The Secretary of Energy
Washington, D.C. 20585

August 20, 2018

The Honorable Bruce Hamilton
Acting Chairman
Defense Nuclear Facilities Safety Board
625 Indiana Avenue NW, Suite 700
Washington, DC 20004

Dear Acting Chairman Hamilton:

This responds to the Defense Nuclear Facilities Safety Board's (Board) May 17, 2018, letter regarding the structural integrity of the H-Canyon Exhaust Tunnel (CAEX) at the Savannah River Site (SRS).

The Department of Energy (DOE) recognizes the structural integrity of the CAEX tunnel is important to ensuring continued safe operations and adequate protection of the public.

Although CAEX tunnel degradation has occurred, DOE has implemented compensatory measures to assure continued safe operations of H-Canyon while we perform a more detailed structural analysis of the tunnel. Preliminary results from computer modeling provide confidence that the proposed analysis and modeling methodology can be implemented and that the tunnel has sufficient safety margin to accommodate the anticipated design basis seismic demands. In addition, DOE and the SRS Management and Operations contractor, Savannah River Nuclear Solutions (SRNS), have commenced or are planning the following actions as detailed in the enclosed report:

1. Continued remote visual inspections of the tunnel with enhanced inspection techniques to monitor for additional degradation.
2. Completing the comprehensive "non-linear" structural analysis of the tunnel. This non-linear analysis, coupled with continued inspections, supports estimates of future viability of the tunnel over time. The results of the comprehensive non-linear analysis of the tunnel will inform a decision regarding potential alternatives/remedies.
3. SRNS is taking further action to ensure continued safe operations by enhancing training and procedures related to required actions following a seismic event.

In accordance with your reporting requirement, we will coordinate a briefing with the Board to discuss this response. We appreciate the Board's perspectives and look forward to continued positive interactions with you and your staff to ensure the continued structural integrity of the CAEX Tunnel.

If you have any questions, please contact me or Mr. Michael D. Budney, Manager of the Savannah River Operations Office, at (803) 952-7243.

Sincerely,

Rick Perry

Rick Perry

Enclosure

Enclosure for Continued Structural Integrity of the H-Canyon Exhaust Tunnel
Response to DNFSB Letter of May 17, 2018

The Department of Energy (DOE) recognizes from periodic remote inspections, that after over 60 years of service, the H-Canyon Exhaust (CAEX) Tunnel interior concrete surfaces have degraded to the point that aggregate and steel reinforcement bars are exposed. To ensure a qualified CAEX Tunnel is available and capable of performing its safety function, the DOE is pursuing a multi-prong/multi-year strategy that addresses the current tunnel conditions and capabilities, determination of remaining capacity, and plans for CAEX Tunnel repair and/or replacement, when the performance of a non-linear structural analysis is complete. The key elements of this strategy consist of:

1. **Continued Structural Integrity Program Inspections**
   Periodic remote visual inspections monitor current physical conditions to detect changes in the CAEX Tunnel by comparison with previous inspections. These inspections confirm conditions remain within the bounds of the qualification calculations and provide insight into the degradation rate for future planning. Inspections are conducted at 2-year intervals using a remotely operated crawler with video recording cameras.

   A new crawler is currently being developed. The new crawler will have higher camera resolution than the previous 2015 and 2017 inspections [19, 7], and it will have an elevated mast to enable viewing more of the wall surfaces. Fabrication and assembly of the unit is expected to be complete in 2018. Mock-up testing of the unit to simulate the challenging tunnel conditions will be performed in early 2019 to support the scheduled spring 2019 deployment. Additionally, a crawler chassis like the 2017 crawler is being purchased as a contingency.

   In collaboration with the Office of Environmental Management's Office of Technology Development, additional non-destructive examination sensors are also being investigated. Light Detection and Ranging (LiDAR) remote sensing technology that provides high-resolution topographic mapping and 3-dimensional surface modeling appears to be the most promising. Plans are to test the LiDAR sensor in the summer of 2018 to determine readiness for the tunnel deployment in 2019.

   Additionally, pole camera inspections are performed, such as the visual inspection of a concrete coupon in the CAEX Tunnel air stream. While this is a localized inspection, it does provide additional information to understand patterns of change.

2. **Use of Analytical Methods to Confirm Field Conditions meet Safety Requirements**
   The CAEX Tunnel has a Safety Class function to convey radiologically contaminated air from the Canyon to the Sand Filter during and after a Performance Category (PC)-3 seismic event. Exposure to nitric acid vapors, high air velocity, and water ingress has led to significant degradation of the CAEX Tunnel interior surfaces. Interior reinforcing bars are exposed in many areas [7]. Due to the extent of the degradation, traditional code-based qualifications efforts are no longer sufficient to show the CAEX Tunnel can perform its safety function with additional degradation. A non-linear probabilistic fragility analysis is being performed to evaluate if the CAEX Tunnel can meet the required PC-3 Target Performance Goal of an annual probability of failure of less than or equal to 2×10^{-4} per DOE-STD-1020-2012 [3] and American Society of Civil Engineers (ASCE)-43 [2].

A similar approach was used to qualify both F- and H-Canyon concrete structures in the mid- 1990's [15, 16]. Overall, this qualification effort began in late 2017. Due to the volume and complexity of calculations required it is scheduled to be completed in May 2019.

To date, the following progress has been made:

1) T-ESR-H-00034, Rev 0 – *Engineering Position on Chemically Altered Concrete in H-Canyon Exhaust Tunnel* was developed and issued in February 2018. This document describes the engineering basis and judgment used to determine the range of concrete degradation to be considered in the non-linear probabilistic fragility analysis of the CAEX Tunnel. The report concludes that consideration of up to -2 inches of potentially degraded concrete beyond the concrete surface baseline (located behind the backside of the innermost horizontal reinforcing bars) is appropriate given the probabilistic nature of the CAEX Tunnel analysis. The selected range has a conservative bias, appropriately accounts for the potential that the altered concrete material is degraded, and encompasses an independent peer review recommendation [17] that some material should be discounted.

2) T-TRT-H-00018, Rev 1 – *H-Canyon Exhaust (CAEX) Tunnel Non-linear Fragility Analysis Methodology and Acceptance Criteria* was developed and issued May 22, 2018. This document identifies the criteria used in the Structural Mechanics (SM) evaluation of the degraded CAEX Tunnel using non-linear probabilistic fragility techniques. Appropriate structural acceptance criteria and evaluation methods are described in detail. Revision 1 addresses comments (T-ESR-H-00039) [14] resulting from the independent peer review of Revision 0 of this document to ensure the specified approach is technically defensible.

3) Independent Peer Review – The independent peer review contract was awarded on March 21, 2018. According to the issued scope of work, T-SOW-G-00015, Rev 2, the peer reviewer initially reviewed the Methodology and Acceptance Criteria document (T-TRT-H-00018, Rev 0). A mid-point peer review is currently scheduled for mid-July 2018, and will focus on the specific permutations and parameter variations to be considered to ensure they adequately represent potential variability in the analysis and meet the Methodology and Acceptance Criteria. Once all calculations are completed, the peer reviewer will review a summary report of all calculations to ensure the methodology and acceptance criteria have been appropriately implemented. The target date for completion of [?] this review is early 2019.

4) Calculations T-CLC-G-00334 and T-CLC-G-00335 – Development of acceleration time series for the design basis earthquake (DBE) and seismic margins earthquake (SME) respectively (approx. 1000 pages each). These calculations were issued on May 17th and 21st, 2018, respectively. The CAEX Tunnel will be evaluated for two earthquake levels – the PC-3 DBE and a $1x10^{-4}$ hazard exceedance probability ground motion – an SME. In each of these calculations, fourteen real earthquake records (acceleration vs. time) are selected and modified so the resulting response spectra appropriately matches the target DBE or SME response spectrum per ASCE 43 [2] criteria. For each earthquake, from the

fourteen spectrum compatible acceleration time series developed, the eleven that satisfy the matching criteria without excessive conservatism are selected for further use in the CAEX Tunnel analysis.

5) T-CLC-H-01249 – *Non-linear Rotational Spring Properties* (approx. 900 pages). This was issued June 5, 2018. This calculation documents the development of the non-linear rotational spring properties (moment vs. rotation) used to represent the non-linear behavior of the wall-slab joints in the CAEX Tunnel. The calculations are based on concrete theory including concrete cracking, reinforcing bar yield and slip - up to ultimate moment. Based on the CAEX Tunnel layout, properties are developed for a single tunnel and a double tunnel section. Non-linear spring properties are developed for: 1) twelve locations in the single tunnel and twenty-one locations in the double tunnel; 2) two sets of concrete and rebar material properties – conservative (95% probability of non-exceedance), and median; and 3) six levels of concrete degradation, including zero to six inches of additional degradation beyond the baseline in one-inch increments. Therefore, almost 400 different sets of properties for non-linear rotational springs are calculated.

6) T-CLC-H-01271 – *Free-field SHAKE analysis* (approx. 700 pages). This calculation documents the soil column analyses used to determine lateral (racking) displacements (i.e., demands) in the soil column between the top and bottom elevations of each tunnel section. Initial computer runs have been made to determine the expected order of magnitude of racking displacements. Computer input files have been developed and are being checked for consistency before final batch runs are performed and the data processed and analyzed.

   In this calculation, one dimensional soil column analyses are performed using the SHAKE computer program. Calculations are performed for:

   a) Three sets of soil properties – best estimate, upper bound, and lower bound – per ASCE 4 [1];
   b) Two earthquake levels (DBE and SME);
   c) Eleven acceleration time series; and
   d) Two tunnel sections since the depth to the two sections are different.

   Therefore, at least 132 soil column analyses are performed. The SHAKE output is further processed to calculate the relative differential displacement in the soil column at the top and bottom elevations of the CAEX Tunnel. Once the relative displacements are determined, statistical analyses will be performed to determine average displacements and standard deviations.

   The preliminary results indicate relative displacement in the soil columns between elevations at the top and bottom of the CAEX Tunnel to be less than ⅛ inches for the DBE and less than ¼ inches for the SME. The DBE displacements are approximately the same as observed in prior CAEX Tunnel calculations [6] for similar seismic levels.

The 2014 SRS Probabilistic Seismic Hazard Analyses (PSHA) [18] contain maximum soil shear strains (median and one standard deviation) that can also be used to determine free-field lateral soil displacements and will be used for comparison purposes.

7) Single Tunnel ANSYS Model – Using the engineering simulation software suite from ANSYS, Inc., a 2-D finite element model of the single tunnel section has been developed using the preliminary rotational spring properties from T-CLC-H-01249 and is currently being checked. Initial runs have been made to assess the stability and lateral displacement capacity of the model and develop preliminary backbone curves. Routines have been developed to automate post-processing of results and generation of plots.

   A schematic of the model is shown in Figure 1. The model consists of rigid beam elements at the wall/slab joints, non-linear rotational springs at the top, bottom, and middle of each wall or slab, and beam elements (that represent the walls and slabs) connecting the non-linear rotational springs. Since the interior reinforcing bars are considered exposed and ineffective, there is essentially zero moment capacity for tension on the inside face of the tunnel. Under certain load conditions, a mechanism could form in the model allowing nearly free rigid body rotation of sections of the tunnel. The vertical and lateral soil loads have opposite effects on the tunnel – vertical soil loads cause downward deflection of the roof and outward deflection of the walls while lateral soil loads on the walls cause deflections in the opposite direction. Consequently, the model is expected to be stable under the combined vertical and lateral soil loading. Application of increasing levels of lateral racking displacements are expected to eventually cause the formation of a mechanism indicated by a significant reduction in load capacity or non-convergence of the solution.

   Preliminary backbone curve results indicate the structure (with conservative material properties) remains stable up to a lateral displacement of approximately 0.6 inches. This lateral displacement capacity was achieved for both 0 inches and 2 inches of additional concrete degradation. However, as expected, less force is required to achieve the same displacement in the more degraded model. While this is not a very large lateral displacement capacity overall, it is still several times larger than the preliminary DBE displacements from SHAKE (see discussion for Item #6 above). This is true, even considering the soil displacements discussed in Item #6 above, and will need to be factored to account for the relative stiffness between the soil and tunnel structure as recommended by Wang [13]. Preliminary results indicate a higher displacement capacity for median material properties, as expected, given the results from conservative material properties.

8) Double Tunnel ANSYS Model – A 2-D finite element model of the double tunnel section has been developed using the preliminary rotational spring properties from T-CLC-H-01249 and is currently being checked. Initial runs have been made to assess the stability and lateral displacement capacity of the model and develop preliminary backbone curves.

Since the Center Section Exhaust Tunnel does not contact process air, it is assumed to not be degraded in the model, the double tunnel model is inherently more stable than the single tunnel model and has less lateral displacement compared to the single tunnel for the same lateral load. A schematic of the model is shown in Figure 2.

Over the next several months the focus will be on the following activities:

1) Completion of soil column displacement analyses (T-CLC-H-01271), including statistical analyses of resulting displacements.

2) Continued testing and verification of the ANSYS models – A detailed review of the ANSYS model results will be conducted to ensure the model is behaving as expected at all loading phases – gravity loads, low level seismic loads, and increasing seismic loads until significant loss of capacity or solution non-convergence. At least informally, this testing will involve comparison of ANSYS results with those from hand calculations and alternative calculation methods and programs to provide further confidence in results.

3) Production runs of ANSYS models to produce backbone curves (pushover analyses) – Final production runs of the ANSYS models will be performed. At least 16 different pushover analyses are required to determine results from the single and double tunnels, conservative and median material properties, two different seismic load configurations, upward and downward vertical seismic loads, and pushover of the CAEX Tunnel models to the left and to the right. The pushover analyses will be run until a significant decrease in capacity occurs or non-convergence of the solution occurs.

4) A Mid-Point Peer Review is scheduled for summer of 2018. The focus will be on the specific permutations and parameter variations to be considered to ensure they adequately represent potential variability in the analysis and meet the Methodology and Acceptance Criteria.

Subsequent calculations will be performed as described below to determine the annual probability of failure of the CAEX Tunnel.

1) Calculation of non-linear hinge failure probabilities: Based on the reinforced concrete section properties and reinforcing details, a fragility curve (probability of failure, P_f, vs rotation) will be developed for each of the approximately 200 non-linear rotational springs.

2) Calculation of structural displacements: Using the design charts provided in Wang [13] the lateral soil displacements will be converted to structural displacements expected in the CAEX Tunnel. The lateral soil displacements will be increased or reduced based on the relative stiffness of the soil vs the CAEX Tunnel sections. An iterative process may be required since the lateral stiffness decreases with increasing levels of displacement (per the backbone curves).

3) Determination of controlling hinge: The pushover analysis results can provide rotations at each hinge as a function of lateral displacement. This information will be used to determine a P_f vs lateral displacement fragility curve for each hinge in each model. Previously determined structural displacements will be used to guide the number of sub-steps needed in the pushover analyses to ensure sufficient points are generated on the fragility curve. The fragility of all ~200 hinges for each of the pushover analyses (roughly 3200 permutations) will be determined and a bounding fragility (that may consist of a single hinge or envelope of multiple hinges) will be determined.

4) Evaluation of analytical parameter variation: The impact on the probability of failure due to variation of the following parameters will be quantified by fitting the results to lognormal distributions:

   a. Ground motion (DBE and SME);
   b. Soil stiffness (Best estimate, upper bound, lower bound);
   c. Reinforced concrete material properties (95% and median);
   d. Plastic hinge fragility; and
   e. Concrete degradation (0 inches – 2 inches of additional degradation).

   A composite variability taking into consideration the variability of all the parameters will be determined.

5) Annual probability of failure calculation: The resulting composite variability will be combined with the median displacement capacity of each CAEX Tunnel section (single and double), the design displacement demand on each CAEX Tunnel section, and the slope of the seismic hazard curve to calculate an annual probability of failure of each CAEX Tunnel section.

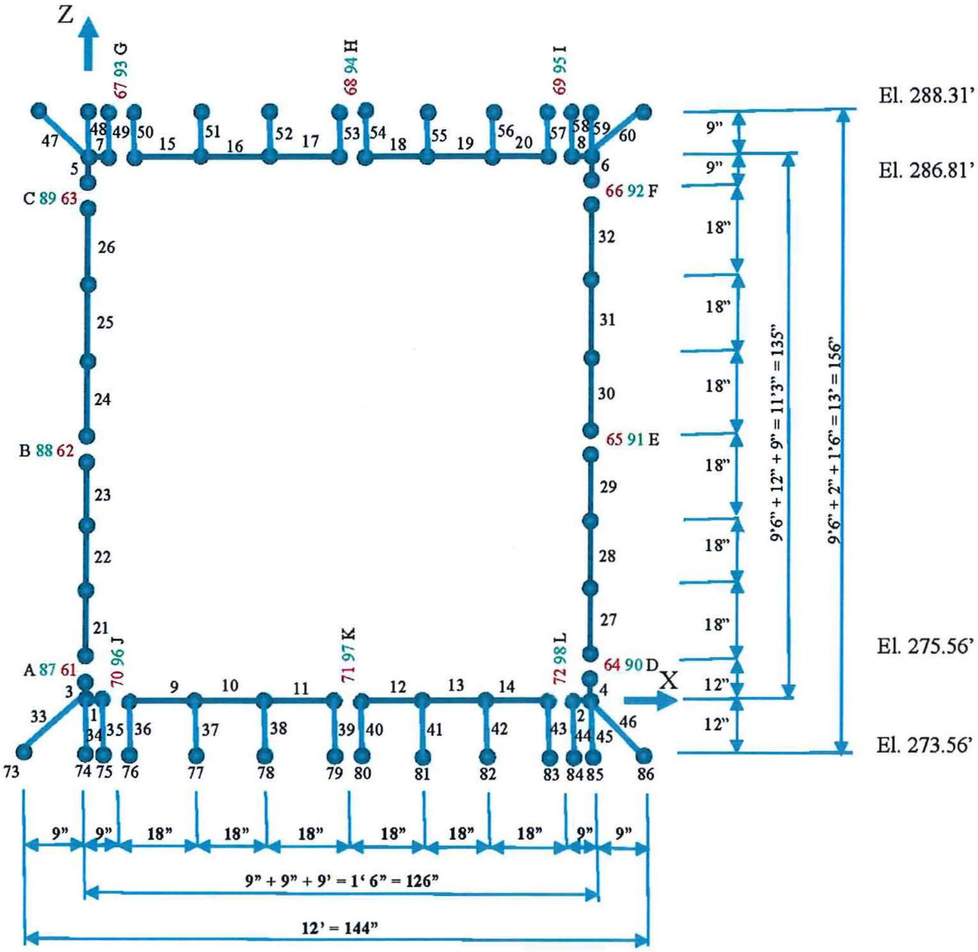
The discussion above provides a detailed description of the status of calculations related to the non-linear probabilistic fragility analysis of the CAEX Tunnels. Preliminary results from the single and double tunnel ANSYS models provide confidence that the proposed analysis and modeling methodology can be implemented because a converged solution can be obtained from the finite element analysis, and there is sufficient lateral displacement capacity to accommodate the anticipated lateral displacement demands. The single tunnel model is expected to be bounding over the double tunnel model as the undegraded Center Section Exhaust tunnel provides additional stability.

3. Tunnel Repair and/or Replacement

DOE Order (O) 413.3B, *Program and Project Management for The Acquisition of Capital Assets*, provides the program and project management direction for the acquisition of capital assets within DOE. Any alternative to the CAEX will be a capital asset project. The results of the comprehensive non-linear analysis of the tunnel will inform a decision regarding potential alternatives/remedies in accordance with DOE Order 413.3B. In the interim, refinement of pre-conceptual design(s) will continue in preparation for a Critical Decision (CD)-0.

In addition to the strategy discussed above, SRNS is taking further action to ensure continued safe operations through addressing the following comments made by the Defense Nuclear Facilities Safety Board staff from a review of the H-Canyon Justification for Continued Operations (JCO):

- *SRNS should evaluate the need to reinforce continuing training for standby gang valve operators regarding JCO actions to take following a seismic event.*
    - SRNS has completed training on JCO requirements for all shifts.
- *SRNS should evaluate the need to conduct practical exercises/mini-drills for standby gang valve operators regarding JCO actions to take following a seismic event.*
    - H-Canyon personnel have created administrative checks (mini-drills) with regard to standby gang valve operator JCO actions and mini-drills will be conducted with all gang valve operators during the summer of 2018.
- *SRNS should evaluate procedure 221-H-121, "Seismic Event Standby" for possible improvements.*
    - SRNS has evaluated the procedure and identified that changes were required. The revised procedure is scheduled to be issued during the summer of 2018.

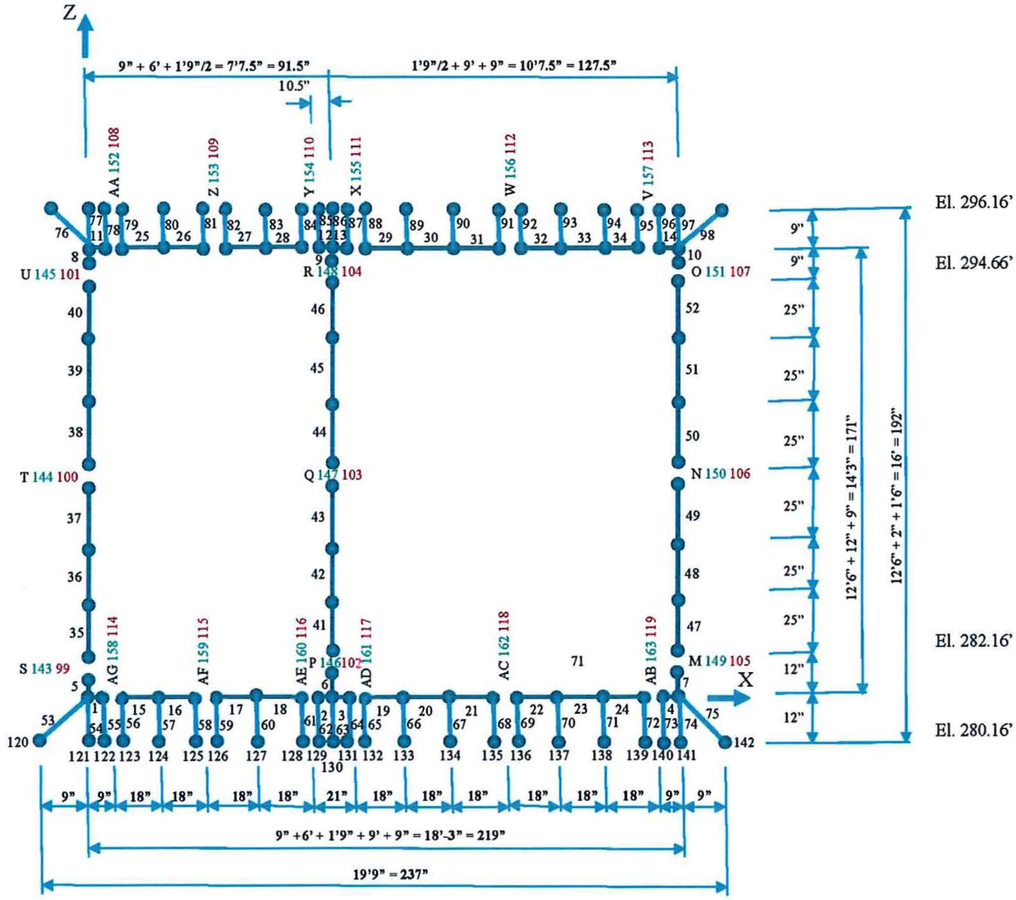


Legend

Green represents element numbers of horizontal and vertical translation springs at plastic hinges

Red represents element numbers of rotational springs at plastic hinges

Figure 1. ANSYS Single Tunnel Model



Legend
Green represents element numbers of horizontal and vertical translation springs at plastic hinges
Red represents element numbers of rotational springs at plastic hinges

Figure 2. ANSYS Double Tunnel Model

References:

[1] ASCE/SEI 4-16, *Seismic Analysis of Safety Related Nuclear Structures, American Society of Civil Engineers,* 2017.

[2] ASCE/SEI 43-05, *Seismic Design Criteria for Structures, Systems and Components in Nuclear facilities, American Society of Civil Engineers,* 2005.

[3] DOE-STD-1020-2012, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, October 2012.

[4] T-CLC-G-00334, *Development of Time Histories Compatible with SRS ES 01060 SDC-3 Site-Specific Spectra*, May 2018.

[5] T-CLC-G-00335, *Development of Time Histories Compatible with H-Canyon SME Site-Specific Spectra*, May 2018.

[6] T-CLC-H-01163, *Soil-Structure-Interaction (SSI) Analysis of Demand on Single and Double Tunnel to obtain Seismic Demands*, Revision 0, March 2016.

[7] T-CLC-H-01235, *H-Canyon Exhaust Tunnel (294-H) - 2017 Structural Integrity Inspection*, Revision 0, November 2017

[8] T-CLC-H-01249, *Rotational Spring Degraded Concrete Properties for ANSYS Model*, DRAFT, March 2018.

[9] T-CLC-H-01271, *Free-Field SHAKE Seismic Analysis for H Area Degraded Tunnel Segments,* DRAFT, March 2018.

[10] T-ESR-H-00034, *Engineering Position on Chemically Altered Concrete in H-Canyon Exhaust Tunnel*, Revision 0, February 2018.

[11] T-SOW-G-00015, *Structural Engineering Consulting Services, Revision 2*, December 2017.

[12] T-TRT-H-00018, *H-Canyon Exhaust (CAEX) Tunnel Non-linear Fragility Analysis Methodology and Acceptance Criteria*, Revision 1, May 2018.

[13] Wang, Jaw-Nan, *Seismic Design of Tunnels: A Simple State-of-the-Art Design Approach*, Parsons Brinkerhoff Quade & Douglas, Inc., June 1993.

[14] T-ESR-H-00039, *Response to CAEX Methodology Peer Review Comments*, Revision 0, May 2018.

[15] DOE/EH-0538, *Independent Review of the Seismic Analysis for the H-Canyon at the Savannah River Site,* December 1996.

[16] DOE/EH-0529, *Independent Review of the Seismic Analysis for the F-Canyon at the Savannah River Site*, August 1996.

[17] CTL Group, *Peer Review of Concrete Characterization for H-Canyon Exhaust at Savannah River Nuclear Site in Aiken, SC*, February 2018.

[18] *Probabilistic Seismic Hazard Analyses (PSHA) for the Savannah River Site (SRS), Rev. 2*, Fugro Consultants Inc., June 2014.

[19] T-CLC-H-01122, *H-Canyon Exhaust Tunnels - 2014 Structural Integrity Inspection Report*, Revision 1, December 2015.