Enclosure 4

Calculation No. CPC-06Q-303, Revision 1,
Analysis of Hypothetical Flaws in VSC-24 Shell and Bottom Plate
(1 paper copy)

STRUCTURAL INTEGRITY Associates, Inc.	**CALCULATION PACKAGE**	**FILE No.: CPC-06Q-303** **PROJECT No.:** CPC-06Q

PROJECT NAME: Analytical Support for Dry Spent Fuel Storage Activities

CLIENT: Consumers Energy (Palisades Nuclear Plant)

CALCULATION TITLE: Analysis of Hypothetical Flaws in VSC-24 Shell and Bottom Plate

PROBLEM STATEMENT OR OBJECTIVE OF THE CALCULATION:

Evaluate potential flaws that could result from undocumented weld repairs, using fracture mechanics methods and as-measured material properties.

Document Revision	Affected Pages	Revision Description	Project Mgr. Approval Signature & Date	Preparer(s) & Checker(s) Signatures & Date
0	1-20 Appendix A	Initial Issue	[signature] 6/2/98	[signature] 6/2/98 [signature] 6/24/98
1	1 – 19 Appendix A	Revised to incorporate client comments.	[signature] 6/24/98	[signature] 6/24/98 [signature] 6/24/98

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1.0 INTRODUCTION

The purpose of the present calculation is to assess the potential impact of the presence of undocumented weld repairs in the VSC-24 shell or bottom plate on the structural integrity of the component. The intent is to show that flaws with similar dimensions to those that have been observed at ANO do not invalidate the integrity of the components. Consequently, the flaws postulated in the following analysis are intended to be conservative with respect to those that could reasonably occur in the components. It is not the intent of this calculation to provide screening or acceptance criteria for specific flaws.

The postulated flaws occur at the location of local weld repairs in the VSC-24 shell or bottom plate. These welds may have been performed following removal of temporary attachments used during shell fabrication. The repairs are assumed to be shallow surface repairs of minimal thickness (e.g., 1 welded layer). It is assumed that the welding process produced a local heat affected zone, but did not affect the bulk of the shell thickness. The material properties in the weld metal and the local heat affected zone are indeterminate.

The analysis uses the methods of ASME Section XI, IWB-3600 and Appendix A of that Code, to evaluate limiting hypothetical flaws. The results of recent material tests are considered where applicable in the following.

2.0 CODE APPLICABILITY

In the present analysis, the methods of ASME Section XI, IWB-3600 and Appendix A [1] are used to determine allowable flaw sizes under the limiting loading conditions. IWB-3600 and Appendix A are directly applicable to Class 1 vessels (such as reactor vessels) and piping. Although the dry fuel storage casks are Class 2 (NC) vessels, Section IWC-3600 is still under development, and Section XI permits the use of IWB criteria for flaw evaluations.

3.0 DESIGN BASIS

Sierra Nuclear Corporation calculation [2] defines the design basis thickness of the shell as 0.75 inches. It is this thickness on which the stress analysis results in previous calculations [3, 4] are based. The nominal thickness of the shell is 1 inch, which includes a corrosion allowance of 0.15 inches [2].

The same calculation shows that the design thickness of the bottom plate is the nominal thickness of 0.75 inches. That calculation also shows that a thickness of 0.54 inch is required to meet Code allowable stress limits, and that a thickness of 0.69 inch includes a corrosion allowance of 0.15 inch.

In Sierra Nuclear calculations [3, 4] the ASME Code stress limits were calculated using the material design stress intensity S_m. determined at 600° F. This temperature bounds any expected service temperature for the VSC-24 cask. Since S_m decreases with increasing temperature, use of the value of S_m at 600° F is conservative.

Design basis assumptions and results from previous Sierra Nuclear calculations are not design reviewed here, but are used as stated.

Tables 1 and 2 [3] provides stress data for the cask shell and bottom plate for both normal operation and horizontal drop accident. The drop accident event is considered to be a faulted condition (service level D) event. By comparing the tables, it can be seen that the normal operating stresses are significantly lower than the stresses that are predicted to result from the horizontal drop event.

In the subsequent fracture mechanics analysis, $P_l + P_b$ and Q were used. These were conservatively modeled as tensile membrane stresses.

Such local repairs can produce high tensile residual stresses in the weld metal, and correspondingly high compressive residual stresses in the immediately adjacent material, corresponding approximately to the HAZ. The bulk of the component material will be nearly unaffected by such shallow, local welding, and residual stresses in the components outside of the heat affected zone are assumed to be negligible. Weld residual stresses are steady state secondary stresses, which are not limited by the ASME Code. These stresses are displacement (or strain) controlled, and are self equilibrating.

For normal operating conditions, the limiting (allowable) applied stress intensity K_I (applied) is:

$$K_I \text{ (applied)} < K_{ID} / \sqrt{10} \qquad (1)$$

where K_{ID} is calculated from the lower bound of actual material toughness test results using the methods of Section XI, Appendix A [1]. K_{ID} is used as the critical stress intensity. The safety factor of $\sqrt{10}$ is as defined in Section IWB-3612. The data presented in Section XI, Appendix A represents the lower bound of K_{Ia} and K_{ID} data. For this case, the total applied stress intensity K_{ID} (applied) is determined as

$$K_I \text{ (applied)} = K_I \text{ (membrane)} + K_I \text{ (bending)} + (K_I \text{ (thermal)})/\sqrt{10} \qquad (2)$$

For the emergency/faulted case (horizontal drop), it is still appropriate (and conservative) to use the calculated K_{ID} as the evaluation criterion, because of the dynamic nature of the loading, instead of the K_{IC} (which would be appropriate for static or slow loading rates). For this case (horizontal drop) the applied K_I is limited by

$$K_I \text{ (applied:drop)} < K_{ID} /\sqrt{2} \qquad (3)$$

The applied K_I is given by:

$$K_I\ (\text{applied}) = K_I\ (\text{membrane}) + K_I\ (\text{bending}) + K_I\ (\text{Thermal})/\sqrt{2} \qquad (4)$$

4.0 MATERIAL FRACTURE TOUGHNESS

According to the "Certificate of Conformance for the VSC-24 System," Section 1.2.13, there are administrative limits which prevent moving of the storage casks when the temperature is less than 0°F. Consequently, a horizontal drop accident is judged not to be possible below this temperature.

Article A-4000 of Appendix A to Section XI [1] recommends that the material fracture toughness be determined from the actual material and product form in question, at the actual service temperature. Therefore, to evaluate the fracture toughness of this material, use of actual lower bound toughness data at 0°F is appropriate.

If the administrative temperature limits are raised, a corresponding increase in material toughness would result. This increase would produce significant increases in allowable flaw sizes, especially for short flaws. For the infinite length hypothetical flaws which are conservatively considered here, the primary membrane stress limits continue to govern, as described in Section 3.0 above.

5.0 APPLICATION OF ASME CODE MARGINS

As discussed above, the normal operating and horizontal drop accident events were evaluated. The stresses associated with these two events for the two component locations are defined in Tables 1 and 2 [3].

Using the rules of IWB-3613 (c) [1], the fracture toughness values determined above are reduced as follows to define the limiting allowable K_I for flaws in the two components under both operating conditions:

Normal Operating : (Level A, B)	$K_{I\,allowable} < K_{ID} / \sqrt{10}$	(5)
Drop Event: (Level D)	$K_{I\,allowable} < K_{ID} / \sqrt{2}$	(6)

6.0 ALLOWABLE FLAW CALCULATIONS

6.1 Approach

Because the welding process and resulting material properties in the weld and HAZ are indeterminate, it is assumed for the purpose of analysis that crack-like defects could originate in such weld repairs. Such flaws are assumed to be oriented in the through wall direction in the following analysis. Local weld repairs have been observed on both the inside and outside surfaces of shells and bottom plates at ANO. In the worst case, inside and outside surface repairs have occurred at approximately the same location (the welds are opposed).

Analysis of these hypothetical flaws was performed using linear elastic fracture mechanics methods compatible with those used in ASME Section XI, IWB-3610 and Appendix A [1]. The following methods and assumptions were used:

a. The hypothetical opposed flaw configuration was evaluated using a double edge cracked plate (DECP) model, illustrated in Figure 1.
b. Stresses at the limiting locations in the shell and bottom plate were used, from Tables 1 and 2. Although these stresses have a large primary bending component Pb, all stresses were conservatively treated as pure membrane stresses.
c. A lower bound material toughness value for the shell material was used based on the results of [6]. The value used was K_{ID} = 75 ksi- $\sqrt{(in)}$ at 0° F. Results of previous analyses and test results show that for the material used in the shell and bottom plate (A-516 Grade 70), this value would be representative of material that met the procurement requirement of Charpy V-notch toughness absorbed energy of 15 ft-lb at –50° F [5 and 6].

d. Because of the indeterminate properties of the weld material and HAZ, flaws are assumed to extend entirely through this material. There is therefore no need to quantify the properties of this material. With this assumption, residual stresses can also be neglected.

e. The horizontal drop accident (a level D event) is the most limiting design event.

f. The factors of safety required by ASME Section XI are included in this analysis.

6.2 Fracture Mechanics Analyses

The double edge cracked plate model shown in Figure 1 conservatively represents the potential flaw configuration with opposing flaws on the inside and outside surfaces. The applied stress intensity K_I can be determined for this model from [9]:

$$K_I = \sigma_\infty \sqrt{\pi a}\left(\frac{1.12 - 0.61\left(\frac{a}{w}\right) + 0.13\left(\frac{a}{w}\right)^3}{\sqrt{1-\left(\frac{a}{w}\right)}}\right)$$

where:

σ_∞ = remote tension stress

a = flaw depth (in the through shell or through plate direction)

2W = plate width (corresponding to shell or plate thickness)

The safety factor of $\sqrt{2}$ was applied to the limiting material toughness of 75 ksi $\sqrt{(in)}$ to produce an allowable applied stress intensity factor of 53 ksi $\sqrt{(in)}$. The above equation was iteratively solved, parametrically varying flaw depth a, to determine the depth which would produce an applied K_I equal

to the allowable K_I. These results are presented in spreadsheet format in Appendix A to this calculation.

There is no known mechanism for continued crack propagation of defects in these components [7] once they have extended beyond the heat affected zone of the undocumented welds, so no crack growth calculations have been performed for the assumed defects.

7.0 DISCUSSION

ANO performed inspections of several existing empty casks to evaluate the existence and extent of undocumented weld repairs in the cask shell and bottom plate [8]. The inspection process included etching of the inside and outside surfaces. Where such weld repairs were identified, they were locally excavated to remove the weld material and HAZ. In many cases, flaws were found on both inside and outside surfaces, in approximately opposing locations. Excavation was required on both surfaces in such cases. Following this removal, the depth of the excavation was determined by ultrasonic testing (UT) methods, and the local remaining ligament was determined relative to the nominal initial component thickness.

As discussed above, the general component thickness required to meet ASME Section III primary stress limits is 0.75 inches for the cask shell, and 0.54 inches for the bottom plate. The nominal thicknesses of these components are 1 inch for the shell, and 0.75 inch for the bottom plate.

Fracture mechanics (LEFM) analysis were performed assuming opposing flaws with aspect ratio (a/l) = 0 (double edge cracked plate (DECP) model). These analyses determined that flaw pairs which would produce uncracked ligaments less than the amount required to maintain primary stress limits would meet the criteria of ASME Section XI, under the worst case loading condition (horizontal drop event), including all Section XI factors of safety. For initial evaluation of the observed and hypothetical flaws in undocumented weld repairs, the primary stress limit criteria therefore govern.

The majority of all weld repairs observed at ANO would have been acceptable by these initial conservative criteria, since the remaining ligaments following excavation of the welds and HAZ were in excess of the limiting primary stress criteria. These criteria are very conservative, since they assume general thinning (for the primary stress criteria) or infinitely long pairs of opposed cracks (LEFM/DECP). Any flaws are assumed to have extended entirely through any weld material and HAZ. Actual undocumented weld repairs are very local, and will have minimal effect on general

primary stress adequacy of the component even if flawed. Local flaws several inches long could actually be entirely through wall without reducing the structural adequacy of the component. Those few flaws identified by ANO for which the excavation exceeded the above criteria above are acceptable because of the local nature of the flaws.

8.0 CONCLUSIONS

The flaws that could be present in the shell or bottom plate as a result of undocumented weld repairs will not affect the structural adequacy of the components. Flaws of significant size can be tolerated without presenting a risk of component failure due to brittle fracture. It should be noted that flaws which are potentially present on both the inside and outside surface of the components in the same location are not expected to affect the acceptability of each other, because of the relatively thick component wall compared to expected flaw dimensions. These results are generic and conservative in nature.

Specific conservatism in the present analysis:

1. All factors of safety on applied stress required by ASME Section XI (1989 Edition) were included in this evaluation.

2. The analyses are all based on linear elastic fracture mechanics, assuming that the failure mode is brittle failure. Actual material toughness results show that all materials are very resistant to such failures.

3. The fracture mechanics analyses performed to determine acceptance criteria used analytical models of flaws in flat plates. The actual component configuration provides considerably more restraint. The increased restraint would produce larger allowable flaw sizes.

9.0 REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section XI (with Appendix A and H), 1989 Edition. (The 1995 Edition is used as a Supplementary Reference).

2. Sierra Nuclear Corporation Design Calculation "MSB-24 Corrosion Calculation" WEP-109-002.6, Revision 4, 11/13/97.

3. Sierra Nuclear Corporation Design Calculation "MSB-24 Load Combination Evaluation", WEP-109-002.2, Revision 3, 5/30/95.

4. Sierra Nuclear Corporation Design Calculation "MSB-24 30 Foot Drop Analysis" WEP-109-002.8, Revision 2, 5/30/95.

5. Structural Integrity Associates, "Allowable Flaw Size Definition for VSC-24 Dry Storage Cask Structural Lid to Shell Weld." File CPC-06Q-301, Rev. 2, April 1998.

6. Westmoreland Mechanical Testing & Research Inc. Report WMT&R Report 8-03606, Transmitted by letter from Bruce Young (WMTR) to D. Eric Schultz (WEPCO) dated April 1, 1998.

7. Sierra Nuclear Corporation, "VSC Weld Cracking Evaluation in Response to NRC CAL-97-7-001," July 31, 1997.

8. ANO Work Plan 1409639 "Inspection of Multi-Assembly Sealed Basket Components," Revision 1.

9. Hellan, Kare, Introduction to Fracture Mechanics, McGraw Hill, Inc., 1984.

Table 1

Summary of Stresses (ksi) in the MSB Resulting from the Hypothetical Horizontal Drop

Component		Drop	Pressure	Total
Bottom Plate	P_m	29.4	0.2	29.6
	$P_l + P_b$	44.6	4.3	48.9
Shell	P_m	25.9	0.2	26.1
	$P_l + P_b$	71.8	0.2	72.0
Bottom Weld	P_m	25.9	0.6	26.5
	$P_l + P_b$	44.6	4.3	48.9

Table 2

MSB Maximum Stress Evaluation

Component	Stress	Dead Weight	Pressure	Thermal	Handling	Total
MSB Shell	P_m	0.1	0.2	N/A	0.9	1.2
	$P_l + P_b$	0.1	2.9	N/A	2.4	5.4
	$P + Q$	0.1	2.9	1.0	2.4	6.4
Bottom Plate	P_m	0.02	0.2	N/A	1.0	1.2
	$P_l + P_b$	0.02	4.3	N/A	1.5	5.8
	$P + Q$	0.02	4.3	19.4	1.5	25.2
Bottom-to-Shell Junction	P_m	0.1	0.6	N/A	0.9	1.6
	$P_l + P_b$	0.1	4.3	N/A	1.5	5.9
	$P + Q$	0.1	4.3	19.4	1.5	25.3

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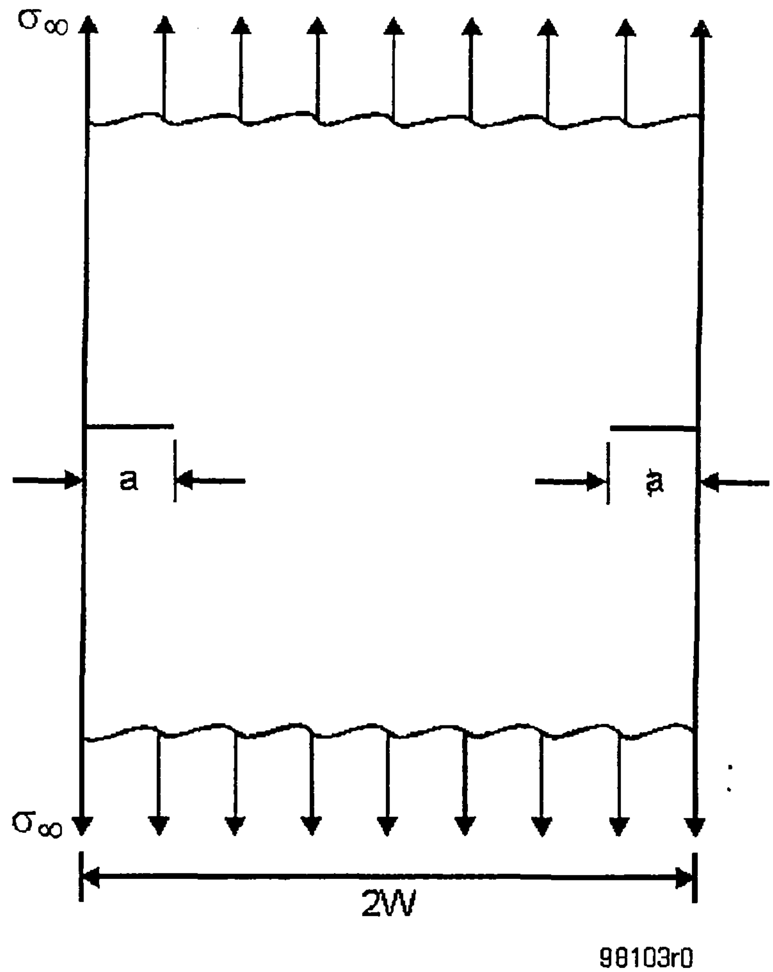

Figure 1. Double Edge Cracked Plate (DECP) Model

APPENDIX A

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Appendix A

Double Edge Cracked Plate Stress Intensity Factor Solutions

Shell at Design Stress

Depth A (in.)	Thickness (in.)	Half T=W (in.)	A/W	Applied Stress (ksi)	KI ksi $\sqrt{in.}$	KI Allowable ksi $\sqrt{in.}$
0.05	1	0.5	0.1	72	31.9	53
0.1	1	0.5	0.2	72	45.1	53
0.13	1	0.5	0.26	72	51.5	53
0.135	1	0.5	0.27	72	52.6	53
0.137	1	0.5	0.274	73	52.97	53

Shell at Factored Stress

0.05	1	0.5	0.1	54	23.9	53
0.15	1	0.5	0.3	54	41.7	53
0.2	1	0.5	0.4	54	48.9	53
0.22	1	0.5	0.44	54	51.8	53
0.228	1	0.5	0.456	54	52.93	53

Bottom Plate and Weld

0.05	0.75	0.375	0.133333	62.6	27.7	53
0.1	0.75	0.375	0.266667	62.6	39.3	53
0.15	0.75	0.375	0.4	62.6	49.1	53
0.16	0.75	0.375	0.4267	62.6	51.0	53
0.17	0.75	0.375	0.4533	62.6	52.94	53

Note: Applied Stress = $(P_L + P_b)_{Drop}$ + Thermal $/\sqrt{2}$

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