ENCLOSURE 1

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Seismic Qualification of Spent Fuel in the Spent Fuel Racks

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NORTH ANNA 3 SEISMIC QUALIFICATION OF SPENT FUEL IN THE SPENT FUEL RACKS

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1. INTRODUCTION

1.1 Purpose

This report demonstrates the seismic adequacy of GE14E fuel in the spent fuel storage racks (FSR) for the North Anna 3 (NA3) ESBWR when subjected to a site-specific safe shutdown earthquake (SSE). The NRC Standard Review Plan Section 3.8.4, Appendix D ("Guidance on Spent Fuel Pool Racks"), provides guidance related to spent FSR and ensuring fuel integrity during storage in the racks. This analysis looks specifically at the seismic response of spent fuel while it is stored in the FSR located in both the spent fuel pool and the buffer pool deep pit. The results demonstrate that the GE14E fuel is qualified to withstand the NA3 site-specific seismic demand.

1.2 Background

GEH Letter to the NRC (Reference 1) was sent as part of the Design Control Document (DCD) approval process in response to NRC questions related to the adequacy of the fuel stored in the spent FSR of the ESBWR standard plant during an SSE event. The letter contained an enclosed engineering evaluation (Reference 2) which analyzed the adequacy of the in-rack fuel using the GEH methodology stipulated in NEDE 21175-3-P-A (Reference 3) for in-core fuel. This methodology ensures the adequacy of fuel by demonstrating that the peak accelerations in the horizontal and vertical direction are below allowable values. Due to the lack of GE14E peak acceleration acceptance criteria at this time, the acceptance criteria for GE14 fuel are utilized. The GE14 bundles are designed for the longer core length of existing Boiling Water Reactor (BWR) designs and have similar cross-sectional mechanical properties. Given the increased bending flexibility of the longer GE14 design, the limiting peak acceleration for GE14 will bound that of GE14E. For a full discussion of the application of GE14 acceptance criteria to the GE14E design see Reference 2.

2. ANALYSIS SUMMARY

For the current report, the transient analysis of the fuel in the fuel rack used for determining the peak fuel acceleration was repeated for NA3. Reference 4 contains the updated transient analysis for the spent fuel pool racks and Reference 5 contains the updated analysis for the buffer pool deep pit racks.

All models, assumptions, methods and load combinations were retained in the Reference 4 and Reference 5 analyses from their standard plant versions. The only difference is the results were generated using the NA3 site-specific SSE input response spectra and corresponding synthesized time histories for this evaluation of the limiting fuel accelerations in the fuel storage racks. This analysis provides information on the generation of the limiting acceleration results and comparisons to the allowable values.

Design Criteria

Reference 2 provides the GE14 horizontal and vertical peak accelerations at the in-core temperature [[.......]], bulk pool temperature limit [[.......]] and the maximum fuel rack exit temperature [[...........]]. The temperature dependent values are provided to account for the considerably lower temperature in the fuel pools than in the reactor. See Reference 2 for a full discussion of the generation of the temperature dependent acceleration limits for the spent fuel and the conservatism of using GE14 fuel limits for a GE14E evaluation.

Acceptance Envelope

The peak acceleration in the horizontal direction at in-core temperature is provided as [[........]] in Reference 1. The acceptance envelope as described in Section II.9 of Reference 3 for the combined vertical and horizontal accelerations of fuel at in-core temperature [[.......]] is shown in Figure 1. In addition, Figure 1 contains the same envelope for fuel at the maximum temperature of steam exiting a fuel assembly stored in a FSR. The maximum steam exit temperature [[.........]] is used as an upper bound for the possible temperature of spent fuel stored in a FSR and is considerably higher than the maximum bulk temperature [[.........]] limit in the spent fuel pools. The limiting horizontal and vertical

accelerations of the fuel at [[.........]] are calculated in Reference 1 and rely on the in-core limits scaled by [[

]]. Spent fuel located in a spent fuel FSR is qualified for horizontal and vertical accelerations that lie in the lower temperature envelope of Figure 1.

Time-History Analysis

The transient analysis of the fuel in the FSR used for determining the peak fuel acceleration was performed as part of the qualification of the adequacy of the FSR to the NA3 seismic demand. Reference 4 contains the analysis for the spent fuel pool FSR and Reference 5 contains the updated analysis for the buffer pool deep pit FSR.

The models used in these transient analyses are simplified finite element models of the FSR and fuel bundle. The fuel bundle was modeled as a continuous beam with gap elements at both the top and bottom of the bundle. An element damping value of 4% was used for both the FSR and the fuel bundles. A damping value of 4% is appropriate for the FSR per Reg. Guide 1.61 as the racks are made of welded steel. However applying a damping value of 4% to the fuel is extremely conservative. GEH design criterion (Reference 6) states 6% damping is to be used for fuel bundle analysis.

The time history results from the top node, middle node and bottom node of the fuel were extracted from the time history analyses. The maximum vertical accelerations were taken at each node for the FSR. In the horizontal direction, the middle node peak accelerations in the X and Y direction are combined by Square Root of the Sum of Squares (SRSS). To add conservatism, the non-time consistent accelerations are combined, meaning the maximum accelerations across the entire time history for a given fuel bundle are combined by SRSS regardless of the actual timing of these peaks in the analysis.

Input Exceedances

The following sections contain discussions of two potential non-conservatisms identified in the FSR qualifications which have the potential to impact the qualification of spent fuel in the two FSR designs. The first issue concerns the cross-correlation coefficients between different direction inputs motions for the spent fuel pool FSR being above the value outlined in Standard Review Plan (SRP) Section 3.7.1 ("Seismic Design Parameters"). The second issue is related to the horizontal time history inputs used in the transient analysis of the fuel in the buffer pool deep pit spent fuel FSR being generated from non-bounding response spectra.

Cross-Correlation of Spent Fuel Pool FSR Input Data

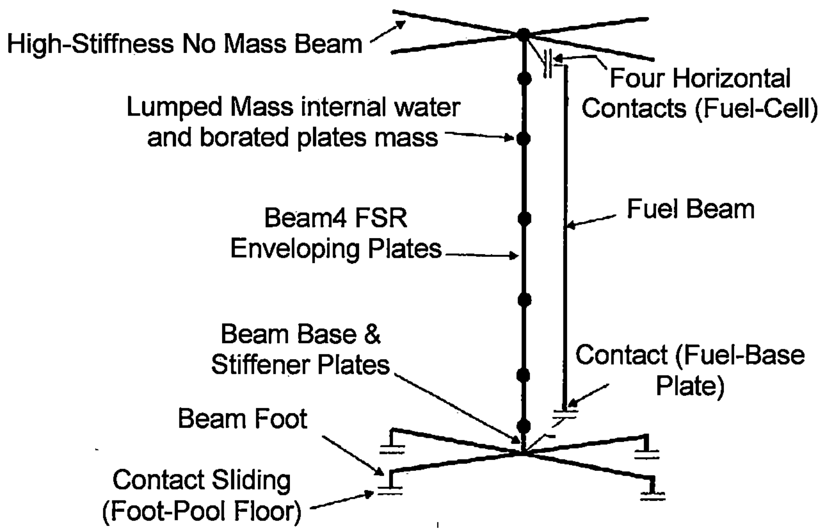
The maximum accelerations of the fuel in the spent fuel pool FSR used in this evaluation were generated in a non-linear time history analysis performed as part of the FSR qualification. The time histories used for that evaluation were not statistically independent as defined in SRP 3.7.1. SRP 3.7.1 defines statistical independence of two time histories as having a cross-correlation coefficient less than 0.16. The input time histories for this analysis have cross-correlation coefficients shown here:

N-S & E-W - 0.18

E-W & Vertical - 0.17

N-S & Vertical - 0.24

The impact of the exceedances in cross-correlation coefficients and their effect on the qualification of the spent fuel pool FSR is discussed below. In particular, the decoupling between the horizontal input and vertical input and the available margin for the fuel in spent fuel pool. The model of the fuel racks used in the spent fuel pool FSR time history evaluation is shown here:



The spent fuel pool FSR model consists of two overlaid beams (shown above as two separated beams for clarity) representing the fuel and the FSR enveloping plate/base plate. The model is tuned to the approximate natural frequency of the detailed model in both horizontal directions. The fuel beam's lowest node is coupled to the FSR in the horizontal directions and a contact element is used in the vertical direction which allows the fuel to lift off the base plate and then return to impact the base plate. The fuel's uppermost node has horizontal contact elements used to evaluate lateral impacts of the fuel with the upper grid structure of the FSR. Four rigid links at the base are connected to sliding contact elements which model sliding friction and contact with the floor. Upper rigid beams have constraints at the end which are used to simulate the displacement constraints imposed by the spent fuel pool FSR crossarms. Twenty of these simplified models are used in the full time history evaluation to assess the impact loads, displacements and peak accelerations of the fuel.

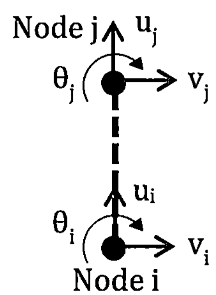
The impact of non-statistically independent time histories is zero if it can be shown that the response of the structure in each direction is decoupled from the input motion in the other two perpendicular directions. While this model is not totally decoupled, the vertical arrangement of the FSR/Fuel and the small displacements resulting from excitation mean that there will be little coupling between directional components and so the impact of non-independent time histories will be limited.

The stiffness matrix for an Euler-Bernoulli beam element in a two dimensional plane is given in Eq. (1) (from Reference 7). Notice that there is no coupling between the motion in the axial direction of the beam element (u) and the transverse direction (v). However, if the beams rotate sufficiently, stiffness components would exist that couples the vertical response to the horizontal input and vice versa due to the transformation of the FSR elements coordinate system to the global system.

$$\begin{bmatrix} F_{ui} \\ F_{vi} \\ M_{\theta i} \\ F_{uj} \\ F_{vj} \\ M_{\theta j} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & -X & 0 & 0 \\ 0 & Y_1 & -Y_2 & 0 & -Y_1 & -Y_2 \\ 0 & -Y_2 & Y_3 & 0 & Y_2 & Y_4 \\ -X & 0 & 0 & X & 0 & 0 \\ 0 & -Y_1 & Y_2 & 0 & Y_1 & Y_2 \\ 0 & -Y_2 & Y_4 & 0 & Y_2 & Y_3 \end{bmatrix} \begin{Bmatrix} u_i \\ v_i \\ \theta_i \\ u_j \\ v_j \\ \theta_j \end{Bmatrix} \quad (1)$$

Where: $X = \frac{AE}{L}$ $Y_1 = \frac{12EI}{L^3}$ $Y_2 = \frac{6EI}{L^2}$ $Y_3 = \frac{4EI}{L} Y_4 = \frac{2EI}{L}$

And:



The horizontal displacements at the top of the FSR are small and the resulting coupled stiffness terms are also small. Additionally, as moments are not transferred from the FSR to the fuel, there is no coupling between the rotation of the FSR and the fuel's response. Thus, for this model the vertical and horizontal responses can be considered practically decoupled and there is little concern that the cross-correlation between the E-W and Vertical and N-S and Vertical time history inputs will result in non-conservative responses.

A similar justification exists between the input in one horizontal direction and the response in the other horizontal direction as the 3-Dimensional beam equations don't have coupling terms between them when the local and global coordinate systems are aligned. Coupling terms will only exist if the fuel experiences rotation

about the vertical direction. However, the fuel beam is axisymmetric and torsional moments aren't transferred from the FSR to the fuel so no fuel rotation about the vertical direction occurs. Thus, the horizontal inputs are decoupled and there is no effect of cross-correlation coefficient exceedances between the horizontal direction input and perpendicular response of the fuel.

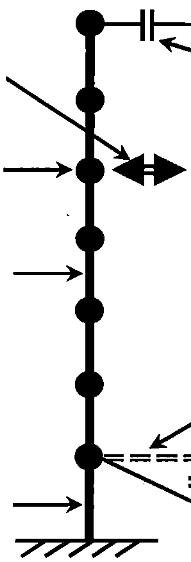
The design margins of the spent fuel pool fuel are discussed next to ensure that minor increases in accelerations do not impact the qualification.

The site-specific peak horizontal and vertical acceleration of the fuel in the spent fuel pool FSR are given in Table 2 and equal to [[ ]] and [[ ]]. Looking at the [[ ]] fuel envelope in Figure 1 at a peak vertical acceleration of [[ ]] the maximum horizontal acceleration is [[ ]]. This means that the horizontal acceleration would have to increase by over 800% to be outside the design envelope. Similarly, the vertical acceleration would have to increase by over 500% to be outside the acceptance envelope at the current horizontal acceleration. Given that the FSR model is practically decoupled and there are sizeable design margins, the cross-correlation coefficient exceedances will not have an impact on the qualification of the fuel in the spent fuel pool.

Non-Bounding Horizontal Spectra for Buffer Pool Deep Pit FSR Results

The maximum accelerations of the spent fuel in the buffer pool deep pit used for this evaluation were generated in a non-linear time history analysis performed as part of the buffer pool deep pit FSR qualification (Reference 5). The horizontal time history used for that evaluation was generated using response spectra for the upper buffer pool which does not envelope the response spectra for the deep pit (see Figure 2). While the vertical response spectra used in the evaluation was conservative (see Figure 3), horizontal exceedances represent a potential non-conservatism which is evaluated here for a potential impact on the qualification of the fuel.

The model used in the deep pit FSR time history evaluation is similar to the model used for the spent fuel pool with the exception that it is fixed at its base and there are no connections to other fuel racks at the top corners as shown here:



The deep pit FSR model is very similar to the spent fuel pool model in that the vertical response is practically decoupled from horizontal input due to the small deflections of the FSR and the fuel which limit cross coupling in the stiffness matrix for the fuel. Thus, the only concern of using non-bounding horizontal spectra is an increase in the horizontal peak acceleration.

To ensure the qualification of the fuel in the deep pit FSR the margin is determined for the horizontal direction acceleration.

The peak response spectra exceedance in the horizontal direction is 76% and occurs at 50 Hz. The effect of increasing the response by 76% in the horizontal direction is evaluated ignoring conservatism in the vertical response spectra. Note that exceedances in the horizontal spectra are below 40% except in the high frequency region from 43-62 Hz. A 76% increase would result in an increase in horizontal accelerations from [[ ]] to [[ ]] which will still be well within the design envelope margin as described in the following evaluation.

The existing horizontal margin relative to the [[ ]] design envelope is calculated at the existing vertical acceleration to ensure an increase in the horizontal peak acceleration would not invalidate the qualification of the fuel. The diagonal line of the outer envelope in Figure 1 connects the following points:

Horizontal Acceleration (g)	Vertical Acceleration (g)
[[ ]]	[[ ]]
[[ ]]	[[ ]]

The equation connecting these points is given in Eq. (2) as well as the limiting horizontal acceleration for the peak vertical acceleration of the spent fuel in the deep pit shown in Table 2. Eq. 2 is represented by dashed red lines in Figure 1.

[[ ]]

[[ ]] (2)

The margin for the horizontal is then given in Eq. 3.

$$Horizontal\ Margin = \frac{Envelope}{Actual} = \frac{[[\quad]]}{[[\quad]]} = 4.31 \qquad (3)$$

The horizontal loads would have to increase by a factor of 4.31 to exceed the design envelope, which is considerably greater than any spectral exceedances in the horizontal direction as shown in Figure 2. There is no concern about the adequacy of the fuel in the buffer pool deep pit.

3. RESULTS

Table 1 contains a repeat of Table 1 from Reference 2. The left half of Table 1 shows the *standard plant* peak acceleration acceptance criteria for the fuel at three temperatures. The right half of Table 1 provides the peak acceleration results for each of the FSR in the horizontal and vertical direction. Note that for the standard plant design, the vertical fuel acceleration in the buffer pool deep pit exceeds the allowable value at the in-core temperature of [[ ]]. This was justified in Reference 2 because it is not reasonable to analyze the fuel in the spent FSR at the reactor internal temperature. To show the fuel in the FSR is adequate, the allowable acceleration limits were also calculated for the bulk fuel pool temperature limit [[ ]] and the maximum exit temperature from the FSR [[ ]]. These limits show that the spent fuel acceleration will remain below the allowable for any reasonable pool temperature for the standard plant.

Table 2 is identical to Table 1 with the exception that the peak accelerations have been updated to the NA3 site-specific values. The NA3 site-specific peak accelerations are all below the allowable values at even the in-core temperature. This demonstrates that the GE14E fuel design is adequate for the NA3 seismic demands that it will be subject to in the spent FSR located in either the spent fuel pool or the buffer pool deep pit.

The results show that there is a reduction in the peak horizontal accelerations in both the spent fuel and buffer pools for NA3 relative to the standard plant design. In the vertical direction, the buffer pool spent fuel saw a reduction in the acceleration from the standard plant design. A small increase was seen in the spent fuel pool vertical acceleration which increased at NA3 to [[ ]]. Given the allowable acceleration at the more conservative in-core temperature of [[ ]] was [[ ]] g's, this increase does not affect the SSE qualification of the fuel in this location.

Figure 1 shows the vertical and horizontal response envelope at in-core temperature [[ ]] as well as the limiting FSR temperature [[ ]]. In addition, Figure 1 shows the location of the spent fuel FSR locations in the combined envelope. The spent fuel pool fuel has small vertical acceleration and is safely within the in-core temperature envelope. The buffer pool deep pit spent fuel is within the in-core temperature envelope but by a narrower margin but is

significantly within the envelope defined at the limiting FSR temperature. Both results demonstrate fuel adequacy for combined vertical and horizontal loading.

Table 1 - Peak Spent Fuel Acceleration - Standard Plant

	GE14 Fuel Design Criteria (In-core @ [[ ]]), g	GE14 Corrected Acceleration Limits (Pool @]]), g	GE14 Corrected Acceleration Limits (Pool @ [[ ]]), g	Spent Fuel Pool, g			Buffer Pool (Deep Pit), g		
Horizontal	[[.....]]	[[.....]]	[[.....]]		Middle			Middle	
					[[.....]]			[[.....]]	
Vertical	[[.....]]	[[.....]]	[[.....]]	Top	Middle	Bottom	Top	Middle	Bottom
				[[.....]]	[[.....]]	[[.....]]	[[.....]]	[[.....]]	[[.....]]

Table 2 – Peak Spent Fuel Acceleration – North Anna 3

	GE14 Fuel Design Criteria (In-core @ [[-]]), g	GE14 Corrected Acceleration Limits (Pool @ [[ ]]), g	GE14 Corrected Acceleration Limits (Pool @ [[ ]]), g	Spent Fuel Pool, g			Buffer Pool (Deep Pit), g		
Horizontal	[[.....]]	[[.....]]	[[.....]]		Middle			Middle	
					[[.....]]			[[.....]]	
Vertical	[[.....]]	[[.....]]	[[.....]]	Top	Middle	Bottom	Top	Middle	Bottom
				[[.....]]	[[.....]]	[[.....]]	[[.....]]	[[.....]]	[[.....]]

[[

]]

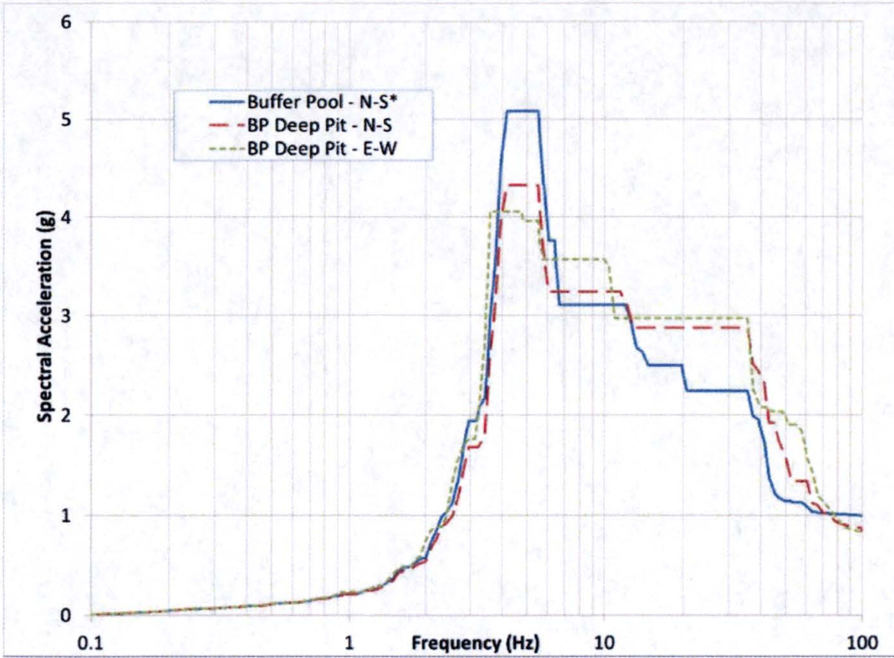


Figure 2: Comparison of Horizontal Response Spectra for BP and BP Deep Pit

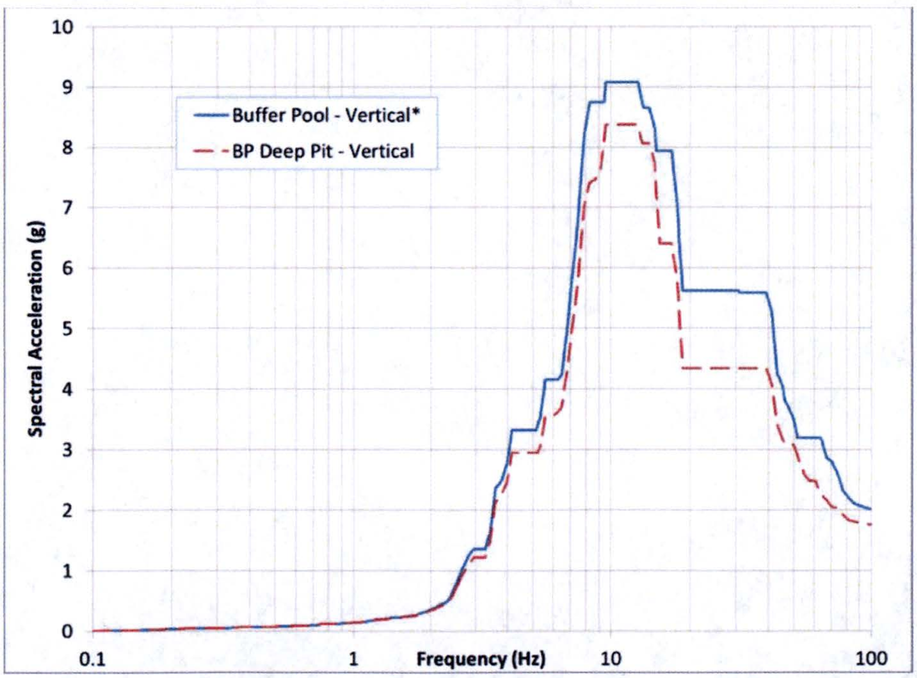


Figure 3: Comparison of Vertical Response Spectra for BP and BP Deep Pit

* Spectra used in the evaluation of the buffer pool deep pit FSR

4. CONCLUSION

The above document, in addition to the existing documentation in Reference 2 describing the methodology, demonstrate that the GE14E fuel design is adequate for the NA3 seismic demand that it will be subject to in the spent FSR located in either the spent fuel pool and the buffer pool deep pit.

5. REFERENCES

1) MFN 11-204, Jerald G. Head letter to the NRC, Clarifications Requested by NRC Staff on Economic Simplified Boiling Water Reactor Fuel Design.

2) DRF Section 0000-0139-1108 Rev. 0, “ESBWR Spent Fuel Seismic Qualification,” September 2011.

3) NEDE 21175-3-P-A, “BWR Fuel Assembly Evaluation of Combined SSE and LOCA Loadings (Amendment No. 3),” October 1984.

4) Document # 092-322-F-M-00001 Rev. 1, “Design Report of the Spent Fuel Storage Racks in the Fuel Building for North Anna 3,” June 2015.

5) Document # 092-322-F-M-00003 Rev. 1, “Design Report of the Spent Fuel Storage Racks in the Reactor Building for North Anna 3,” June 2015.

6) ESBWR Design Control Document/Tier 2, Rev. 10, Table 3.7-1, Damping Values for SSE Dynamic Analysis.

7) Pilkey, W. D. (2005). Formulas for Stress, Strain, and Structural Matrices (2nd Edition).