCCSHEX + FPIP = (0.92g + 0.92g) = 0.92g$  |
| IC/PCC Pool Interconnection (PI)      | $FIC/PCCINT = FIC/PCCI = 0.92g$  |
| Fire Protection Water (FPW)           | $FFPW = FPUMPDD + FTANK + FPIP + FFWSC = (0.92g + 2.82g + 0.92g + 1.10g) = 0.92g$  |
| Structural Integrity Shutdown (SIS)   | $FSTRUCSH = FRBLDG + FCTRBLDG + FRPV + FFASSY + FPEDST + FSHRSPT + FCONT + FCRDHS = (1.22g + 1.71g + 1.06g + 0.92g + 6.76g + 0.92g + 2.41g + 0.92g) = 0.92g$ |

Notes to Table 4-1:

- (1) Refer to nodal fault trees in Section 5.0 for descriptions of the individual fragility basic events.
- (2) Per the MIN-MAX convention used, the overall fragility of a group of inputs combined using OR logic is determined by the lowest fragility input.



## 5.0 RESULTS

The results of the NA3 site-specific SMA HCLPF accident sequence analysis are shown on Table 5-1, Table 5-2, and Table 5-3, and in Figure 5-1 through Figure 5-6. The seismic fault trees for each top event are presented in Figure 5-7 through Figure 5-20.

As supported by the structural seismic fragility analysis and the component seismic fragility assumption in Section 2.1, the NA3 site-specific SMA established that no accident sequence has a HCLPF capacity lower than 0.92 (i.e.,  $1.67 \times \text{SSE}$ ). As such, the NA3 site-specific ESBWR plant and equipment are shown to be capable of withstanding an earthquake with a magnitude at least 1.67 times the SSE.

**Table 5-1: HCLPF Derivation for Figure 5-1 and Figure 5-2 (MIN-MAX Method)**

| SET Sequence      | Sequence HCLPF <sup>(1)</sup>   |
|-------------------|---|
| <u>Figure 5-1</u> |   |
| Sequence 3        | $\text{PI} \times \text{FPW} = 0.92\text{g} \times 0.92\text{g} = 0.92\text{g}$   |
| Sequence 4        | $\text{PCCS} = 0.92\text{g}$  |
| Sequence 5        | $\text{VB} = 0.92\text{g}$  |
| Sequence 6        | $\text{GDCS} = 0.92\text{g}$  |
| Sequence 7        | $\text{DPV} = 0.92\text{g}$   |
| Sequence 8        | $\text{SRV} = 0.92\text{g}$   |
| Sequence 11       | $\text{SCRAM} \times \text{PI} \times \text{FPW} = 0.92\text{g} \times 0.92\text{g} \times 0.92\text{g} = 0.92\text{g}$ |
| Sequence 12       | $\text{SCRAM} \times \text{IC} = 0.92\text{g} \times 0.92\text{g} = 0.92\text{g}$                                       |
| Sequence 13       | $\text{SCRAM} \times \text{SLCS} = 0.92\text{g} \times 0.92\text{g} = 0.92\text{g}$                                     |
| Sequence 14       | $\text{SCRAM} \times \text{SRV} = 0.92\text{g} \times 0.92\text{g} = 0.92\text{g}$                                      |
| Sequence 15       | $\text{DC} = 0.92\text{g}$  |
| Sequence 16       | $\text{SI} = 1.06\text{g}$  |
| <u>Figure 5-2</u> |   |
| Sequence 16       | $\text{IRWCU} = 0.92\text{g}$   |
| Sequence 17       | $\text{SI} = 1.06\text{g}$  |

### Notes to Table 5-1:

- (1) Per the MIN-MAX convention used, the overall fragility of a group of inputs combined using AND logic is determined by the highest fragility input.

**Table 5-2: HCLPF Derivation for Figure 5-3, Figure 5-4, and Figure 5-5 (MIN-MAX Method)**

| SET Sequence      | Sequence HCLPF <sup>(1)</sup>                      |
|-------------------|--|
| <u>Figure 5-3</u> |  |
| Sequence 4        | $IC*FPW*GDCS = 0.92g*0.92g*0.92g = 0.92g$          |
| Sequence 5        | $IC*FPW*DPV = 0.92g*0.92g*0.92g = 0.92g$           |
| Sequence 8        | $IC*SRV*GDCS*FPW = 0.92*0.92g*0.92g*0.92g = 0.92g$ |
| Sequence 9        | $IC*SRV*DPV = 0.92g*0.92g*0.92g = 0.92g$           |
| Sequence 11       | $DC*IC = 0.92g*0.92g = 0.92g$                      |
| Sequence 12       | $SIS = 0.92g$                                      |
| <u>Figure 5-4</u> |  |
| Sequence 3        | $FPW*GDCS = 0.92g*0.92g = 0.92g$                   |
| Sequence 5        | $DC*FPW = 0.92g*0.92g = 0.92g$                     |
| Sequence 6        | $SIS = 0.92g$                                      |
| <u>Figure 5-5</u> |  |
| Sequence 2        | $SIS = 0.92g$                                      |

Notes to Table 5-2:

- (1) Per the MIN-MAX convention used, the overall fragility of a group of inputs combined using AND logic is determined by the highest fragility input.



Table 5-3: NA3 Shutdown Seismic Event Tree Sequences for Figure 5-6 (Sensitivity) (MIN-MAX Method)

| SET Sequence      | Sequence HCLPF <sup>(1)</sup>                        |
|-------------------|--|
| <u>Figure 5-6</u> |  |
| Sequence 4        | $IC*FPW*PI = 0.92g*0.92g*0.92g = 0.92g$              |
| Sequence 5        | $IC*FPW*PCCS = 0.92g*0.92g*0.92g = 0.92g$            |
| Sequence 6        | $IC*FPW*VB = 0.92g*0.92g*0.92g = 0.92g$              |
| Sequence 7        | $IC*FPW*GDCS = 0.92g*0.92g*0.92g = 0.92g$            |
| Sequence 8        | $IC*FPW*DPV = 0.92g*0.92g*0.92g = 0.92g$             |
| Sequence 10       | $IC*SRV*PI = 0.92g*0.92g*0.92g = 0.92g$              |
| Sequence 11       | $IC*SRV*PCCS = 0.92g*0.92g*0.92g = 0.92g$            |
| Sequence 12       | $IC*SRV*VB = 0.92g*0.92g*0.92g = 0.92g$              |
| Sequence 14       | $IC*SRV*GDCS*PI = 0.92g*0.92g*0.92g*0.92g = 0.92g$   |
| Sequence 15       | $IC*SRV*GDCS*PCCS = 0.92g*0.92g*0.92g*0.92g = 0.92g$ |
| Sequence 16       | $IC*SRV*GDCS*VB = 0.92g*0.92g*0.92g*0.92g = 0.92g$   |
| Sequence 17       | $IC*SRV*GDCS*FPW = 0.92g*0.92g*0.92g*0.92g = 0.92g$  |
| Sequence 18       | $IC*SRV*DPV = 0.92g*0.92g*0.92g = 0.92g$             |
| Sequence 20       | $IC*DC = 0.92g*0.92g = 0.92g$                        |
| Sequence 21       | $SIS = 0.92g$  |

Notes to Table 5-3:

- (1) Per the MIN-MAX convention used, the overall fragility of a group of inputs combined using AND logic is determined by the highest fragility input.

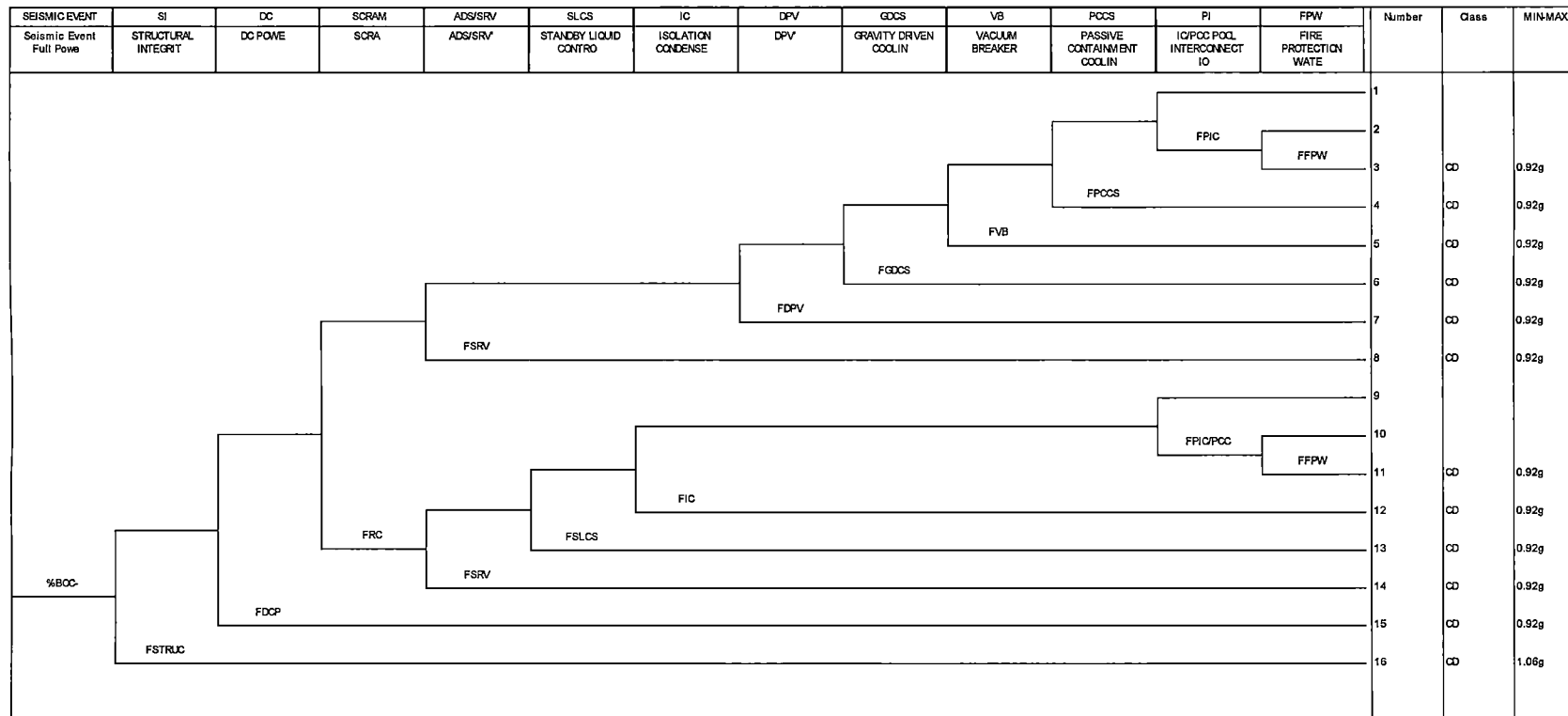


Figure 5-1: Seismic Event Tree (At Power)

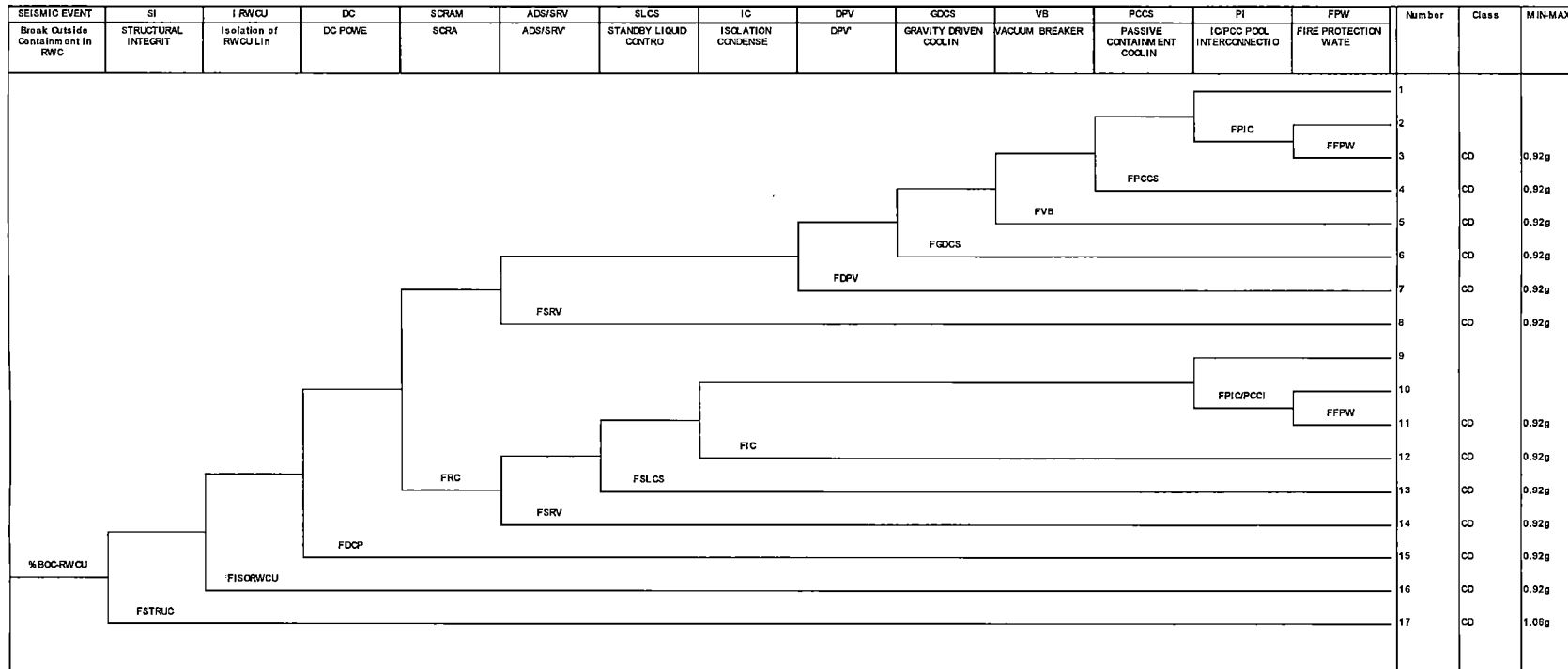


Figure 5-2: Seismic-Induced Break Outside Containment in RWCU Line Event Tree (At Power)

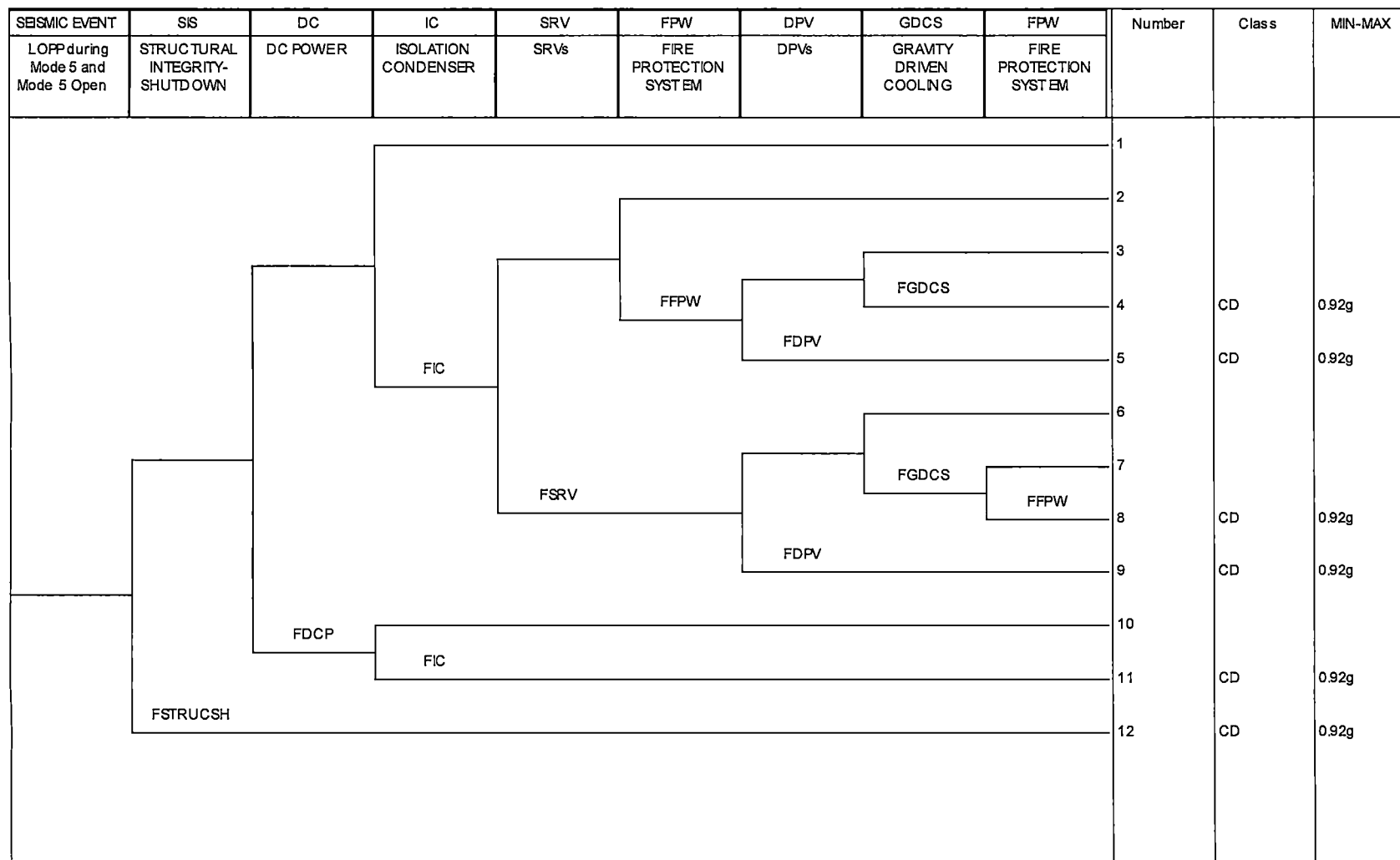


Figure 5-3: Seismic Event Tree – Shutdown Mode 5 and Mode 5 Open

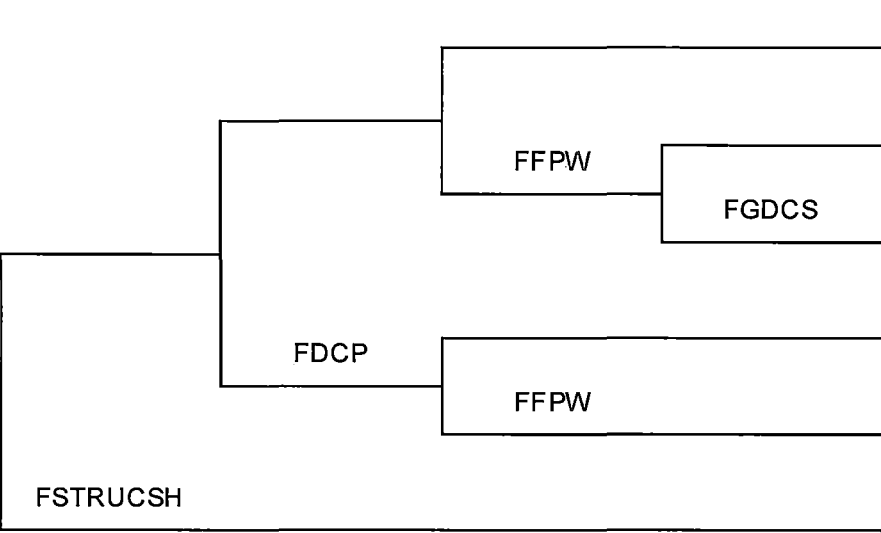
| SEISMIC EVENT  | SIS                                  | DC       | FPW                          | GDCS                         | Number | Class | MIN-MAX |
|--|--------------------------------------|----------|------------------------------|------------------------------|--------|-------|---------|
| LOPP DURING<br>MODE 6<br>UNFLOODED   | STRUCTURAL<br>INTEGRITY-<br>SHUTDOWN | DC POWER | FIRE<br>PROTECTION<br>SYSTEM | GRAVITY<br>DRIVEN<br>COOLING |        |       |         |
|  |                                      |          |                              |                              | 1      |       |         |
|  |                                      |          |                              |                              | 2      |       |         |
|  |                                      |          |                              |                              | 3      | CD    | 0.92g   |
|  |                                      |          |                              |                              | 4      |       |         |
|  |                                      |          |                              |                              | 5      | CD    | 0.92g   |
|  |                                      |          |                              |                              | 6      | CD    | 0.92g   |

Figure 5-4: Seismic Event Tree – Shutdown Mode 6 Unflooded



| SEISMIC EVENT                    | SIS                                 | Number | Class | MIN-MAX |
|----------------------------------|-------------------------------------|--------|-------|---------|
| LOPP DURING<br>MODE 6<br>FLOODED | STRUCTURAL<br>INTEGRITY<br>SHUTDOWN |        |       |         |
|                                  |                                     | 1      |       |         |
|                                  | FSTRUCSH                            | 2      | CD    | 0.92g   |

Figure 5-5: Seismic Event Tree – Shutdown Mode 6 Flooded

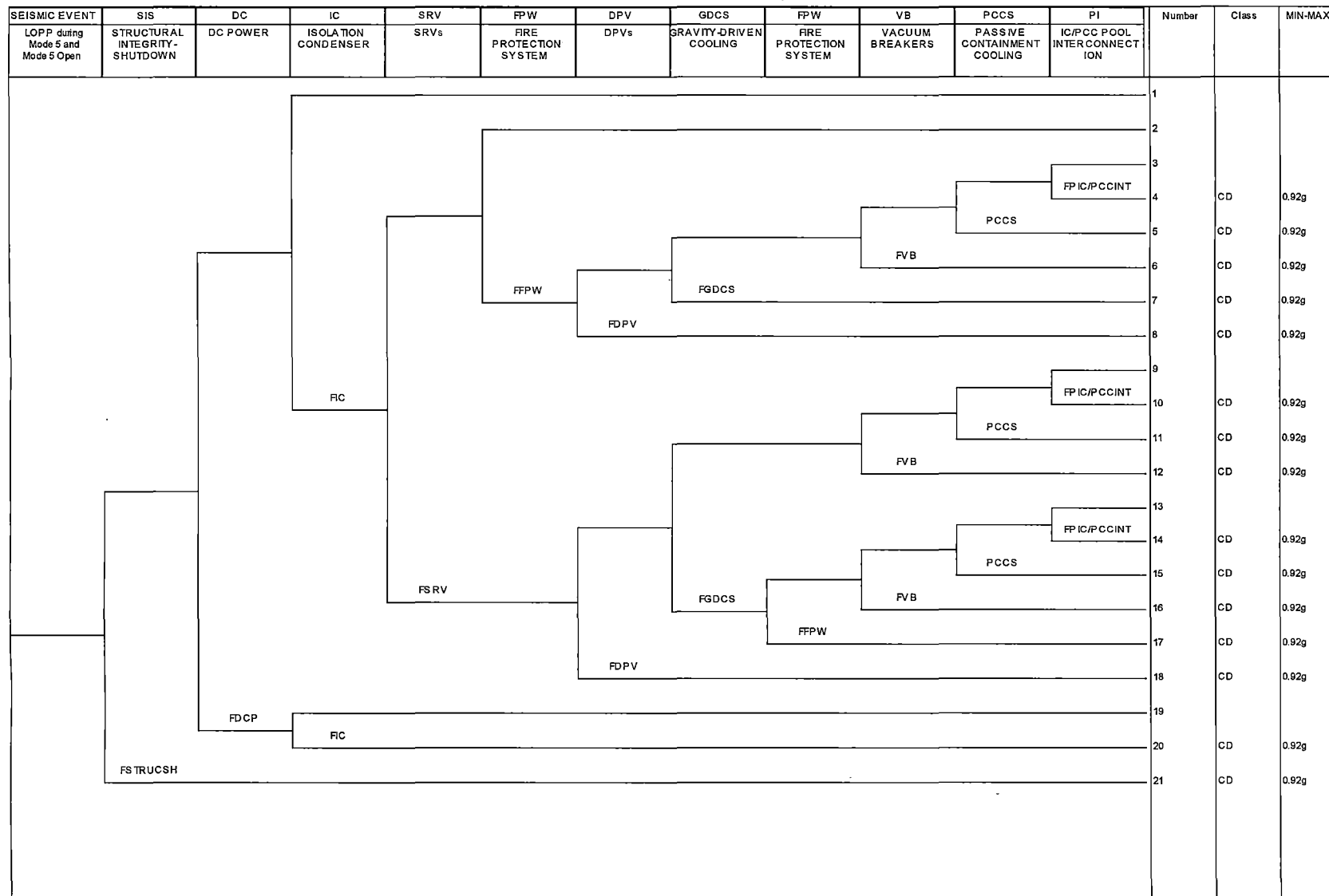


Figure 5-6: Seismic Event Tree – Shutdown Mode 5 and Mode 5 Open (Sensitivity)

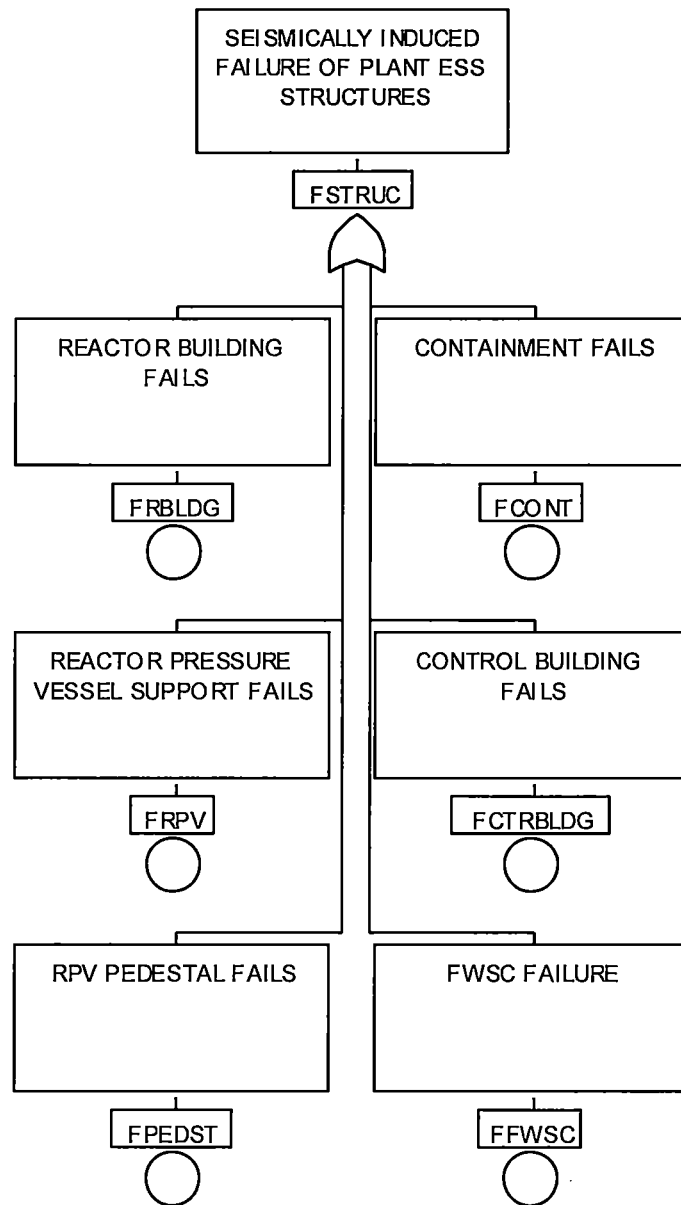


Figure 5-7: Structure Integrity (SI) Seismic Fault Tree (At Power)

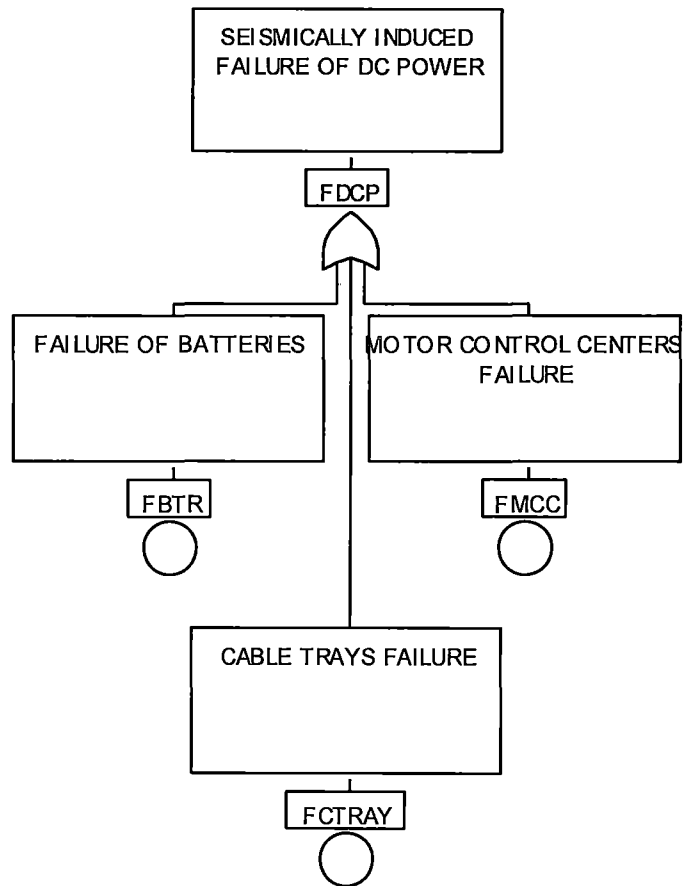


Figure 5-8: DC Power (DC) Seismic Fault Tree

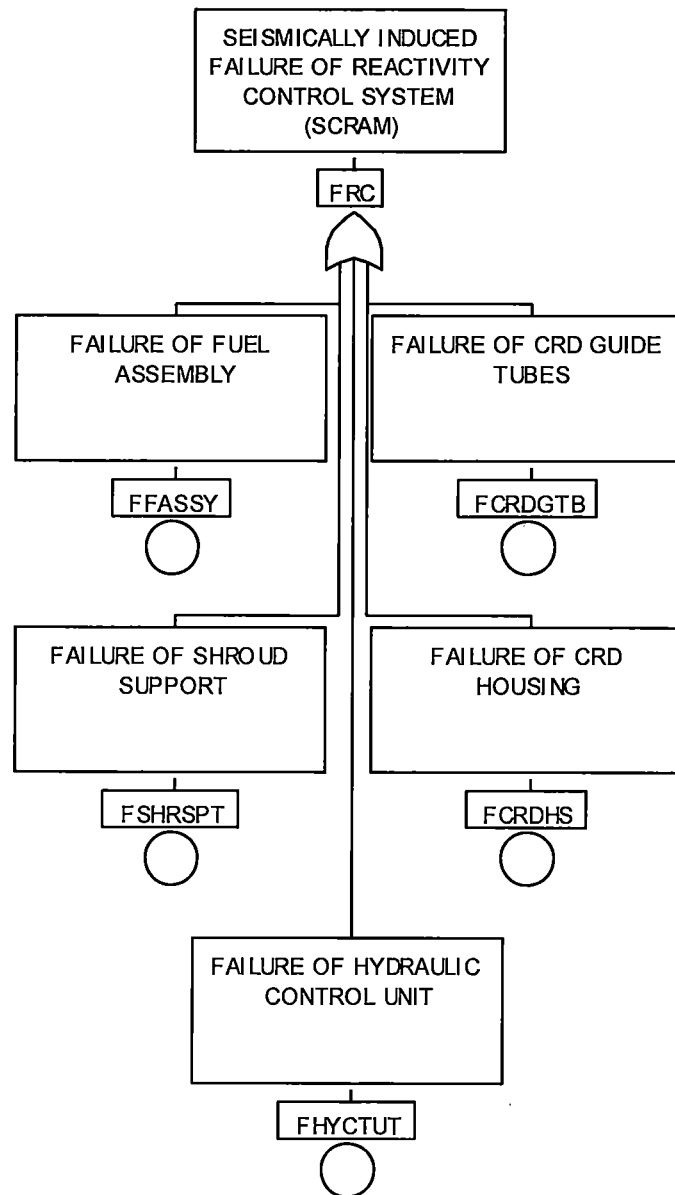


Figure 5-9: Reactivity Control System (SCRAM) Seismic Fault Tree

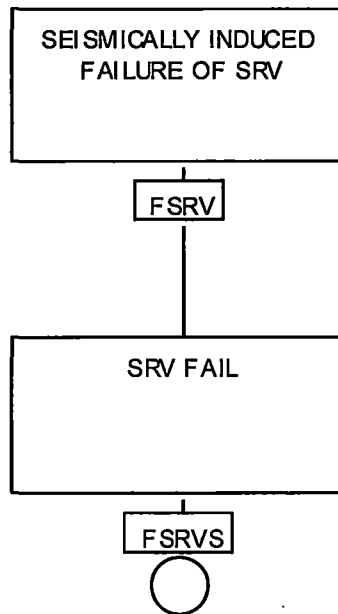


Figure 5-10: Safety Relief Valve (SRV) Seismic Fault Tree

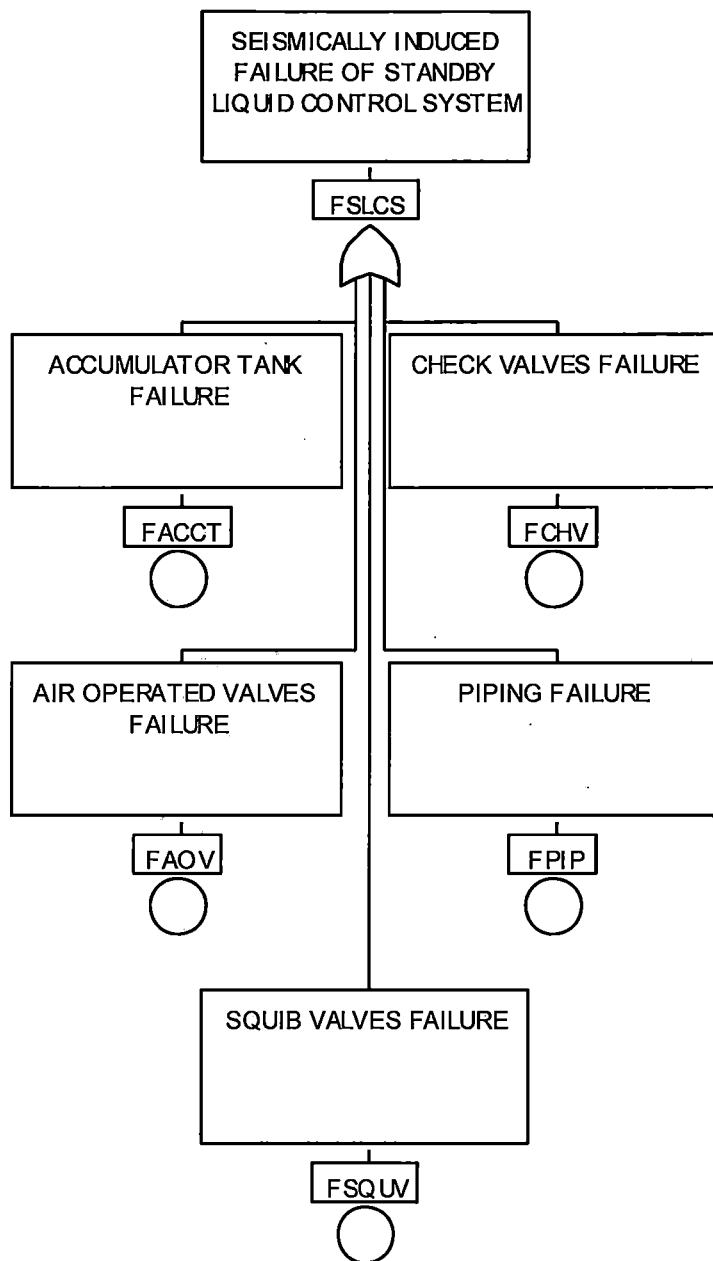


Figure 5-11: Standby Liquid Control System (SLCS) Seismic Fault Tree

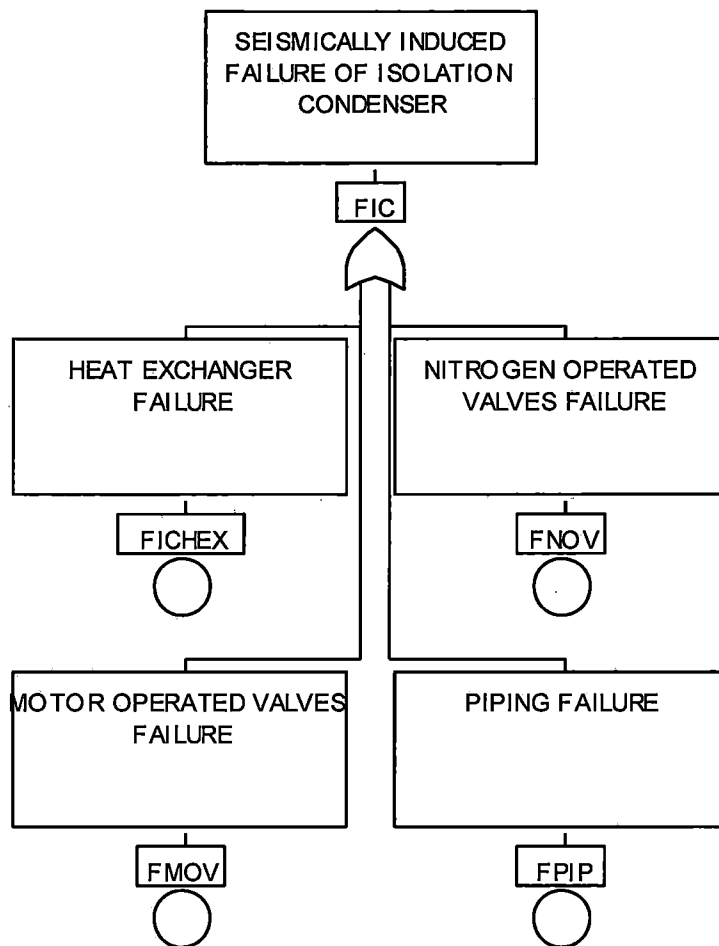


Figure 5-12: Isolation Condenser (IC) Seismic Fault Tree



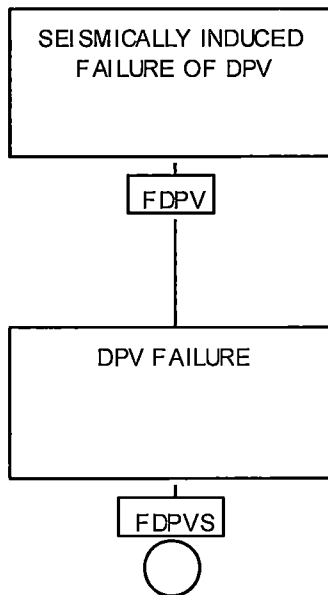


Figure 5-13: Depressurization Valve (DPV) Seismic Fault Tree

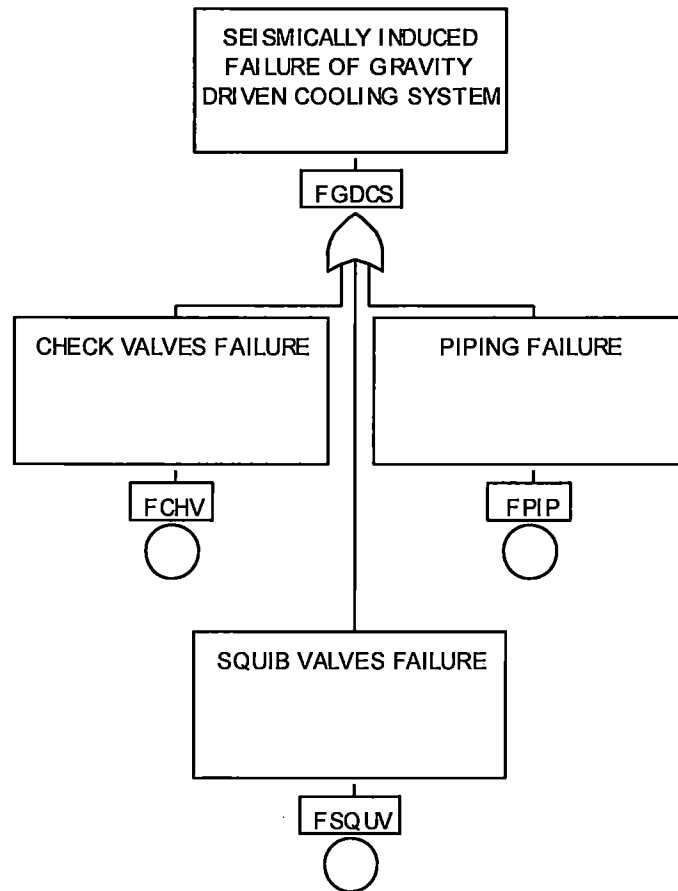


Figure 5-14: Gravity-Driven Cooling System (GDACS) Seismic Fault Tree

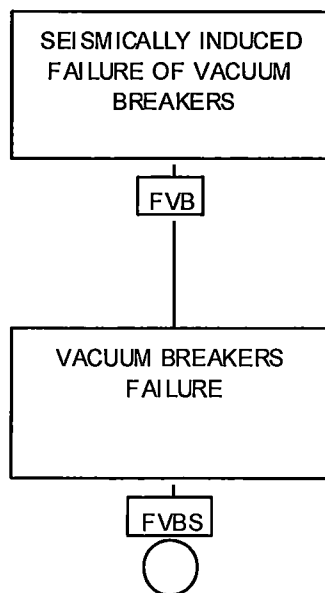


Figure 5-15: Vacuum Breakers (VB) Seismic Fault Tree

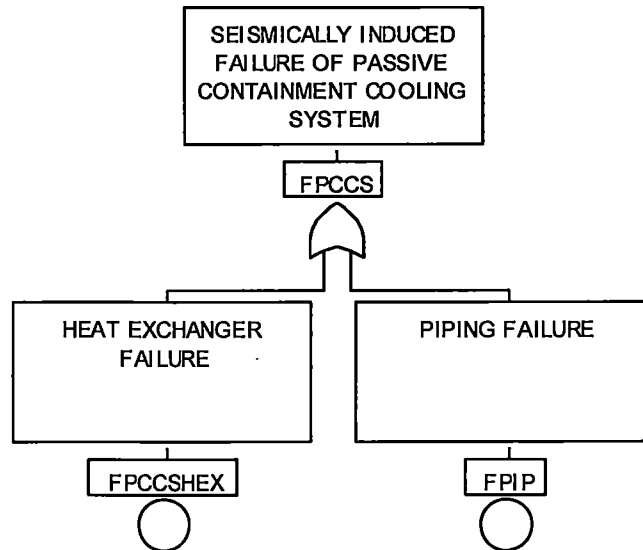


Figure 5-16: Passive Containment Cooling (PCCS) Seismic Fault Tree

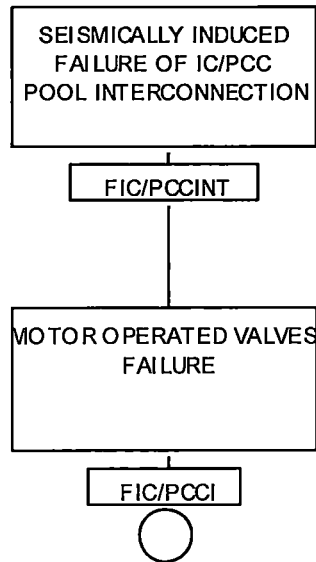


Figure 5-17: IC/PCC Pool Interconnection (PI) Seismic Fault Tree

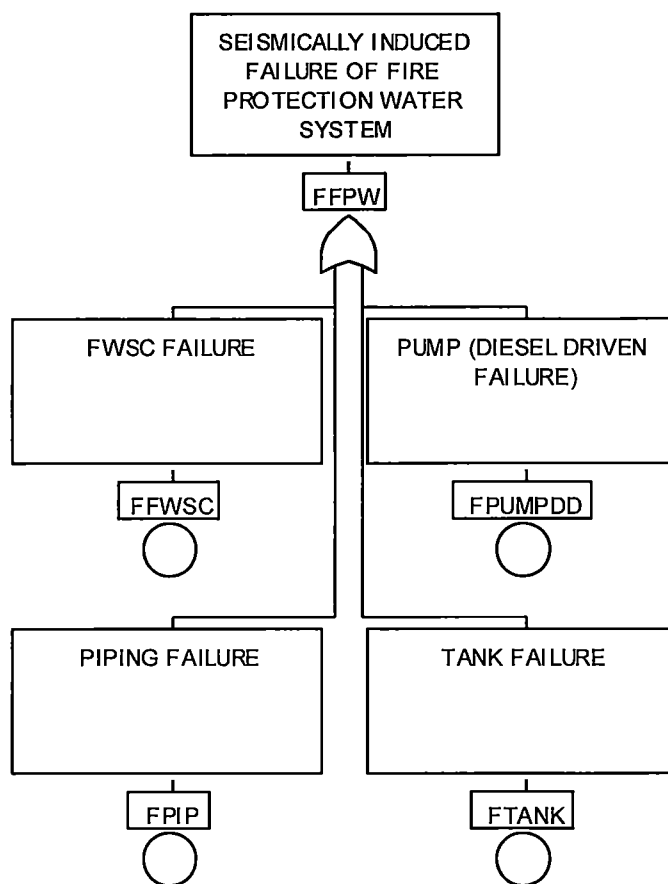


Figure 5-18: Fire Protection Water (FPW) Seismic Fault Tree

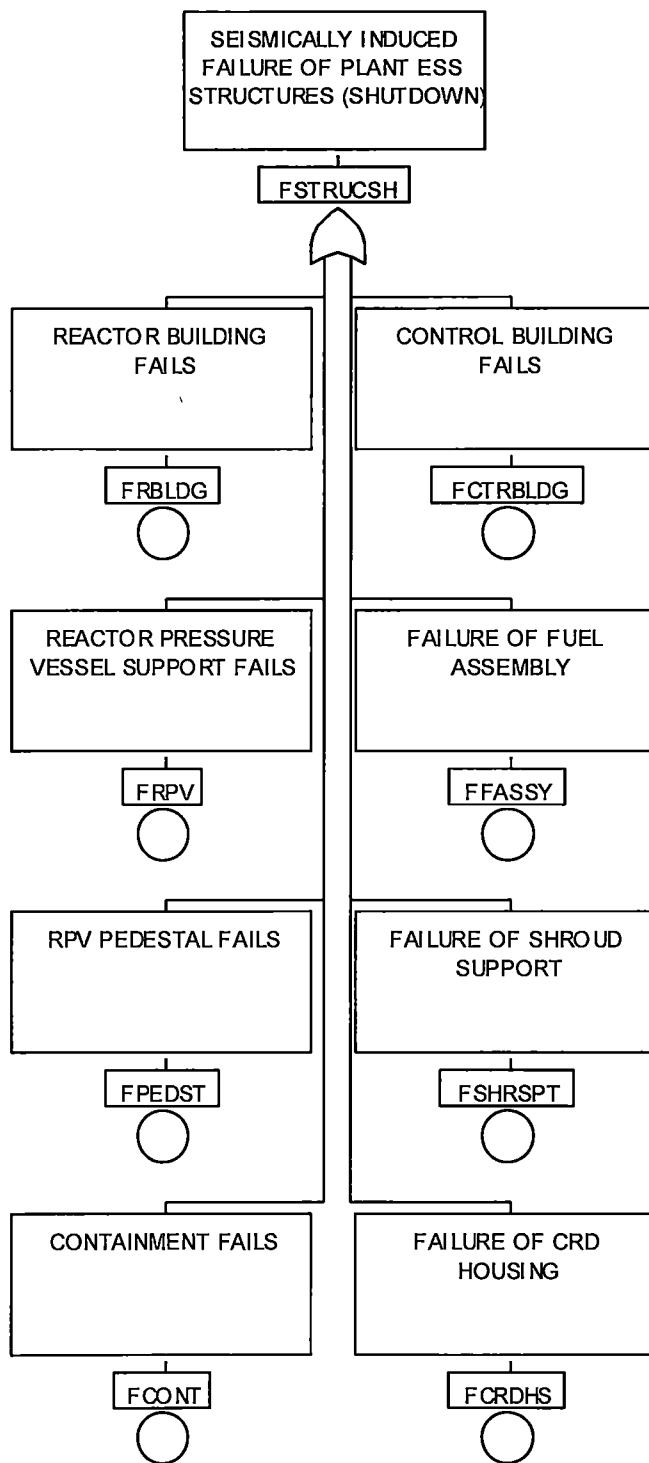


Figure 5-19: Structural Integrity Shutdown (SIS) Seismic Fault Tree

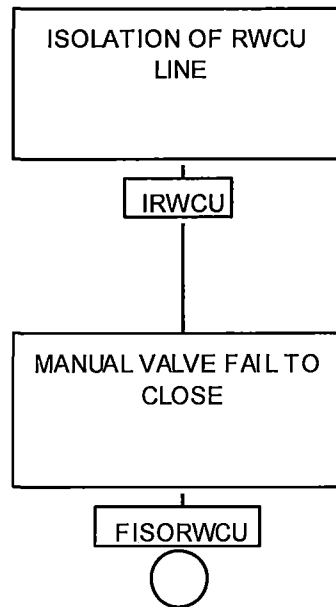


Figure 5-20: BOC in RWCU Line Seismic Fault Tree





## **6.0 INSIGHTS AND CONCLUSIONS**

The NA3 site-specific seismic margins HCLPF accident sequence analysis highlights the following key insights regarding the seismic capability of NA3.

- (1) The NA3 site-specific ESBWR is inherently capable of safe shutdown in response to strong seismic events.
- (2) The most significant HCLPF sequences are seismic-induced losses of DC power and ATWS due to seismic-induced failures of the fuel channels and the SLC tanks (both with 0.92g HCLPF).

The NA3 site-specific ESBWR is inherently capable of safe shutdown in response to strong magnitude earthquakes beyond the design basis earthquake. The structural HCLPF capacities are calculated, and the NA3 site-specific SMA is performed based on a commitment that the safety-related components and structures identified to be potentially important to the seismic risk analysis of the ESBWR plant will be designed with HCLPF capacities of at least 0.92g. On the basis of the analysis, the NA3 site-specific ESBWR has a plant level HCLPF value (0.92g) of at least 1.67 times the NA3 site-specific GMRS (0.55g PGA).



## 7.0 REFERENCES

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