Enclosure 3

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1.0 INTRODUCTION/STATEMENT OF PROBLEM/ OBJECTIVE

In December 2007, Sargent & Lundy (S&L) performed a flaw analysis for a postulated axial surface flaw in the longitudinal weld of the Multi-Assembly Storage Basket (MSB-04) shell [1]. The analysis was performed for an evaluation period of 50 years [1]. For license renewal purposes, Energy Solutions proposes to extend the evaluation period from 50 years to 60 years. Therefore, a re-evaluation of the fatigue crack growth analysis is necessary to address the change in end-of-evaluation period.

2.0 TECHNICAL APPROACH

In the existing S&L flaw analysis [1], the evaluation is based on linear elastic fracture mechanics (LEFM) since the MSB shell is fabricated from carbon steel material. The crack stability is evaluated by comparing the stress intensity factors based on the calculated final flaw size to the MSB material fracture toughness, with appropriate safety factors applied. In this calculation package, the same methodology as that contained in the S&L analysis [1] will be applied. The crack growth will be re-calculated using the new stresses and number of cycles for the extended plant life provided by Energy Solutions [2].

3.0 ASSUMPTIONS AND DESIGN INPUTS

3.1 Assumptions

The existing S&L flaw evaluation is based on the following assumptions [1]:

1. The largest flaw, among the three indications found in the longitudinal weld of MSB 004, is a subsurface flaw measuring 3/4" in length, along the MSB center line, and 3/16" in depth along the MSB radial direction. It is assumed in the existing S&L flaw evaluation, that the initial flaw is 1" in length and 0.5" in depth. Also, the flaw is conservatively assumed to be an internal surface flaw.

2. The effect of the longitudinal weld residual stress on the fatigue crack growth rate is considered by using the ASME Section XI [3] da/dN crack growth curve for R=1.

3. The stress intensity factors are calculated using formulae limited to $R_i/t \leq 10$, conservatively, for the much larger R_i/t ratio of the MSB shell (R_i and t are the MSB shell inside radius and thickness, respectively).

In this calculation, the following assumptions are made, respectively:

1. The initial flaw size is assumed to be the same size as that in the S&L analysis [1]. A maximum of 0.18" of corrosion is predicted on the 1" thick MSB shell over a 60-year service period in a marine environment [2]. As such, using the same initial flaw size assumption leads to an a/t ratio of 0.61, based on a flaw depth of 0.5" and a corroded thickness of 0.82". Although the a/t ratio of 0.5 used in the existing evaluation is smaller than this new a/t ratio, it is still larger than the a/t ratio of 0.23 based on the actual flaw depth (3/16") and the corroded MSB shell thickness (0.82"). Therefore, in this evaluation, the original a/t ratio, 0.5, is still conservatively applied in calculating the stress intensity factors for the crack growth analysis. For the stability analysis, the actual a/t ratio is used.

2. The residual stress is still assumed to be the yield stress of the material [2]. Thus, the R ratio R=1 is assumed in this calculation.

3. Since the actual R_i/t ratio is still much higher than 10, the formulae limited to $R_i/t \leq 10$ are still applied to calculate the stress intensity factors in this analysis, conservatively.

3.2 Design Inputs

Table 1 summarizes the stress range and number of cycles used in the existing S&L fatigue crack growth analysis [1] and Table 2 presents the revised data for the extended service period of 60 years.

Table 1. Stress Range and Number of Cycles in the S&L Calculation

Load Cases	Frequency	Membrane, ksi			Bending, ksi		
		σ_{min}	σ_{max}	$\Delta\sigma_{m1}$	σ_{min}	σ_{max}	$\Delta\sigma_{b1}$
Pressure Test	1/ MSB life time	0	1.2	1.200	0	7.2	7.200
Vacuum Drying	1/ MSB life time	-0.976	1.2	2.176	-10.737	7.2	17.937
Daily Ambient Temp. Fluctuation	365 / year	-0.012	0.052	0.064	-0.135	0.314	0.449
Off-Normal Ambient Temp. Fluctuation	10 / year	-0.1	0.12	0.220	-0.154	1.72	1.874
Seismic/Handling	1 / year	-0.9	0.9	1.800	-1.5	1.5	3.000

Table 2. Stress Range and Number of Cycles for the New Fatigue Crack Growth Calculation

Load Cases	Frequency	Membrane, ksi			Bending, ksi		
		σ_{min}	σ_{max}	$\Delta\sigma_{m2}$	σ_{min}	σ_{max}	$\Delta\sigma_{b2}$
Pressure Test	2/ MSB life time	0	0.85	0.85	0	2.33	2.33
Vacuum Drying	1/ MSB life time	-1.71	0.85	2.56	-4.64	2.33	6.97
Daily Ambient Temp. Fluctuation	365 / year	0.69	0.81	0.12	2.28	2.66	0.38
Off-Normal Ambient Temp. Fluctuation	10 / year	0.78	1.43	0.65	3.71	5.80	2.09
Seismic/Handling	1 / year	-1.24	1.24	2.48	-4.05	4.05	8.10

4.0 FATIGUE CRACK GROWTH ANALYSIS

The ratios between the stress ranges provided in Reference [2] and the corresponding ones used in the S&L calculation are calculated and listed in Table 3 for the all the load cases. The S&L calculation uses Zahoor's formulation for semi-elliptical axial flaw subjected to membrane and bending stress to calculate the stress intensity factors (K_I) [4]. The stress intensity factors are linearly proportional to the applied stress.

The crack growth rate da/dN is calculated using the following equations as documented in the S&L calculation:

$$\frac{da}{dN} = C \cdot \Delta K_I^{\,n}$$

where,

$$C = 1.99 \cdot 10^{-10} \cdot [25.75 \cdot (2.88 - R)^{-3.07}]$$
$$n = 3.07$$
$$\Delta K_I = K_{I\max} - K_{I\min}$$

$$R = \frac{K_{\mathrm{I}min}}{K_{\mathrm{I}max}}$$

As discussed in Section 3, the R ratio is conservatively considered to be R=1 due to residual stresses. Thus, the crack growth rate da/dN is linearly proportional to $\Delta K^{3.07}$. The ratio of crack growth rate between the rates based on the new stresses and the ones in the S&L calculation is calculated as:

$$\text{da/dN ratio} = \Delta\sigma \text{ ratio}^{3.07}$$

where,

$\Delta\sigma$ ratio = $\Delta\sigma_{m2}/\ \Delta\sigma_{m1}$ for membrane stress range and $\Delta\sigma_{b2}/\Delta\sigma_{b1}$ for bending stress range

The da/dN ratios are listed in Table 3 for each load case. The total number of cycles for 50-year service life in the S&L analysis and for 60-year service life used in this calculation is also presented in Table 3 for each load case.

The crack growth rate of each load case evaluated in S&L calculation is presented in Table 4. The new crack growth values are calculated using the S&L crack growth rates, the da/dN ratios of each load case (conservatively taking the maximum ratio between the membrane and bending stress ratios) and the total number of cycles presented in Table 3 as follows:

$$\Delta a_2 = \Delta a_1 (\frac{da}{dN})(\frac{N_2}{N_1})$$

where,

Δa is the crack growth
N is the number of cycles
da/dN is the ratio of crack growth rates, i.e., da/dN ratio
Subscripts 1 and 2 refer to old and new values, respectively

For example, for the Daily Ambient Temperature Fluctuation condition, the crack growth in the depth direction is: Δa_2 = 7.27E-08 x 6.888 x 21900/18250 = 6.009E-07 inch.

The crack growth results from all the load cases are then summed to obtain the final depth and length of the postulated flaw after 60 years of crack growth. The resulting final flaw sizes are:

Flaw depth = 0.5 + 0.0000203 = 0.5000203 inch

Flaw length = 1.0 + 0.0000193 = 1.0000193 inches

Table 3. Change in Stress, Number of Cycles and Crack Growth Rate

Load cases	Total cycles		Ratios on Membrane		Ratios on Bending		Maximum da/dN Ratio
	50 years	60 years	$\Delta\sigma$ ratio	da/dN ratio	$\Delta\sigma$ ratio	da/dN ratio	
Pressure Test	1	2	0.708	0.347	0.324	0.031	0.347
Vacuum Drying	1	1	1.176	1.647	0.389	0.055	1.647
Daily Ambient Temp. Fluctuation	18250	21900	1.875	6.888	0.846	0.599	6.888
Off-Normal Ambient Temp. Fluctuation	500	600	2.955	27.823	1.115	1.398	27.823
Seismic/Handling	50	60	1.378	2.675	2.700	21.100	21.100

Note: $\Delta\sigma$ ratio = $\Delta\sigma_{m2}/\Delta\sigma_{m1}$ for membrane stress range and $\Delta\sigma_{b2}/\Delta\sigma_{b1}$ for bending stress range

Table 4. Fatigue Crack Growth Results

Load Cases	S&L Flaw Growth		Modified Flaw Growth	
	Depth (in)	Length (in)	Depth (in)	Length (in)
Pressure Test	2.34E-08	9.20E-09	1.62E-08	6.38E-09
Vacuum Drying	2.835E-07	8.26E-08	4.67E-07	1.36E-07
Daily Ambient Temp. Fluctuation	7.27E-08	2.48E-08	6.01E-07	2.05E-07
Off-Normal Ambient Temp. Fluctuation	1.342E-07	3.79E-08	4.48E-06	1.27E-06
Seismic/Handling	5.807E-07	6.99E-07	1.47E-05	1.77E-05
Total Crack Growth	1.0945E-06	8.54E-07	2.03E-05	1.93E-05

5.0 CRACK STABILITY ANALYSIS

The flaw stability analyses in the existing S&L calculation were performed using the rules of IWB-3610 and IWB-3620 of Section XI of the ASME Boiler &Pressure Vessel Code [3]. The postulated flaw is stable, and thus acceptable, if the applied stress intensity factor for the final flaw size meets the prescribed acceptance criteria.

5.1 Acceptance Criteria

Per IWB-3612, the flaw is acceptable if

- For normal (including upset and test) conditions

$$K_I < K_{Id}/\sqrt{10}$$

where,

K_I is the maximum applied stress intensity factor for the final flaw size
K_{Id} is the material fracture toughness based on crack arrest at the crack tip temperature

- For emergency and faulted conditions

$$K_I < K_{Ic}/\sqrt{2}$$

where,

K_I is the maximum applied stress intensity factor for the final flaw size
K_{Ic} is the material fracture toughness based on crack initiation at the crack tip temperature

5.2 Material Fracture Toughness

The fracture toughness of the weld material is taken from the existing S&L calculation [1]. The values of both the fracture toughness based on crack arrest (K_{Id}) and the fracture toughness based on crack initiation (K_{Ic}) were therein obtained from certified material test reports of the weld metal used for the seam weld of MSB#4 shell at 0°F (less than the minimum MSB shell service temperature of 5°F, conservatively) and material Charpy V-notch impact energy (CVN) correlations:

$$K_{Id} = 89.247 \text{ ksi}\sqrt{\text{in}} \text{ and } K_{Ic} = 153.011 \text{ ksi}\sqrt{\text{in}}$$

5.3 Loads

Table 5 presents the normal and accident condition loads for flaw stability analysis in the existing S&L calculation [1] and the corresponding new loads provided in Reference 2.

Table 5. Loads Applied for Flaw Stability Analysis

Load Conditions	S&L Calculation [1]		Modified Stresses [2]	
	P_m, ksi	P_b, ksi	P_m, ksi	P_b, ksi
Normal Condition[1]	1.2	61.2	2.09	61.45
Off-Normal Condition[1]			3.49	65.11
Faulted/Accident[2]	26	101	47.0	54.3

Notes: 1. Bending Stresses are calculated as (P_L+P_b+Q-P_m) plus 54 ksi residual stress [1].
2. Bending Stresses are (P_L+Pb-Pm) plus 54 ksi residual stress.

5.4 Calculations

The flaw stability analyses were performed in the existing S&L calculation using the rules of IWB-3610 and IWB-3620 and Appendix A of the EPRI Ductile Fracture Handbook [4], as summarized in the following equations. The applied stress intensity factor is calculated as:

$$K_a(a,b,\sigma_m,\sigma_b)=K_{Ima}(a,b,\sigma_m)+K_{Iba}(a,b,\sigma_b)$$

where,

For membrane stress

The stress intensity factor at the deepest point is calculated as

$$K_{Ima}(a,b,\sigma_m)=\sigma_m\cdot(\pi t)^{0.5}\cdot G_0\,(\alpha_m(a,b))$$

with, $$G_0(\alpha)=\frac{1.7767\alpha-2.5975\alpha^2+2.752\alpha^3-1.3237\alpha^4+0.2363\alpha^5}{(0.102\frac{Ri}{t}-0.02)^{0.05}}$$

$$\alpha_m(a,b)=\frac{a/t}{(a/b)^{0.58}}$$

where,

σ_m = membrane stress (ksi)

a = flaw depth (in)

b = half flaw length (in)

t = MSB shell thickness (in)

R_i = MSB shell inner radius (in)

The stress intensity factor at the surface point is calculated as

$$G_{S0}(\alpha,b) = [1.06 + 0.28(\frac{a}{t})^2](\frac{a}{b})^{0.41} G_0(\alpha_m(a,b))$$

$$K_{Imb}(a,b,\sigma_m) = \sigma_m \cdot (\pi t)^{0.5} \cdot Gs_0\,(a,b)$$

For bending stress

The stress intensity factor at the deepest point is calculated as

$$K_{Imb}(a,b,\sigma_b) = \sigma_b \cdot (\pi t)^{0.5} \cdot G_1\,(\alpha_b(a,b))$$

$$G_1(\alpha) = \frac{0.1045\alpha_b(a,b) + 0.4189\alpha_b(a,b)^2}{(0.102\frac{Ri}{t} - 0.02)^{0.05}}$$

$$\alpha_b(a,b) = \frac{a/t}{(a/b)^{0.22}}$$

The stress intensity factor at the surface point is calculated as

$$G_{S1}(\alpha,b) = [0.25 + 0.2(\frac{a}{t})^2](\frac{a}{b})^{0.26} G_1(a,b)$$

$$K_{Ibb}(a,b,\sigma_b) = \sigma_b \cdot (\pi t)^{0.5} \cdot Gs_1\,(a,b)$$

As shown in Section 4, the final flaw sizes corresponding to a 60-year service life are:

Flaw depth, a = 0.50002 in
Half-flaw length, b = 0.50001 in

The stress intensity factors at the final flaw size for each service level are calculated and presented in Table 6 along with the corresponding safety factors, SF, calculated based on the acceptance criteria presented in Section 5.1 (SF = K_{Id}/K_a or K_{Ic}/K_a, as appropriate).

Table 6. Flaw Stability Analysis

Service Level	K_a, ksi√in	K_{Id} or K_{Ic}, ksi√in	Safety Factor
Normal Condition	23.588	89.247[1]	3.78
Off-Normal Condition	26.177	89.247[1]	3.41
Accident/Faulted	62.764	153.011[2]	2.44

Notes: 1. For normal and off-normal conditions, the material plane strain dynamic fracture toughness (K_{Id}) is used [1].
2. For accident/faulted condition, the lower bound critical crack initiation stress intensity (K_{Ic}) is used [1].

6.0 CONCLUSIONS

The fatigue crack growth evaluation performed using the new stresses for the MSB shell based on the current licensing basis calculations for the VSC-24 storage system has shown that, after 60 years of service, the postulated flaw in the MSB longitudinal weld grows 2.03E-05 inch in the depth direction and 1.93E-05 inch in the axial direction.

For the normal and off-normal conditions, the safety factors of the predicted final flaw after 60 years of service are larger than the ASME Section XI safety factor of $\sqrt{10}=3.162$. For the accident/faulted conditions, the corresponding safety factor is larger than the ASME Section XI safety factor of $\sqrt{2}=1.414$.

Therefore, this updated evaluation has demonstrated that the predicted flaw growth in the MSB shell weld is negligible and the flaw remains stable under the specified loads for the 60-year service life.

7.0 REFERENCES

1. Sargent & Lundy Calculation No. 2007-20168, Revision 00, "Palisades Weld Flaw Analysis for Loaded Spent Fuel Cask MSB No. 4," Structural Integrity Associates, Inc. File No. 1200250.201.
2. Energy Solutions Calculation No. VSC-04.3205, Revision 0, "Palisades MSB #4 Crack Growth Analysis Inputs," Structural Integrity Associates, Inc. File No. 1200250.201.
3. ASME Boiler & Pressure Vessel Code, Section XI, 1992 Edition.
4. Zahoor Akram, "Ductile Fracture Handbook," Vol. 3, Electric Power Research Institute, Research Project 1757-69, Section 8.1.3 and 8.1.4.