Enclosure 3

Calculation No. VSC-04.3207, Revision 0,
VCC Concrete Thermal Fatigue Analysis
(1 paper copy)

EnergySolutions Spent Fuel Division	CALCULATION PACKAGE	Calc. Pkg No. VSC-04.3207 File No.: VSC-04.3207 Revision: 0

PROJECT/CUSTOMER:

VSC-04

TITLE:

VCC Concrete Thermal Fatigue Analysis

SCOPE:

Product:	☐ FuelSolutions™	☒ VSC-24		☐ Other ______
Service:	☒ Storage	☐ Transportation		☐ Other ______
Conditions:	☒ Normal	☒ Off-Normal	☐ Accident	☐ Other ______

Component(s):

VSC-24 system VCC reinforced concrete

Prepared by:

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RECORD OF REVISIONS

REV.	AFFECTED PAGES	AFFECTED MEDIA	DESCRIPTION	NAMES (Print or Type)	
				PREPARER	CHECKER
0	All	N/A	Initial Issue	Steven Sisley	Kent Smith

RECORD OF VERIFICATION

	YES	NO	N/A
(a) The objective is clear and consistent with the analysis.	☒	☐	
(b) The inputs are correctly selected and incorporated into the design.	☒	☐	☐
(c) References are complete, accurate, and retrievable.	☒	☐	☐
(d) Basis for engineering judgments is adequately documented.	☒	☐	☐
(e) The assumptions necessary to perform the design activity are adequately described and reasonable.	☒	☐	☐
(f) Assumptions and references, which are preliminary, are noted as being preliminary.	☐	☐	☒
(g) Methods and units are clearly identified.	☒	☐	☐
(h) Any limits of applicability are identified.	☒	☐	☐
(i) Computer calculations are properly identified.	☐	☐	☒
(j) Computer codes used are under configuration control.	☐	☐	☒
(k) Computer codes used are applicable to the calculation.	☐	☐	☒
(l) Input parameters and boundary conditions are appropriate and correct.	☒	☐	
(m) An appropriate design method is used.	☒	☐	
(n) The output is reasonable compared to the inputs.	☒	☐	
(o) Conclusions are clear and consistent with analysis results.	☒	☐	

COMMENTS:

No comments.

Verifier:

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1. INTRODUCTION

1.1 Objective

Determine if VCC reinforced concrete is susceptible to fatigue failure due to repeated cycles of seasonal and diurnal thermal variations over a period of 60 years.

1.2 Purpose

To address the (potential) issue of thermal fatigue of the VCC reinforced concrete for a storage period of up to 60 years. This evaluation supports the extension of the VSC-24 storage license from 20 years to 60 years.

1.3 Scope

These calculations only apply for the reinforced concrete of the VCC assembly.

2. REQUIREMENTS

2.1 Design Inputs

None.

2.2 Regulatory Commitments

None.

3. <u>REFERENCES</u>

3.1 Energy*Solutions* Calculation Packages

3.1.1 Calculation Package No. WEP-109.003.4, "VCC-24 Thermal-Hydraulic Analysis," Revision 2.

3.1.2 Calculation Package No. VSC02.6.2.3.18, "VCC Thermal Stress Analysis," Revision 2.

3.2 General References

3.2.1. American Concrete Institute, ACI 215R-74, *Considerations for Design of Concrete Structures Subjected to Fatigue Loading*, Revised 1992/Reapproved 1997.

4. ASSUMPTIONS

4.1 Design Configuration

The VCC assembly is a right circular cylindrical structure that is fabricated primarily from carbon steel and steel-reinforced normal-weight concrete. Carbon steel is used to form the inside cavity and air inlet and outlet ducts of the VCC assembly. Carbon steel is also used for the cask lid (i.e., weather cover) and the shield rings. The VCC assembly concrete is constructed from Type II Portland cement and is reinforced with A615 Grade 60 steel bars. The concrete has a density of 144 pounds per cubic foot (pcf) and a minimum compressive strength of 4,000 pounds per square inch (psi).

The VCC assembly has a 132.0-inch outside diameter, a 70.5-inch cavity diameter, and three different overall heights to accommodate the different MSB assembly configurations. The long, standard, and short VCC assembly overall heights are 225.1 inches, 213.0 inches, and 196.7 inches, respectively. The internal cavity of the VCC assembly is lined by a 1.75-inch thick carbon steel shell and a 2-inch thick carbon steel bottom plate. A carbon steel shield ring assembly is provided at the top end of the VCC assembly to reduce radiation streaming from the VCC annulus. The top end of the VCC assembly is covered with a ¾-inch thick lid that is secured to the VCC assembly by bolts.

4.2 Design Criteria

Thermal fatigue of the VCC reinforced concrete will not occur provided that the stress cycles in the VCC reinforced concrete are under the applicable S-N curves from ACI 215R-74 (Ref. 3.2.1).

4.3 Calculation Assumptions

4.3.1 Extreme fluctuations in ambient air temperature from -40°F to 100°F (i.e., seasonal variations) are conservatively postulated to occur 10 times per year.

4.3.2 Diurnal fluctuations in ambient air temperature are assumed to occur once per day.

5. CALCULATION METHODOLOGY

The thermal fatigue analysis of the VCC reinforced concrete is performed using the temperature and stress results from the design-basis calculations (References 3.1.1 and 3.1.2). The temperature gradients through the wall of the VCC concrete are determined based on the results of the thermal hydraulic calculation (Reference 3.1.1) and the thermal conditions that produce the largest difference in the thru-wall temperature gradient are identified. The stresses in the VCC concrete and rebar for the normal long-term storage condition, which are calculated in the VCC thermal stress calculation (Reference 3.1.2), are then factored by the ratio of the thru-wall temperature gradients to determine the stresses in the concrete for other thermal conditions. The stress ranges in the concrete and rebar are calculated as the difference between the maximum and minimum stresses for the range of thermal conditions. The resulting stress ranges in the concrete and rebar are compared to the fatigue S-N curves for concrete and reinforcing steel from ACI 215R-74 (3.2.1) to determine if thermal fatigue of the VCC reinforced concrete is a credible aging mechanism.

6. CALCULATIONS

The VCC reinforced concrete is subjected to repeated cycles of thermal stress due to seasonal and diurnal variations in ambient conditions. Extreme fluctuations in ambient air temperature from -40°F to 100°F (i.e., seasonal variations) are conservatively postulated to occur 10 times per year (Assumption 4.3.1). Therefore, the total number of thermal cycles due to seasonal variations in ambient temperature over 60 years is:

N_S = 10 cycles/year x 60 years = 600 cycles

Diurnal fluctuations in ambient air temperature occur once per day (Assumption 4.3.2). Therefore, the total number of thermal cycles due to diurnal variations in ambient temperature over 60 years is:

N_D = 1 cycles/day x 365 days/year x 60 years = 21,900 cycles

Thus, the total number of thermal cycles due to seasonal and diurnal variations in ambient temperature over 60 years is:

$N = N_S + N_D$ = 22,500 cycles

Thermal stresses in the VCC reinforced concrete are caused by the temperature gradient through the wall of the VCC assembly. The inside surface of the concrete wall is hotter than the outside surface of the concrete wall, which causes compressive stresses in the VCC inner liner and concrete near the inside of the concrete wall and tensile stresses in the rebar near the outside of the concrete wall. The magnitude of the thermal stresses in the VCC reinforced concrete is roughly proportional to the thru-wall temperature gradient. The concrete thru-wall temperature gradients calculated in the VSC-24 system thermal hydraulic analysis (Ref. 3.1.1), which are summarized below, ranges from 73°F for the severe cold (-40°F ambient air temperature) condition to 95°F for the normal long term storage condition. Thus, the maximum stresses in the concrete are expected to result from the normal long-term condition, while the minimum stresses in the concrete are expected to result from the extreme cold condition. Although the extreme hot case produces the highest temperatures in the VCC concrete, the thru-wall temperature gradient for the extreme hot case is lower than that for the normal long-term condition due to the effects of solar heating on the outside of the VCC assembly.

Thermal Conditions(1)	Peak Concrete Temperatures(2) (°F)		Thru-Wall Temperature Gradient (°F)
	I.D.	O.D.	
Severe Cold (-40°F ambient, no solar)	41	-32	73
Normal Long-Term (75°F ambient, no solar)	180	85	95
Severe Hot (100°F ambient, solar)	214	135	79

Notes:

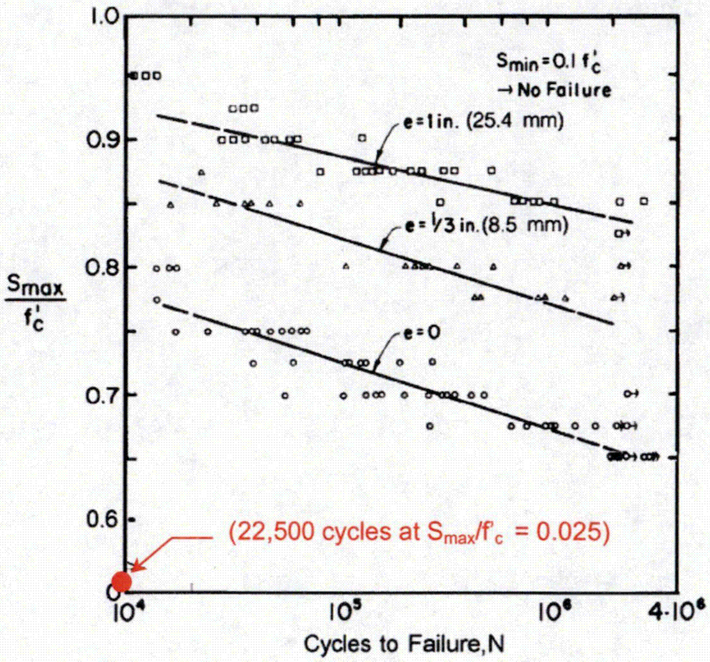
(1) Steady-state conditions for 24 kW heat load.

(2) Temperatures at the hottest axial location on the inside diameter and outside diameter of the VCC side wall from Reference 3.1.1, Figures 4, 5, and 6.

The results of the thermal stress analysis of the VCC assembly for the steady-state normal long-term storage condition (Ref. 3.1.2) show that the maximum compressive stress in the concrete is 0.4 ksi and the maximum tensile stress in the rebar is 28.8 ksi. Thus, the extreme cold condition will result in a

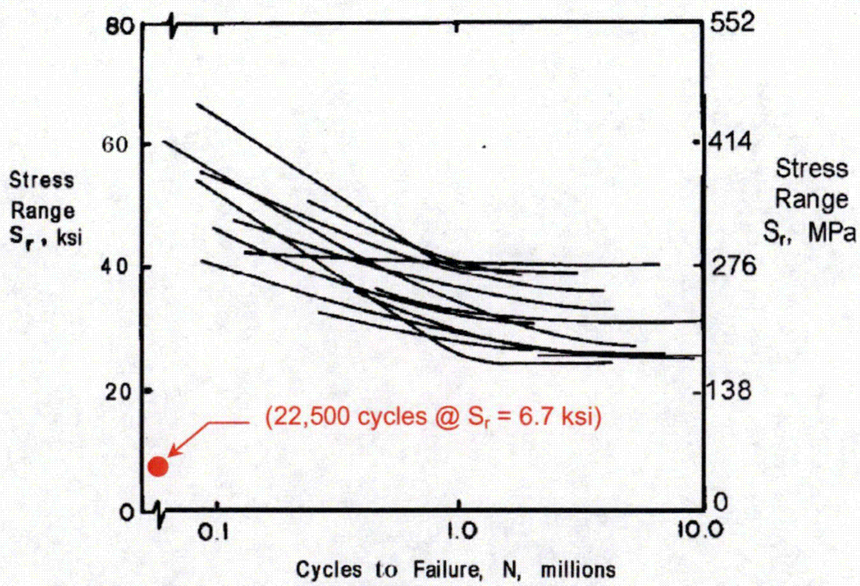
maximum concrete compressive stress of approximately 0.3 ksi (i.e., 0.4 ksi x 73°F/95°F) and a maximum tensile stress in the rebar of approximately 22.1 ksi (i.e., 28.8 ksi x 73°F/95°F). Therefore, the maximum range of concrete compressive stress and rebar tensile stress due to seasonal variations in ambient temperature are approximately 0.1 ksi (= 0.4 ksi – 0.3 ksi) and 6.7 ksi (= 28.8 ksi – 22.1 ksi), respectively.

The ratio of the maximum range of concrete compressive strength (S_{max}) to its design strength (f'_c) is only 0.025 (i.e., 0.1 ksi/4 ksi). As shown in Figure 1 (which is Figure 3 of Ref. 3.2.1) the maximum compressive stress range in the concrete at the maximum number of thermal cycles (i.e., S_{max}/f'_c = 0.025 at 22,500 cycles) is much lower than the lowest S-N curve for compressive stress in concrete, and therefore, the fatigue failure of the VCC concrete is not a credible aging mechanism. Similarly, as shown in Figure 2 (which is Figure 6 of Ref. 3.2.1), the maximum tensile stress range in the rebar at the maximum number of thermal cycles (i.e., S_r = 6.7 ksi at 22,500 cycles) is much lower than the lowest S-N curve for tensile stress in rebar, and therefore, fatigue failure of the reinforcing steel in the VCC concrete is not a credible aging mechanism.



(Source: ACI 215R-74 [Ref. 3.2.1], Figure 3)

Figure 1 - S-N Curves for Concrete in Compression



(Source: ACI 215R-74 [Ref. 3.2.1], Figure 6)

Figure 2 - S-N Curves for Rebar in Tension

7. CONCLUSIONS

7.1 Results

The analysis results show that the VCC assembly will be subjected to a total of 22,500 cycles of thermal stress cycles due to seasonal and diurnal variations in ambient temperature over a 60-year period. The maximum range of concrete compressive stress and rebar tensile stress due to seasonal variations in ambient temperature are approximately 0.1 ksi and 6.7 ksi, respectively. Based on ACI 215R-74 (Ref. 3.2.1), fatigue failure of the VCC reinforced concrete will not result from 22,500 cycles of thermal stress at these stress ranges.

7.2 Compliance With Requirements

The results of this analysis demonstrate that the failure of the VCC reinforced concrete due to thermal fatigue is not credible.

7.3 Range of Validity

The analysis is valid and bounding for the short, standard, and long versions of the VCC assembly with the design-basis heat load of 24 kW.

7.4 Summary of Conservatism

The following conservative assumptions are used in this analysis:

- The thermal stresses in the VCC reinforced concrete are calculated based on the maximum allowable heat load of 24 kW, with no credit taken for thermal decay over time. The highest heat load in any of the loaded VSC-24 casks is less than 15 kW and a proposed condition will limit the maximum heat load in any future VSC-24 casks to 15 kW. Therefore, the maximum stresses in the VCC reinforced concrete will be significantly lower than those used in this analysis. Furthermore, as the thermal load decays over time, the thermal stresses in the concrete will be reduced.

- Extreme fluctuations in ambient air temperature from -40°F to 100°F (i.e., seasonal variations) are conservatively postulated to occur 10 times per year, for a total of 600 cycles over 60 years (Assumption 4.3.1). However, seasonal variations of this magnitude are expected to occur only once per year.

- The maximum stress ranges in the VCC reinforced concrete calculated for the extreme fluctuations in ambient air temperature from -40°F to 100°F (i.e., seasonal variations) are conservatively used for all thermal cycles, including diurnal cycles. The actual thermal stress ranges in the concrete and rebar associated with diurnal cycles will be much lower since the fluctuation in ambient air temperature between day and night is much lower than that between summer and winter seasons.

7.5 Limitations or Special Instructions

None.

8. <u>ELECTRONIC FILES</u>

8.1 Computer Runs

None.

8.2 Other Electronic Files

None.