Enclosure 4

Sargent and Lundy Calculation No. 2007-20168, Revision 00,
Palisades Weld Flaw Analysis for Loaded Spent Fuel Cask MSB No. 4
(1 paper copy)

CALCULATION FORMAT TEMPLATE
GEG-0402-02, Revision 0

ISSUE SUMMARY
Form SOP-0402-03

DESIGN CONTROL SUMMARY	
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* The reviewer's signature indicates compliance with S&L procedure SOP-0402 and the verification of, as a minimum, the following items: correctness of mathematics for manual calculations, appropriateness of input data, appropriateness of assumptions, and appropriateness of the calculation method.

NOTE: PRINT AND SIGN IN THE SIGNATURE AREAS

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1. PURPOSE

1.1 PURPOSE

Evaluation of flaws in the longitudinal weld in Spent Fuel Cask MSB 004, Calculation EA-FC-864-50, was reviewed by the NRC staff. A Request for Additional Information (See Attachment E) was issued regarding to the parameter R value of 0.9 used in the fatigue crack growth rule, where the parameter R is the ratio of minimum stress and the maximum stress of the fatigue stress range. By conservatively assuming a uniform welding residual stress of 54 ksi (base material yield stress), the parameter R for stress in the MSB longitudinal is in the range of $0.9 < R < 1$. A value of $R = 1$ would yield a higher fatigue crack growth rate than the crack growth rate in calculation EA-FC-864-50.

The purpose of this calculation is to reassess the calculation in EA-FC-864-50 to determine the flaw size at the end of 50-year life using the R value of 1.0.

2. DESIGN INPUTS

2.1 The postulated flaw is defined using a conservative interpretation of the MSB 004 indications. The characterization of the flaw for use in the flaw propagation analysis is defined in Section 2.2. The fatigue crack growth is calculated based on the fatigue load cases identified in the Safety Analysis Report, Reference 8.1. These load cases include the pressure test, vacuum drying, daily ambient temperature changes and the off-normal ambient temperature extremes. The effects of the daily changes in ambient temperature are defined using the thermal analysis results of Reference 8.1. For each of these load cases, the membrane and bending stresses for the pressure and temperature loads are calculated in Sections 2.3 and 2.4 respectively.

2.2 Flaw Model for Analysis

Reference 8.3 describes and characterizes the three indications found in the longitudinal weld of MSB 004. This reference concludes that the largest flaw is a subsurface flaw measuring 3/4" in length, along the MSB center line, and 3/16" in depth along the MSB radial direction. This flaw is located at the center of the shell thickness 52" from the top of the MSB. The other two indications are smaller in length and depth and meet the separation requirements of Reference 8.2, therefore, the evaluation of the largest flaw will envelope these indications. Since this evaluation assumes the largest MSB shell stress is acting at the postulated flaw and perpendicular to the flaw plane, the orientation of the other indications is in Reference 8.3 would permit a smaller subsurface flaw to be evaluated, this evaluation will assume a very conservative flaw model. The flaw is assumed to be an axial semi-elliptical surface flaw on the inside surface of the MSB. It is assumed to be 1" in length and 0.5" in depth.

2.3 Pressure Stress Cycles

Each subsection below defines the membrane and bending stress due to pressure for the defined loading events. These stresses are determined from the results reported in References 8.1. These results did not define the location or orientation of the maximum stress values, therefore this evaluation assumes the maximum reported stress is acting at the postulated flaw and is oriented perpendicular to the postulated flaw plane.

2.3.1 Pressure Test Events:

Maximum stresses in the MSB shell during the hydrostatic pressure test at 7 psi are (Section 3.4.4.1.7 of Reference 8.1):

$\sigma_m = 1.2$ Ksi

$\sigma_b = 8.4 - 1.2$ Ksi $\qquad \sigma_b = 7.2$ Ksi

Two cycles of pressure test were assumed in Reference 8.1.

2.3.2 Vacuum dry at 3mm Hg:

To remove the moisture in the MSB cavity, a vacuum pressure of 3mm Hg (0.058 psia or -14.642 psig) is maintained in the MSB for 30 minutes as defined in Section 12.2.2.2 of Reference 8.1. The MSB shell stresses are proportional to the pressure stress for -1.5 psig reported in Table 3.4-5 of Reference 8.1.

$\sigma_m = -0.1*(14.642 / 1.5)$ $\qquad$ $\sigma_m = -0.9761$ Ksi

$\sigma_b = (-1.2 - (-0.1))*(14.642 / 1.5)$ $\qquad$ $\sigma_b = -10.7375$ Ksi

2.3.3 Pressure Changes Due to Off-normal Ambient Temperature Extremes:

This event defines shell membrane and bending stress caused by the internal pressure changes when the ambient temperature reaches the extremes of 100 F and -40 F. These ambient temperatures are postulated to occur 10 times each year.

For the -40°F temperature extreme, the MSB pressure is -1.5 psi and the shell stresses reported in Table 3.4-5 of Reference 8.1 are listed below. This external pressure is assumed to generate a negative stress. To be consistent, a positive internal pressure is assumed to generate a positive pressure stress.

$\sigma_m = -0.1$ Ksi

$\sigma_b = -1.2 - (-0.1)$ Ksi $\qquad$ $\sigma_b = -1.1$ Ksi

For 100°F day, the MSB pressure is 0.7 psi and the shell stresses are taken as 1/10 of the above test stress at 7 psi.

$\sigma_m = 0.12$ Ksi

$\sigma_b = 0.72$ Ksi

2.3.4 Pressure Changes Due to Normal Daily Ambient Temperature Change:

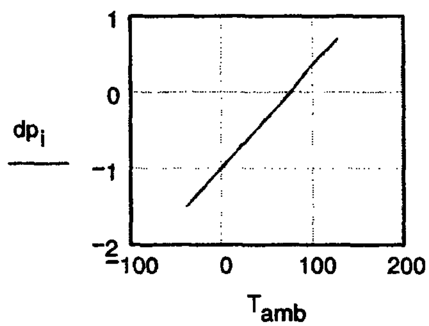
The average ambient temperature fluctuation on a daily basis is assumed to be 36°F. This assumption is based on the maximum ambient temperature change of 20°C from figure 4.1.1 of Reference 8.1. The average daily temperature reported in Reference 8.1 is 75°F; therefore, the daily temperature range of 57°F to 93°F will be used in the fatigue crack growth analysis.

From Table 3.4.2 of Reference 8.1:

Ambient T (°F) MSB Internal Pressure (psi)

$$T_{amb} := \begin{pmatrix} -40 \\ 75 \\ 100 \\ 125 \end{pmatrix} \qquad dp_i := \begin{pmatrix} -1.5 \\ 0 \\ .4 \\ .7 \end{pmatrix}$$

$i := 0..3$



MSB Pressure, dp v.s.
Ambient Temperature, Ta

It can be seen from these plots that the MSB maximum shell pressure is linearly proportional to the ambient temperature. Therefore, the following linear relationship is established to calculate the MSB pressure for the defined daily temperature fluctuations.

$$P_{msb}(T_{amb}) := 0.4 - \left[\frac{[0.4 - (-1.5)]}{100 - (-40)}\right] \cdot (100 - T_{amb})$$

Therefore, the daily ambient temperature change of 57°F to 93°F will cause the following pressure change:

For 57°F ambient temperature the MSB pressure from Eq. (2) is:

$$P_{msb}(57) = -0.1836 \quad \text{psi}$$

This is a negative pressure (less than the atmospheric pressure); therefore, the MSB shell stresses are proportional to the stresses in Table 3.4-5 of Reference 8.1 for P=-1.5 psi. Furthermore, these stress values are conservatively assumed to be negative hoop stresses located near the axial flaw.

σ_m = -0.1 * (-0.184 / -1.5) Ksi $\qquad \sigma_m$ = -0.0123 Ksi

σ_b = (-1.2 + 0.1) * (-0.184 / -1.5) Ksi $\qquad \sigma_b$ = -0.1349 Ksi

For 93°F ambient temperature the MSB pressure is:

$$P_{msb}(93) = 0.305 \quad \text{psi}$$

This is a positive pressure; therefore, the stresses are proportional to the pressure test stress reported in Reference 7.1.

$$\sigma_m = 1.2 * (0.305 / 7) \text{ Ksi} \qquad \sigma_m = 0.0523 \text{ Ksi}$$

$$\sigma_b = (8.4 + 1.2) * (0.305 / 7) \text{ Ksi} \qquad \sigma_b = 0.3137 \text{ Ksi}$$

2.4 Thermal Stress Cycle

Reference 8.1 reported the maximum shell stress was caused by the -40°F extreme ambient temperature condition. This stress is a shell bending stress caused by the MSB temperature gradient. For this evaluation, this bending stress is assumed to be at the postulated flaw and acting perpendicular to it. This section defines the membrane and bending stress resulting from the MSB temperature gradients for the defined fatigue loading events.

2.4.1 Temperature Changes Due to Off-Normal Ambient Temperature Extremes:

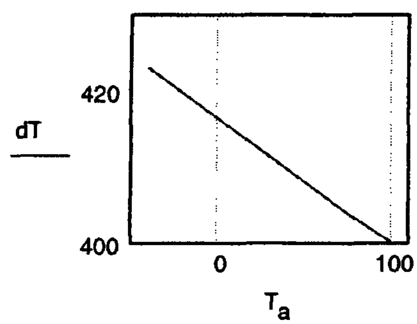
The extreme ambient temperature range per Reference 8.1, Section 4, is -40°F with no solar load and 100°F with maximum solar load and is assumed to occur 10 times a year.

Per section 3.4.4.1.1 of Reference 8.1, the maximum axial temperature gradients in the MSB for different ambient temperatures are listed below.

Ambient T (F) — Maximum Temperature Gradient

$$T_a := \begin{pmatrix} -40 \\ 75 \\ 100 \end{pmatrix} \qquad dT := \begin{pmatrix} 423 \\ 404 \\ 400 \end{pmatrix}$$

$$i := 0..2$$



MSB Temperature gradient, dT
v.s. Ambient Temperature, Ta

It can be seen from the above plot that the MSB maximum temperature gradient is linearly proportional to the ambient temperature. The MSB shell thermal stress is proportional to this temperature gradient. Therefore, the thermal stress corresponding to different ambient temperatures can be estimated from the thermal stress of 1 Ksi for the -40°F case.

For -40°F ambient:

$\sigma_b =$ 1.0 Ksi

For 100°F ambient:

$\sigma_b =$ (400 / 423) * 1.0 Ksi $\qquad\sigma_b =$ 0.9456 Ksi

2.4.2 Temperature Changes Due to Daily Ambient Temperature Changes:

The daily ambient temperature change of 36° F will not significantly change the MSB temperature gradient and the associated shell stress. This conclusion is supported by the magnitude of the stress change for the -40°F to 100°F ambient temperature change calculated in the previous section.

2.5 Seismic and Handling Loads

The handling load associated with moving the MSB was not required to be considered in the fatigue evaluation of Reference 8.1, however for conservatism, the effects of the handling load will be considered for the flaw propagation and stability analysis. In Reference 8.1, the seismic load is defined as an accident condition load and not required to be included in the fatigue evaluation, however for conservatism, it also will be considered in the flaw propagation analysis. The seismic load was determined to be enveloped by the handling load in Reference 8.1. Therefore, the MSB shell stress values for the handling load can be used to conservatively represent the seismic stress values. Considering the probability of a seismic event occurring to be equivalent to the design basis for the station, the enveloped seismic and handling loading events are conservatively assumed to occur 5 times during the design life of the cask with 10 maximum stress cycles associated with each occurrence. The handling stress values are defined in Table 3.4-5 of Reference 8.1 and listed below.

$\sigma_m =$ 0.9 Ksi

$\sigma_b =$ 2.4 - 0.9 Ksi $\qquad\sigma_b =$ 1.5 Ksi

2.6 Residual Stress in the Longitudinal Weld

Welding residual stress is required to be considered in the ferritic fatigue crack growth and crack stability evaluations per ASME Section XI Code, Reference 8.2. The residual stress does not affect the primary driving force for the fatigue crack growth, i.e. the stress intensity range ΔK. It does affect the stress intensity ratio, R, (K_{min} / K_{max}) which is a secondary variable in determining the fatigue crack growth rate. This evaluation considers the effect of the longitudinal weld residual stress on the fatigue crack growth rate by using the ASME Section XI da/dN crack growth curve for R=1. The value of R=1 is chosen because the stress ranges defined in Sections 2.2 and 2.3 are relatively small and adding the large residual stress to K_{min} and K_{max} would yield an R ratio close to one. For the crack stability analysis, the through wall residual stress distribution in the MSB longitudinal double V weld is required. Therefore, the following engineering judgments are made to justify that the magnitude of the residual stress distribution in a double V weld is significantly less than the magnitude of the residual stress in a typical single V weld in piping.

-The weld metal volume in a double V is less than in single V weld therefore, there is less weld shrinkage.

-Double V weld is symmetric with respect to the mid thickness plane, hence residual stress distribution is more uniform than that of a single V weld.

-Double V weld creates compressive residual stress in the weld root area where the flaw is characterized.

-As the R/t ratio increases, the shell stiffness decreases. The relationship tends to reduce the weld residual stress magnitude in large R/t cylinder.

It is concluded that the residual magnitude in the MSB double V weld is significantly less than the typical residual stress magnitude in a circumferential single V butt weld for piping. The maximum magnitude of the residual stress in a typical circumferential single V butt weld in piping is in tension at the pipe inside surface and approximately equal to the yield of the base material. The yield stress of the MSB shell material is 54 ksi (see Section 4.0) and is assumed to be the bounding stress magnitude for the double V weld. Note that the residual stress is highly non-linear in nature; however, for simplicity and conservatism the peak residual stress is added into the bending stress field in the MSB weld.

2.7 Summary of Loading Stress Ranges for Flaw Propagation

Initial pressure test stress range (1 Event per MSB life time)

Membrane (Ksi)		Bending (Ksi)	
Minimum	Maximum	Minimum	Maximum
0	1.2	0	7.2

Vacuum dry / pressure test stress range (1 Event per MSB life time)

Membrane (Ksi)		Bending (Ksi)	
Minimum	Maximum	Minimum	Maximum
–0.976	1.2	–10.737	7.2

Daily stress range (365 cycles / year)

	Membrane (Ksi)		Bending (Ksi)	
	Minimum	Maximum	Minimum	Maximum
Pressure	–0.012	0.052	–0.135	0.314
Temp. Gradient	N/A	N/A	N/A	N/A
Total	–0.012	0.052	–0.135	0.314

Off-Normal Ambient Temperature Extremes (10 Cycles per year)

	Membrane (Ksi)		Bending (Ksi)	
	Minimum	Maximum	Minimum	Maximum
Pressure	–0.1	0.12	–1.1	0.72
Temp. Gradient	N/A	N/A	0.946	1.0
Total	–0.1	0.12	–0.154	1.72

Seismic and Handling Stress Range

	Membrane (Ksi)		Bending (Ksi)	
	Minimum	Maximum	Minimum	Maximum
Seismic / Handling	–0.9	0.9	–1.5	1.5

2.8 Normal and Accident Condition Loads for Flaw Stability Analysis

The loads used for the flaw stability analysis are determined from the normal and off-normal (Service Level B only) condition load combinations defined in Table 2.2-4 of Reference 8.1. The maximum combined membrane and bending stress values for the controlling load combination are given in Table 3.4-5 of Reference 8.1 and are listed below.

MSB Shell Maximum Normal Condition Stress Values - Ksi

	Dead Weight	Pressure	Thermal	Handling	Total
P_m	0.1	0.1	N/A	0.9	1.1
$P_L + P_b$	0.1	1.2	N/A	2.4	3.7
$P + Q$	0.1	1.2	N/A	2.4	4.7

The pressure test condition loads which must be elevated as a normal condition load are taken from Section 3.4.4.1.7 of Reference 8.1. The maximum MSB shell stress values for the pressure test are listed below. These stress values are greater than the other load combinations and therefore, used in the normal condition flaw stability evaluation.

Pressure Test Stress Values - Ksi

P_m	1.2
$P_m + P_b$	8.4

Residual Stress - Ksi

P_L	54.0

For the accident condition flaw stability evaluation, the controlling load combination identified in Table 2.2-4 as Horizontal Drop load. These maximum shell stress values, listed below, are used for the accident condition flaw stability analysis.

Accident Condition Horizontal Drop Stress - Ksi

	Dead Weight	Pressure	Thermal	Handling	Total
P_m	N/A	0.1	N/A	25.9	26.0
$P_L + P_b$	N/A	1.2	N/A	71.8	73.0

Residual Stress - Ksi

P_b	54.0

3. ASSUMPTIONS

3.1 The maximum MSB shell stress values reported in Reference 8.1 are assumed to be acting on the flaw and perpendicular to the flaw plane.

3.2 The average ambient temperature fluctuation on a daily basis is assumed to be 36°F.

3.3 The longitudinal weld residual stress is assumed to be a maximum tensile stress equal to the yield stress, i.e. 54.0 Ksi.

4. ACCEPTANCE CRITERIA

The following acceptance criteria will be used to determine if the results satisfy the purpose of the calculation:

4.1 Material Properties

4.1.1 Base metal: (Reference: Traveler RE022, Heat #61066-32)

Specification	ASME SA-516 Gr 70
Yield Stress	367 MPa = 53.23 Ksi
Ultimate Stress	541 MPa = 78.47 Ksi
Elongation	52%

Average Charpy Impact Energy

CVN = 77KJ = 56.875 ft-lbs at -46°C or -50°F

4.1.2 Weld Metal: (Attached CMTR for weld metal)

Specification	ASME SFA 5.01 Sec. II Part C and ASME Sec III
Yield Stress	89.9 Ksi
Ultimate Stress	93.2 Ksi
Elongation	23%
Charpy Impact CVN	64, 65, 54 ft-lbs at 0 deg°F

4.1.3 Weld test coupon POR No. 205 - 92

Ultimate Stress 82.7 Ksi

Weld Metal Impact Energy Value:

Cv = 24, 20, 18 ft-lbs at -50 deg°F

Heat Affected Zone (HAZ) Impact Energy Value

Cv = 56, 60, 52 ft-lbs at -50 deg°F

4.2 Material Fracture Toughness

The linear elastic fracture mechanics (LEFM) model of a postulated part through the wall axial crack in the MSB shell longitudinal weld shall meet the IBW-3612 acceptance criteria based on applied stress intensity factor.

The fracture toughness of weld material is determined by two properties K_{Ic} and K_{Id}. K_{Id} is the lower bound of critical crack arrest stress intensity at temperature. K_{Ic} is the lower bound of critical crack initiation stress intensity at temperature. These two material toughness properties have a correlation to the material Charpy V-notch impact energy, CVN. Reference 8.4, provides a review of many empirical correlations between CVN and K_{Ic} and K_{Id}.

Note that K_{Id}, is the material plane strain dynamic fracture toughness which is essentially identical to the Code K_{Id} toughness. Reference 8.4 provides the following simple correlations of K_{Ic} and K_{Id} with the CVN value.

$$K_{Ic} := 2 \cdot CVN^{\frac{3}{2}} \qquad ksi \cdot \sqrt{in}, ft - lb$$

$$K_{Id} := 5 \cdot CVN \qquad ksi \cdot \sqrt{in}, ft - lb$$

Since the lowest MSB shell temperature is 5°F, section 11.1.1.3 of Reference 8.1 and the MSB will not be transported when the ambient temperature less than 0°F, the minimum CVN value for the weld metal at 0°F (54 ft-lbs) is used to calculate K_{Ic} and K_{Id}.

$$CVN := 54 \cdot ft \cdot lb \qquad E := 29.5 \cdot 10^{6} \cdot psi$$

$$K_{Ic} := \sqrt{2 \cdot E \cdot CVN^{1.5}} \qquad K_{Ic} = 153.0105 \quad ksi \cdot \sqrt{in}$$

$$K_{Id} := \sqrt{5 \cdot E \cdot CVN} \qquad K_{Id} = 89.2468 \quad ksi \cdot \sqrt{in}$$

4.3 Acceptance Criteria per IWB-3612

The allowable stress intensification factor for the normal condition including the upset and test condition is:

$$K_I < \frac{K_{Ia}}{\sqrt{10}}$$

The allowable stress intensification factor for the emergency and faulted condition is:

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

5. METHODOLOGY

5.1 Methodology

The fatigue crack growth analysis and the flaw stability analysis are performed using the rules of IWB-3610 and IWB-3620 (for ferritic components less than 4" thick) and Appendix A of Reference 8.2. EPRI's Ductile Fracture Handbook, Reference 8.5, is used to calculate stress intensity factors for membranes and bending stress for the postulated flaw in the MSB shell weld.

To define the stress intensity factor, K_I, for this evaluation, Zahoor's formulation for a semi-elliptical axial flaw subjected to membrane and bending stress in Reference 8.5 is used. The stress intensity formulae are limited to ($R_i \leq 10$). For larger R_i/t ratios, the above formulae are a conservative approximation. The plots in Reference 8.5 (Figures 8.1-19 and 8.1-30) show the convergence of the stress intensity coefficients as the R_i/t ratio approaches 10 and these coefficients decrease as the R_i/t ratio increases. Therefore, the above formulae are conservative for a part through wall flaw in a cylinder with higher R_i/t ratio.

5.1.1 Stress Intensity Factor K_I formulas for uniform stress distribution:

Geometry:

$t := 1$	Model Thickness (in)
$R_i := 10$	Model Inner Radius (in)
$a := 0.5$	Postulated initial flaw depth (in)
$b := 0.5$	Half of postulated initial flaw length (in)
$\frac{a}{t} = 0.5$	Flaw depth / thickness ratio
$\frac{a}{b} = 1$	Flaw aspect ratio

Membrane Stress

$\sigma_m := 1$ Ksi (Initial Value)

Parameter α for membrane stress field in Reference 8.5 (page 8.1.23) as a function of a and b:

$$\alpha_m(a,b) := \frac{\frac{a}{t}}{\left(\frac{a}{b}\right)^{0.58}} \qquad \alpha_m(a,b) = 0.5$$

The applicable stress intensity factor, K_{Ima}, at the maximum flaw depth for a/b >0.2 and α <2 is calculated below:

$$G_o(\alpha) := \frac{1.7767\cdot\alpha - 2.5975\cdot\alpha^2 + 2.752\cdot\alpha^3 - 1.3237\cdot\alpha^4 + .2363\cdot\alpha^5}{\left(.102\cdot\frac{R_i}{t} - .02\right)^{.05}}$$

$$K_{Ima}(a,b,\sigma) := \sigma\cdot(\pi\cdot t)^{.5}\cdot G_o(\alpha_m(a,b)) \qquad \text{Ksi}\cdot\sqrt{\text{in}}$$

The applicable stress intensity factor, K_{lmb}, at the maximum flaw length location is below:

$$G_{so}(a,b) := \left[1.06 + .28\cdot\left(\frac{a}{t}\right)^2\right]\cdot\left(\frac{a}{b}\right)^{.41}\cdot G_o(\alpha_m(a,b))$$

$$K_{Imb}(a,b,\sigma) := \sigma\cdot(\pi\cdot t)^{.5}\cdot G_{so}(a,b) \qquad Ksi\cdot\sqrt{in}$$

5.1.2 Stress Intensity Factor K_I for Linear Stress Distribution:

From Reference 8.5, page 8.1-37

$$\sigma_o := \sigma_b\cdot\left(\frac{z}{t}\right)$$

A linear stress distribution (Ksi) with z is a distrance from ID and σ_b is the maximum bending stress.

The above linear stress distribution is equivalent to the a stress distribution of a bending stress σ_b, plus a membrane stress of $\sigma_b/2$. Therefore, it is conservative to use the above linear stress distribution for bending stress.

From Reference 8.5 (page 8.1-37), parameter α for a linear stress distribution as a function of flaw sizes a and b is:

$$\alpha_b(a,b) := \frac{\frac{a}{t}}{\left(\frac{a}{b}\right)^{.22}}$$

The applicable stress intensity factor, K_{Iba}, at the maximum flaw depth location is calculated below:

$$G_1(a,b) := \frac{0.1045\cdot\alpha_b(a,b) + .4189\cdot\alpha_b(a,b)^2}{\left(.102\cdot\frac{R_i}{t} - .02\right)^{0.05}}$$

$$K_{Iba}(a,b,\sigma) := \sigma\cdot(\pi\cdot t)^{.5}\cdot G_1(a,b) \qquad Ksi\cdot\sqrt{in}$$

The applicable stress intensity factor, K_{Ibb}, at the maximum flaw length location is below:

$$G_{s1}(a,b) := \left[0.25 + .2 \cdot \left(\frac{a}{t}\right)^2\right] \cdot \left(\frac{a}{b}\right)^{.26} \cdot G_1(a,b)$$

$$K_{Ibb}(a,b,\sigma) := \sigma \cdot (\pi \cdot t)^{.5} \cdot G_{s1}(a,b) \qquad \text{Ksi}\cdot\sqrt{\text{in}}$$

5.1.3 Combined Stress Intensity Factor KI for Membrane Plus Bending Stress

The above stress intensity factors are combined to formulate the stress intensity factor for a combined membrane plus bending stress field.

$$K_a(a,b,\sigma_m,\sigma_b) := K_{Ima}(a,b,\sigma_m) + K_{Iba}(a,b,\sigma_b) \qquad \text{At the maximum crack depth}$$

$$K_b(a,b,\sigma_m,\sigma_b) := K_{Imb}(a,b,\sigma_m) + K_{Ibb}(a,b,\sigma_b) \qquad \text{At the maximum crack length}$$

5.2 Fatigue Crack Growth Analysis:

The fatigue crack growth analysis is performed per the requirements of Reference 2.1.2 using the flaw model and fatigue loading stress ranges defined in Section 2.0.

5.2.1 Crack Growth Law:

ASME Section XI, Appendix A, Fall 1993 Addenda, ferrictic material fatigue crack growth in air environment:

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

where

$$C := 1.99 \cdot 10^{-10} \cdot \left[25.75 \cdot (2.88 - R)^{-3.07}\right]$$

$$n := 3.07$$

$$\Delta K_I := K_{Imax} - K_{Imin}$$

$$R := \frac{K_{Imin}}{K_{Imax}}$$

per Section 2.6, the effect of residual stress on fatigue crack growth is considered by conservatively using R=1.

5.3 Computer Programs Used

5.3.1 MathCAD Version 11.2 Enterprise Edition, S&L Program No.: 03.7.548-11.2

6. CALCULATIONS

6.1 Fatigue Crack Growth Calculation

6.1.1 Initial Hydro-test:

Number of circle is 1. Number of calculation block is 1

Calculation block index $i := 1$

Initial flaw dimension: (in) $a_0 := 0.5$ $b_0 := 0.5$

Stress range (Ksi): $\sigma_{mmax} := 1.2$ $\sigma_{bmax} := 7.2$

$\sigma_{mmin} := 0$ $\sigma_{bmin} := 0$

R Ratio $R := 1$

Fatigue Crack Growth Coefficient

$$C := 1.99 \cdot 10^{-10} \cdot \left[25.75 \cdot (2.88 - R)^{-3.07}\right]$$

$$n := 3.07$$

Flaw size after the first hydro test:

$$a_i := C \cdot \left(K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + a_{i-1}$$

$$b_i := C \cdot \left(K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + b_{i-1}$$

$a_i = 0.5000000234$ $b_i = 0.5000000046$

Strress Intensity Factors used in the above crack growth calculation:

(for checking purpose)

$K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) = 3.0829597014$ $K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) = 1.8210363457$

$K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right) = 0$ $K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right) = 0$

$$\Delta K_a := \left(K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)$$

$$\Delta K_a = 3.0829597014$$

$$\Delta K_b := \left(K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)$$

$$\Delta K_b = 1.8210363457$$

6.1.2 Vacuum Drying - Hydro-test Stress Range :

Number of circle is 1. Number of calculation block is 1

Calculation block index $i := 2$

Initial flaw dimension: (in) $a_0 := 0.5$ $b_0 := 0.5$

Stress range (Ksi): $\sigma_{mmax} := 1.2$ $\sigma_{bmax} := 7.2$

$\sigma_{mmin} := -0.976$ $\sigma_{bmin} := -10.737$

R Ratio $R := 1$

Fatigue Crack Growth Coefficient $C := 1.99 \cdot 10^{-10} \cdot \left[25.75 \cdot (2.88 - R)^{-3.07}\right]$

$n := 3.07$

Flaw size after the vaccum - leak test:

$$a_i := C \cdot \left(K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + a_{i-1}$$

$$b_i := C \cdot \left(K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + b_{i-1}$$

$a_i = 0.5000003069$ $b_i = 0.5000000459$

Strress Intensity Factors used in the above crack growth calculation:

(for checking purpose)

$K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) = 3.0829598475$

$K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) = 1.8210364451$

$K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right) = -3.8655$ $K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right) = -1.8885$

$$\Delta K_a := \left(K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)$$

$\Delta K_a = 6.9485$

$$\Delta K_b := \left(K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)$$

$\Delta K_b = 3.7096$

6.1.3 Daily Temperature and Pressure Stress Range for 50-year :

Numbers of circle per block is 365. Number of calculation block is 50

Calculation block index $i := 3..52$

Initial flaw dimension: (in) $a_2 = 0.5000003069$ $b_2 = 0.5000000459$

Stress range (Ksi): $\sigma_{mmax} := 0.052$ $\sigma_{bmax} := 0.314$

$\sigma_{mmin} := -0.012$ $\sigma_{bmin} := -0.135$

R Ratio $R := 1$

Fatigue Crack Growth Coefficient

$$C := 1.99 \cdot 10^{-10} \cdot \left[25.75 \cdot (2.88 - R)^{-3.07} \right]$$

$$n := 3.07$$

Fatigue calculation for 50 blocks of 365 cycles

$C := 365 \cdot C$ $Year_i := i - 2$

First, calculated flaw depth at a constant aspect ratio b/a: $ba := \frac{b_2}{a_2}$

$$a_i := C \cdot \left(K_a\left(a_{i-1}, ba \cdot a_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_a\left(a_{i-1}, ba \cdot a_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + a_{i-}$$

Then, calculate crack length

$$b_i := C \cdot \left(K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + b_{i-1}$$

and crack depth

$$a_i := C \cdot \left(K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + a_{i-1}$$

Flaw size change in 50 years due to daily temperature change

Year — Flaw depth (in) — Flaw length (in) — $j := 3 .. 32$

$Year_j =$	$a_j =$	$2 \cdot b_j =$
1	0.5000003084	1.0000000924
2	0.5000003098	1.0000000929
3	0.5000003113	1.0000000933
4	0.5000003127	1.0000000938
5	0.5000003142	1.0000000943
6	0.5000003156	1.0000000948
7	0.5000003171	1.0000000953
8	0.5000003185	1.0000000958
9	0.5000003200	1.0000000963
10	0.5000003214	1.0000000968
11	0.5000003229	1.0000000973
12	0.5000003243	1.0000000978
13	0.5000003258	1.0000000983
14	0.5000003273	1.0000000988
15	0.5000003287	1.0000000993
16	0.5000003302	1.0000000998
17	0.5000003316	1.0000001003
18	0.5000003331	1.0000001008
19	0.5000003345	1.0000001013
20	0.5000003360	1.0000001018
21	0.5000003374	1.0000001023
22	0.5000003389	1.0000001028
23	0.5000003403	1.0000001033
24	0.5000003418	1.0000001037
25	0.5000003432	1.0000001042
26	0.5000003447	1.0000001047
27	0.5000003461	1.0000001052
28	0.5000003476	1.0000001057
29	0.5000003491	1.0000001062
30	0.5000003505	1.0000001067

Year　　Flaw depth (in)　　Flaw length (in)　　$j := 33..52$

$Year_j =$	$a_j =$	$2 \cdot b_j =$
31	0.5000003520	1.0000001072
32	0.5000003534	1.0000001077
33	0.5000003549	1.0000001082
34	0.5000003563	1.0000001087
35	0.5000003578	1.0000001092
36	0.5000003592	1.0000001097
37	0.5000003607	1.0000001102
38	0.5000003621	1.0000001107
39	0.5000003636	1.0000001112
40	0.5000003650	1.0000001117
41	0.5000003665	1.0000001122
42	0.5000003679	1.0000001127
43	0.5000003694	1.0000001132
44	0.5000003709	1.0000001137
45	0.5000003723	1.0000001141
46	0.5000003738	1.0000001146
47	0.5000003752	1.0000001151
48	0.5000003767	1.0000001156
49	0.5000003781	1.0000001161
50	0.5000003796	1.0000001166

6.1.4 Off-normal Ambient Temperature Extremes, 10 cycles per year for 50-year:

Numbers of circle per block is 10. Number of calculation block is 50

Calculation block index $i := 53..\,102$

Initial flaw dimension: (in) $a_{52} = 0.5000003796$ $b_{52} = 0.5000000583$

Stress range (Ksi): $\sigma_{mmax} := 0.12$ $\sigma_{bmax} := 1.72$

$\sigma_{mmin} := -0.1$ $\sigma_{bmin} := -0.154$

R Ratio $R := 1$

Fatigue Crack Growth Coefficient

$$C := 1.99\cdot 10^{-10}\cdot\left[25.75\cdot(2.88 - R)^{-3.07}\right]$$
$$n := 3.07$$

Fatigue calculation for 50 blocks of 365 cycles

$$C := 10\cdot C \qquad Year_i := i - 52$$

First, calculated flaw depth at a constant aspect ratio b/a: $ba := \dfrac{b_{52}}{a_{52}}$

$$a_i := C\cdot\left(K_a\left(a_{i-1}, ba\cdot a_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_a\left(a_{i-1}, ba\cdot a_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + a_{i-}$$

Then, calculate crack length

$$b_i := C\cdot\left(K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_b\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + b_{i-1}$$

and crack depth

$$a_i := C\cdot\left(K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}\right) - K_a\left(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin}\right)\right)^n + a_{i-1}$$

Flaw size change in 50 years due to off-normal ambient temperature change

Year Flaw depth (in) Flaw length (in) $j := 53 .. 84$

$Year_j =$	$a_j =$	$2 \cdot b_j =$
1	0.5000003823	1.0000001174
2	0.5000003849	1.0000001181
3	0.5000003876	1.0000001189
4	0.5000003903	1.0000001197
5	0.5000003930	1.0000001204
6	0.5000003957	1.0000001212
7	0.5000003984	1.0000001219
8	0.5000004010	1.0000001227
9	0.5000004037	1.0000001234
10	0.5000004064	1.0000001242
11	0.5000004091	1.000000125
12	0.5000004118	1.0000001257
13	0.5000004145	1.0000001265
14	0.5000004172	1.0000001272
15	0.5000004198	1.000000128
16	0.5000004225	1.0000001287
17	0.5000004252	1.0000001295
18	0.5000004279	1.0000001303
19	0.5000004306	1.000000131
20	0.5000004333	1.0000001318
21	0.5000004359	1.0000001325
22	0.5000004386	1.0000001333
23	0.5000004413	1.000000134
24	0.5000004440	1.0000001348
25	0.5000004467	1.0000001356
26	0.5000004494	1.0000001363
27	0.5000004520	1.0000001371
28	0.5000004547	1.0000001378
29	0.5000004574	1.0000001386
30	0.5000004601	1.0000001393

Year Flaw depth (in) Flaw length (in) $j := 83..102$

$Year_j =$	$a_j =$	$2 \cdot b_j =$
31	0.5000004628	1.0000001401
32	0.5000004655	1.0000001409
33	0.5000004681	1.0000001416
34	0.5000004708	1.0000001424
35	0.5000004735	1.0000001431
36	0.5000004762	1.0000001439
37	0.5000004789	1.0000001446
38	0.5000004816	1.0000001454
39	0.5000004842	1.0000001462
40	0.5000004869	1.0000001469
41	0.5000004896	1.0000001477
42	0.5000004923	1.0000001484
43	0.5000004950	1.0000001492
44	0.5000004977	1.0000001499
45	0.5000005004	1.0000001507
46	0.5000005030	1.0000001515
47	0.5000005057	1.0000001522
48	0.5000005084	1.000000153
49	0.5000005111	1.0000001537
50	0.5000005138	1.0000001545

6.1.5 Seismic and Normal Handling Stress Range, 1 cycles per year for 50-year:

Numbers of circle per block is 1. Number of calculation block is 50

Calculation block index $i := 103..152$

Initial flaw dimension: (in) $a_{102} = 0.5000005138$ $b_{102} = 0.5000000772$

Stress range (Ksi): $\sigma_{mmax} := 0.9$ $\sigma_{bmax} := 1.5$

$\sigma_{mmin} := -0.9$ $\sigma_{bmin} := -1.5$

R Ratio $R := 1$

Fatigue Crack Growth Coefficient

$$C := 1.99 \cdot 10^{-10} \cdot \left[25.75 \cdot (2.88 - R)^{-3.07}\right]$$

$$n := 3.07$$

Fatigue calculation for 50 blocks of 1 cycle

$C := 1 \cdot C$ $Year_i := i - 102$

First, calculated flaw depth at a constant aspect ratio b/a: $ba := \frac{b_{52}}{a_{52}}$

$$a_i := C \cdot \left(K_a(a_{i-1}, ba \cdot a_{i-1}, \sigma_{mmax}, \sigma_{bmax}) - K_a(a_{i-1}, ba \cdot a_{i-1}, \sigma_{mmin}, \sigma_{bmin})\right)^n + a_{i-1}$$

Then, calculate crack length

$$b_i := C \cdot \left(K_b(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}) - K_b(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin})\right)^n + b_{i-1}$$

and crack depth

$$a_i := C \cdot \left(K_a(a_{i-1}, b_{i-1}, \sigma_{mmax}, \sigma_{bmax}) - K_a(a_{i-1}, b_{i-1}, \sigma_{mmin}, \sigma_{bmin})\right)^n + a_{i-1}$$

Flaw size change in 50 years due to seismic and normal handling loads:

Year Flaw depth (in) Flaw length (in) $j := 103..134$

$Year_j =$	$a_j =$	$2 \cdot b_j =$
1	0.5000005254	1.0000001685
2	0.5000005370	1.0000001825
3	0.5000005486	1.0000001965
4	0.5000005602	1.0000002104
5	0.5000005718	1.0000002244
6	0.5000005835	1.0000002384
7	0.5000005951	1.0000002524
8	0.5000006067	1.0000002664
9	0.5000006183	1.0000002804
10	0.5000006299	1.0000002944
11	0.5000006415	1.0000003084
12	0.5000006532	1.0000003224
13	0.5000006648	1.0000003363
14	0.5000006764	1.0000003503
15	0.5000006880	1.0000003643
16	0.5000006996	1.0000003783
17	0.5000007112	1.0000003923
18	0.5000007228	1.0000004063
19	0.5000007345	1.0000004203
20	0.5000007461	1.0000004343
21	0.5000007577	1.0000004482
22	0.5000007693	1.0000004622
23	0.5000007809	1.0000004762
24	0.5000007925	1.0000004902
25	0.5000008041	1.0000005042
26	0.5000008158	1.0000005182
27	0.5000008274	1.0000005322
28	0.5000008390	1.0000005462
29	0.5000008506	1.0000005602
30	0.5000008622	1.0000005741

Year   Flaw depth (in)   Flaw length (in) $j := 133..152$

$Year_j =$	$a_j =$	$2 \cdot b_j =$
31	0.5000008738	1.0000005881
32	0.5000008854	1.0000006021
33	0.5000008971	1.0000006161
34	0.5000009087	1.0000006301
35	0.5000009203	1.0000006441
36	0.5000009319	1.0000006581
37	0.5000009435	1.0000006721
38	0.5000009551	1.0000006861
39	0.5000009668	1.0000007
40	0.5000009784	1.000000714
41	0.5000009900	1.000000728
42	0.5000010016	1.000000742
43	0.5000010132	1.000000756
44	0.5000010248	1.00000077
45	0.5000010364	1.000000784
46	0.5000010481	1.000000798
47	0.5000010597	1.0000008119
48	0.5000010713	1.0000008259
49	0.5000010829	1.0000008399
50	0.5000010945	1.0000008539

6.2 Flaw Stability Calculation

After 50 years of service with the loading conditions defined in Section 2, the final crack size is:

$a_{152} = 0.5000010945$ in $\qquad b_{152} = 0.500000427$ in

In this section, the flaw stability evaluation is based on the calculated final flaw size with R=1. The maximum loading under the normal condition and the accident condition will be considered. The ASME Section XI stress intensity factors acceptance criteria stated in Section 4.0 will be used in the evaluation.

The minimum weld CVN impact energy at 0°F degree (see Section 4.0) is

$CVN := 54$ ft-lbs

$E := 29.5$ E+6 psi, elastic modulus

Material facture toughness per Section 4.2

$$K_{IC} := \sqrt{2 \cdot E \cdot CVN^{1.5}}$$

$K_{IC} = 153.011$ $ksi \cdot \sqrt{in}$

$$K_{Id} := \sqrt{5 \cdot E \cdot CVN}$$

$K_{Id} = 89.247$ $ksi \cdot \sqrt{in}$

6.2.1 Normal Loading Condition

The maximum combined stress for the normal condition is defined in Section 2.8. The bounding welding residual stress of 54 ksi is conservative added to the bending stress of the normal condition.

$\sigma_m := 1.2$ ksi $\qquad \sigma_b := 8.4 - 1.2 + 54$ ksi

$K_a(a_{152}, b_{152}, \sigma_m, \sigma_b) = 18.107 \quad ksi \cdot \sqrt{in}$

$K_b(a_{152}, b_{152}, \sigma_m, \sigma_b) = 6.328 \quad ksi \cdot \sqrt{in}$

Safety Factor for the normal condition: $\dfrac{K_{Id}}{18.107} = 4.929$

Therefore, the safety factor of the postulated flaw after 50 year of service is larger than the required safety factor of $\sqrt{10} = 3.162$ per ASME Section XI.

6.2.2 Faulted Loading Condition

The maximum combined stress for the accidental load stress from the Horizontal Drop load case is defined in Section 2.8. The bounding welding residual stress of 54 ksi is conservative added to the bending stress of the normal condition.

$\sigma_m := 26$ ksi $\qquad \sigma_b := 73 - 26 + 54$ ksi

$K_a(a_{152}, b_{152}, \sigma_m, \sigma_b) = 51.495 \quad ksi \cdot \sqrt{in}$

$K_b(a_{152}, b_{152}, \sigma_m, \sigma_b) = 34.865 \quad ksi \cdot \sqrt{in}$

Safety Factor for the faulted condition: $\dfrac{K_{IC}}{51.485} = 2.972$

Therefore, the safety factor of the postulated flaw after 50 year of service is larger than the required safety factor of $\sqrt{2} = 1.414$ per ASME Section XI.

7. RESULTS

7.1 This evaluation was based on a conservative flaw model assumed to be half the MSB wall thickness in depth and 1" in length. The loads used for the fatigue crack growth included all normal, test and normal handling loads, as well as the seismic load. The normal condition flaw stability evaluation used the maximum combined loads from the normal operating, test and upset conditions. The emergency and faulted condition flaw stability evaluation used the maximum combined accident loads which were from the transportation drop load event. The shell stress values used in both evaluations were based on the maximum stress values reported for the MSB in the SAR, Reference 8.1, although the maximum shell stress did not occur at the location of the flaw. The direction of the shell stress values for each load were assumed to act in the shell hoop direction, i.e. perpendicular to the flaw plane, although some of these stress values are actually acting in the longitudinal direction,i.e parallel to the flaw plane. Although the residual stress for a double grove weld was shown to be less in magnitude than a single grove circumferential weld, the residual stress is consistent with a typical residual stress magnitude for single grove circumferential welds.

Using the conservatively defined loads and flaw model, the fatigue crack growth for the 50 year life of the MSB was shown to be insignificant, i.e. less than 0.00001" in depth and length. The normal condition flaw stability yielded a margin of 4.93 compared to the ASME code safety factor of 3.16. The faulted condition flaw stability yielded a margin factor of 2.97 compared to the ASME Code safety factor of 1.414.

These results demonstrate that the stress levels in the MSB shell are very low and are insufficient to significant crack growth. Also, the postulated flaw remains stable when subjected to accident conditions. Consequently, it has been demonstrated that the postulated flaw will not grow through wall when subjected to fatigue loads or a one time accident condition load.

8. REFERENCES

8.1 Safety Analysis Report for the Ventilated Storage Cask, PSN-91-001, Revision 1, October, 1991.

8.2 ASME B&PV Code, Section XI, 1992 Edition.

8.3 Postulated Causes for MSB #4 Flaws, J.C. Nordby to M.A. Ferens, August 22, 1994, JCN94*031.

8.4 Interpretive Report on Small-Scale Test Correlations with K_b Data, WRC Bulletin 265.

8.5 Zahoor Akram, "Ductile Fracture Handbook," Vol. 3, Electric Power Research Institute, Research Project 1757-69. Section 8.1.3 and 8.1.4.

8.6 Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping, NUREG-0313, Revision 2.

9. ATTACHMENTS

		Total Number of Pages
A.	Alloy Rod Corporation Certificate of Analysis	3
B.	Testing Engineers, Inc, QM-483 Suggested Format for Procedure Qualification Record	3
C.	Testing Engineers, Inc, Charpy V-Notch Impact Test Laboratory Number: M1061	2
D.	Testing Engineers, Inc, Work Request Number M1031	2
E.	NRC Letter	~~2~~ 3

ATTACHMENT A

Alloy Rod Corporation Certificate of Analysis

Total Number of Pages Including this Cover Page = 3

Attachment to EA-FC-860-050 Appendix 2

ALLOY RODS CORPORATION — CERTIFICATE OF ANALYSIS

P.O. BOX 517/1500 KAREN LANE
HANOVER, PA 17331
(717) 637-8911

CERTIFIED MATERIALS TEST REPORT

CMTR COVERS RICHMOND ENTERPRISES PO#1648; WELDSTAR NUCLEAR SHIPPING TICKET N910953

WELDSTAR CO.
1750 MITCHELL RD.
AURORA, IL 60504

Customer Order No.: 9094
Order No.: 142928-2

This Material Conforms to Specification: ASME SFA 5.20 SEC. II PART C & ASME SEC. III, SUBSEC. NB FOR CLASS 1 MATERIAL 1989 ED., 1989 ADD., ASME SFA 5.01, CLASS T-2, SCHEDULE K, 10 CFR PART 21 APPLIES

Trade Name or Trademark: Dual Shield 7100 Ultra
Diameter Size: 1/16" x 60# CL. — Type: E71T-1
Weight: 7,680 lbs. — Test No.: 2-16854-00
Lot Number: 28365

X-Rays Satisfactory

Carbon:	.03
Manganese:	1.14
Chromium:	.04
Nickel:	.01
Silicon:	.74
Columbium+:	
Tantalum:	
Molybdenum:	.01
Tungsten:	
Copper:	.02
Titanium:	
Phosphorus:	.012
Sulphur:	.015
Vanadium:	.02
Cobalt:	

Type Steel A-285

Full	Split	Triple	Quad	Volts	Amps	
1	5	--	--	29	300	DC+

Test Results:	As Welded
Yield	83,900
Tensile	93,200
Elongation (2"), %	23.0
Red. of Area	57.3

Charpy V-Notch Impacts Tested @ 0°F.

Ft. Lbs.	64-65-54
Lat. Exp.	56-48-51
% Shear	30-30-30

Shielding gas: CO_2

Preheat: 65°F.
Interpass: 325°F.
Fillets: OK Vertical/Overhead

Tensile Specimen .505"
Impact Specimen .394" x .394"

THIS MATERIAL IS CERTIFIED TO BE FREE OF ANY MERCURY CONTAMINATION.

Location & Orientation of Charpy-V-Notch/Tensile Specimens is I/A/V ASME NX-2322 and/or ASME/SFA specifications as applicable.

Quality Systems Certificate No. QSC-221
Expiration Date: September 8, 1993.

State of Pennsylvania)
) SS:
County of York)

Subscribed and sworn to before me this 4th day of April, 1991.

SEAL: Linda C. Myers
Notary Public

The undersigned certifies that the contents of this report are accurate and that all operations performed by the undersigned or sub-contractors are in compliance with requirements of the material specification and ASME Boiler and Pressure Vessel Code, Section III, Division I, Subsection NCA-3800.

ALLOY RODS CORPORATION

By: D. A. Smith
D. A. Smith, Supervisor, Q. A. Services

NOTARIAL SEAL
LINDA C. MYERS, Notary Public
Penn Township, York County
My Commission Expires April 13, 1992.

QA DOCUMENT

Sargent & Lundy LLC	Calcs. For Palisades Weld Flaw Analysis for Loaded Spent Fuel Cask MSB No. 4			Calc. No. 2007 - 20168
				Rev. 00 Date: 12/04/07
	X	Safety-Related	Non-Safety Related	Page A3 of A3

Client	Entergy
Project	Palisades
Project No.	12122 - 035

Prepared by	A. Reiter	Cdm A. Reiter	Date 12/04/07
Reviewed by	P. Hoang		Date
Approved by	A. Dermenjian		Date

Attachment to EA-FC-864-050 Appendix 2 2/6

RAUTARUUKKI OY
RAAHEN TERÄSTEHDAS

AINESTODISTUS TEST REPORT
WERKSZEUGNIS RELEVE DE CONTROLE

A 3/7
25387 -08

TEST REPORT ASME SA-20/ASTM A-20

STENCOR USA INC.
EMPIRE STATE BUILDING

HOUSTON

01.10.1990

[illegible]398

T-0094

ASME SA-516 GR 70

ASME SA-20

PRESSURE VESSEL STEEL ACC.TO ASME SA-20 1989 SECTION II

Pos	Thickness (mm)	Heat No.		C	SI	MN	P	S	AL	NB	V	CU	CR	NI	MO
006	15.88	61459		.22	.35	1.09	.020	.004	.051	.001	.009	.008	0.02	0.03	.004
006	15.88	61522		.23	.36	1.15	.020	.003	.044	.001	.015	.012	0.02	0.02	.005
007	19.05	61486		.21	.39	1.14	.015	.001	.031	.001	.006	.025	0.03	0.03	.005
008	19.05	61066		.22	.36	1.13	.010	.003	.036	.002	.005	.010	0.02	0.03	.005
008	19.05	61459		.22	.35	1.09	.020	.004	.051	.001	.009	.008	0.02	0.03	.004
009	25.40	60895		.24	.33	1.12	.011	.003	.036	.001	.008	.023	0.02	0.04	.006
009	25.40	61095		.21	.36	1.11	.021	.002	.041	.001	.020	.011	0.02	0.03	.005
010	25.40	61066		.22	.36	1.13	.010	.003	.036	.002	.005	.010	0.02	0.03	.005
010	25.40	61284		.26	.35	1.11	.016	.002	.031	.001	.007	.008	0.03	0.03	.005
011	31.75	60663		.20	.36	1.10	.016	.006	.037	.002	.007	.007	0.02	0.03	.006
011	31.75	61066		.22	.36	1.13	.010	.003	.036	.002	.005	.010	0.02	0.03	.005
012	31.75	60663		.20	.36	1.10	.016	.006	.037	.002	.007	.007	0.02	0.03	.006

MEETS ALSO THE REQUIREMENTS OF ASME SA515 GR70 EXCEPT PRODUCED TO FINE GRAIN PRACTICE
N 920C,T=1.1(MIN)XTHICKN(MM).

Pos	Heat / Sample	Cond	K2	REH	Rm	A5		K3	°C	1	2	3	Average
006	61459 21	N	11	363	551	40		111	-46	068	048	079	065
006	61522 21	N	11	380	577	41		111	-46	070	072	066	069
	61486 12	N	11	360	556	40		111	-46	073	047	067	062
	61486 31	N	11	357	551	44		111	-46	068	054	052	058
[illegible]	61066 13	N	11	363	553	50		111	-46	112	077	095	095
008	61459 11	N	11	364	558	40		111	-46	058	044	058	053
008	61459 12	N	11	366	557	40		111	-46	079	059	064	067
008	61459 42	N	11	364	552	44		111	-46	080	072	061	071
009	60895 23	N	11	388	567	45		111	-46	054	063	054	057
009	61095 33	N	11	377	545	50		111	-46	079	117	116	104
009	61095 42	N	11	373	545	54		111	-46	106	105	090	100
010	61066 32	N	11	367	541	52		111	-46	105	049	076	077
010	61284 21	N	11	406	589	50		111	-46	051	046	045	047
011	60663 49	N	11	343	527	50		111	-40	083	103	110	099
011	61066 31	N	11	341	533	52		111	-40	090	084	059	078
012	60663 11	N	11	339	520	56		111	-40	066	092	071	076

B. TIO

K2: 11=TOP, TRANSVERSE
K3: 111=CH-V/ISO-V(J),10X10,TOP,LONGIT.

RAUTARUUKKI OY 02.10.90 LJ

PENTTI KASKENTOLA

QA DOCUMENT

ATTACHMENT B

Testing Engineers, Inc. QM-483 Suggested Format For Procedure Qualification Record

Total Number of Pages Including this Cover Page = 3

Attachment to EA-FC-864-050 Appendix 2

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TESTING ENGINEERS, INC.

2811 Adeline Street • P.O. Box 24075 • Oakland, CA 94623 • (415)835-3142

QW-483 SUGGESTED FORMAT FOR PROCEDURE QUALIFICATION RECORD (PQR)

(See QW-201.2, Section IX, ASME Boiler and Pressure Vessel Code)

Record of Actual Conditions Used to Weld Test Coupon

COMPANY NAME [illegible]

PROCEDURE QUALIFICATION RECORD NO. [illegible] DATE [illegible]

WPS NO. [illegible]

WELDING PROCESS(ES) [illegible]

TYPE (MANUAL, AUTOMATIC, SEMI-AUTO.) [illegible]

JOINTS (QW-402)

Groove Design of Test Coupon

(For combination qualification, the deposited weld metal thickness shall be recorded for each filler metal or process used.)

BASE METALS (QW-403)

Material Spec. [illegible]

Type or Grade [illegible]

P-No. [illegible] to P-No. [illegible]

Thickness of Test Coupon [illegible]

Diameter of Test Coupon N/A

Other N/A

FILLER METALS (QW-404)

Weld Metal Analysis A-No. [illegible]

Size of Filler Metal [illegible]

Filler Metal F-No. [illegible]

SFA Specification [illegible]

AWS Classification [illegible]

Other [illegible]

Deposited Weld Metal [illegible]

POSITION (QW-405)

Position of Groove 1G

Weld Progression (Uphill, Downhill) N/A

Other N/A

PREHEAT (QW-406)

Preheat Temp. [illegible]

Interpass Temp. [illegible]

Other N/A

POSTWELD HEAT TREATMENT (QW-407)

Temperature N/A

Time N/A

Other N/A

GAS (QW-408)

Type of Gas or Gases [illegible]

Composition of Gas Mixture [illegible]

Other [illegible]

ELECTRICAL CHARACTERISTICS (QW-409)

Current [illegible]

Polarity [illegible]

Amps. [illegible] Volts [illegible]

Tungsten Electrode Size N/A

Other N/A

TECHNIQUE (QW-410)

Travel Speed [illegible]

String or Weave Bead [illegible]

Oscillation N/A

Multipass or Single Pass (per side) [illegible]

Single or Multiple Electrodes [illegible]

Other N/A

JAN 28 '92 10:16 4088832348 PAGE [illegible]

Attachment to EA-FC-864-050 Appendix 2 4/6

QW-483 SUGGESTED FORMAT FOR PROCEDURE QUALIFICATION RECORD (PQR)

(See QW-201.2, Section IX, ASME Boiler and Pressure Vessel Code)

Record of Actual Conditions Used to Weld Test Coupon

(Cont'd)

PQR No. [illegible]

TENSILE TEST (QW-150)

Specimen No.	Width	Thickness	Area	Ultimate Total Load (lb)	Ultimate Unit Stress (psi)	Type of Failure & Location
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

GUIDED-BEND TESTS (QW-160)

Type and Figure No.	Results
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

TOUGHNESS TESTS (QW-170)

Specimen No.	Notch Location	Notch Type	Test Temp.	Impact Values	Lateral Exp. % Shear	Lateral Exp. Mils	Drop Weight Break	Drop Weight No Break
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				
[illegible]	[illegible]	"	"	[illegible]				
[illegible]	[illegible]	"	"	[illegible]				
[illegible]	[illegible]	"	"	[illegible]				
[illegible]	[illegible]	"	"	[illegible]				
[illegible]	[illegible]	"	"	[illegible]				

FILLET-WELD TEST (QW-180)

RESULT – SATISFACTORY: YES____ NO____ PENETRATION INTO PARENT METAL: YES____ NO____

MACRO – RESULTS____

OTHER TESTS

TYPE OF TEST [illegible]

DEPOSIT ANALYSIS____

OTHER____

WELDER'S NAME [illegible] CLOCK NO.____ STAMP NO. [illegible]

TESTS CONDUCTED BY:____ LABORATORY TEST NO.____

We certify that the statements in this record are correct and that the test welds were prepared, welded and tested in accordance with the requirements of Section IX of the ASME Code.

[illegible], INCORPORATED Manufacturer [illegible]

By [signature] By [signature]

1/20/92 1/20/92

Date Date

(Detail of record of tests are illustrative only and may be modified to conform to the type and number of tests required by the Code.)

JAN 20 '92 10:10

ATTACHMENT C

Testing Engineers, Inc. Charpy V-Notch Impact Test, Laboratory Number M1061

Total Number of Pages Including this Cover Page = 2

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Attachment to EA-FC-864-050 Appendix 2

Quality Assurance Serv.
Materials Consult.

Testing Engineers, Inc.

CHARPY V-NOTCH IMPACT TEST

LABORATORY NUMBER: M1061

PROJECT NO.: [illegible]

DATE: 1/17/[illegible]

PROJECT: Richmond [illegible]

DESCRIPTION: WPS # 11A[illegible]

TESTED AT [illegible] ° F

SAMPLE ID	SIZE	ABSORBED ENERGY FT. LB.
WELD	10MM x 10MM	[illegible]
WELD	10MM x 10MM	[illegible]
WELD	10MM x 10MM	18
		AVG [illegible]
HAZ	10MM x 10MM	[illegible]
HAZ	10MM x 10MM	[illegible]
HAZ	10MM x 10MM	[illegible]
		AVG [illegible]

REPORTED TO: Jim [illegible]
RICHMOND ENTERPRISES
[illegible] Meridian Road
[illegible], CA [illegible]

BY: *signature*
Dan Watanabe, Assistant Metallurgist

2811 Adeline Street, P.O. Box 24075, Oakland, California 94623 • (415) 835-3142

JAN 28 '92 18:18

ATTACHMENT D

Testing Engineers, Inc, Work Request Number M1031

Total Number of Pages Including this Cover Page = 2

Sargent & Lundy LLC	Calcs. For	Palisades Weld Flaw Analysis for Loaded Spent Fuel Cask No. 4	Calc. No.	2007 - 20168
			Rev. 00	Date: 12/04/07
	X	Safety-Related / Non-Safety Related	Page	D2 of D2

Client	Entergy
Project	Palisades
Project No.	12122 - 035

Prepared by	A. Reiter	*[signature]*	Date 12/04/07
Reviewed by	P. Hoang		Date
Approved by	A. Dermenjian		Date

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Attachment to EA-FC-864-050 Appendix 2

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MECHANICAL TESTS

DATE 01/16/92

WORK REQUEST NO. N1031

PROJECT NO: 29415

Richmond Enterprises

WPS 0115-92

ATTACHMENT E

NRC Letter

Total Number of Pages Including this Cover Page = 3

April 9, 2007

MEMORANDUM TO: Jamnes L. Cameron, Branch Chief
Division of Nuclear Material and Safety, Region III

FROM: Gordon Bjorkman, Branch Chief /RA/
Spent Fuel Storage and Transportation Division, NMSS

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION; REGION III TAR REQUESTING ASSESSMENT OF PALISADES WELD FLAW ANALYSIS FOR LOADED SPENT FUEL CASK MSB NO. 4
TAC No. A10126

The Division of Spent Fuel Storage and Transportation (SFST) staff finds that additional information is required in order to complete the ongoing TAR for assessing the adequacy of the Palisades weld flaw analysis for loaded spent fuel cask MSB No. 4.

During our review of the fatigue crack growth calculation, it was noted that one input variable was fixed at a possibly non-conservative value. As a consequence of this assumption, the associated fatigue crack growth rates could also be non-conservative. The result could thus under-predict the eventual flaw size, possibly by a very significant margin. Consequently, attached is a request for additional information in regards to this calculation.

Please contact Jerry Chuang, Senior Structural Engineer, of my staff at 301-415-8586, if you require clarification of this issue.

Enclosure: Request for Additional Information

DISTRIBUTION:
NMSS r/f SFST r/f JChuang MDebose GHornseth BWhite
MGryglak

ML070880519

OFC:	SFST	SFST	SFST	SFST
NAME:	JChuang	MDebose	GHornseth	GBjorkman
DATE:	04/05/2007	04/05/2007	04/05/2007	04/09/2007

OFFICIAL AGENCY RECORD

REQUEST FOR ADDITIONAL INFORMATION

Palisades Weld Flaw Analysis for Loaded Spent Fuel Cask MSB No. 4

Model No. VSC-24

Reference:

Licensee supplied calculation EA-FC-864-50, Appendix 2 to MSB No. 4 "Structure Integrity Assessment," page 18.

Issue:

The fatigue crack growth analysis set a fixed value of R at 0.9 in a fatigue crack growth law provided by ASME Section XI, Article A-4000 for all stress cycles. Provide fatigue crack growth data for a surface crack in ASTM SA-516, Grade 70 ferritic steel for the range of $0.9 < R < 1.0$ and re-analyze the case using the data to demonstrate that the final crack length determined by the referenced calculation is conservative.

Background:

The Division of Spent Fuel and Storage and Transportation (SFST) staff reviewed the fatigue crack growth calculation for an initial semi-circular surface crack present in the MSB No. 4, considering 50 years of cyclic service conditions. The calculations assumed all loading cycles had a constant R value of 0.9. However, due to the level of residual stresses imposed in the assumptions, it appears to the staff that most of the loading cycles are in the range of $0.9 < R < 1.0$.

It is well known that higher values of R yield a larger crack growth rate per cycle for a fixed stress amplitude. Thus, fatigue crack growth data for a semi-circular surface crack in ASTM SA-516, Grade 70 ferritic steel for this R-range ($0.9 < R < 1.0$), in air, at room temperature are needed. Using such data, a new analysis should be performed to show that the final calculated crack sizes at the end of a 50 year service life remain stable.

Absent such data and re-analysis, the SFST staff are unable to determine if the flaw propagation after 50 years of cyclic loads would remain stable, thus assuring the integrity of the cask.