

Evaluation of the Refueling Water Storage Tank Bottom Plate Crack

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Volume 1 of 1

Prepared for:

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altran



Report Record

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ENGINEERING MANAGER: William McBrine Date: 1/31/00

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	Initials
1. The inputs come from an appropriate and controlled source, and are clearly referenced.	<u>BME</u>
2. The inputs from uncontrolled sources or assumptions are properly justified and documented.	<u>BME</u>
3. The inputs or assumptions that are not adequately justified are identified for later confirmation.	<u>NIA</u>
4. Design, analysis, testing, examination, and acceptance criteria are specified and complied with.	<u>BIAE</u>
5. Appropriate interface control was administered during the process of this report.	<u>BME</u>
6. The computer programs used are authorized for use and/or properly verified.	<u>BME</u>
7. Applicable codes, standards, or regulatory requirements are properly specified and complied with.	<u>BME</u>
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10. Specimens are controlled by identification number and their traceability is maintained.	<u>BME</u>
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13. The report is neat and legible and suitable for reproduction.	<u>BME</u>
14. The formatting and technical requirements of applicable procedures are complied with.	<u>BME</u>
15. Critical numerical computations have been checked in detail.	<u>BME</u>
16. The endorsements of all originators and verifiers have been properly recorded.	<u>BME</u>
17. Appropriate construction, operation, and/or maintenance considerations have been considered.	<u>NIA</u>
18. The conclusions satisfy stated objectives, and they are consistent with the input.	<u>BME</u>
19. All material specified are compatible with their service environment.	<u>NIA</u>
20. Procedural requirements for report revisions and subsequent reviews are complied with.	<u>BME</u>

Clarify significant comments:

THIS REPORT CONTAINS FAILURE ANALYSIS INVESTIGATION. ALL TESTING IS DESCRIBED IN DETAIL WITHIN. NO SEPARATE TEST PROCEDURES ARE REQUIRED.

All comments are resolved and incorporated into the report except as noted here:

Mooy H. Lee
Originator's concurrence

1/24/00
Date

[Signature]
Verifier's concurrence

1/24/2000
Date

Computer File Index



Report No. 00115-TR-001 Rev.: 0 Sheet: 4

By: Thomas ServicePhD Date: 1-20-00 Chk: B. Skwirz Date: 1-20-00

PROGRAM NAME: ANSYS VERSION NO.: 5.5.1

USERNAME: /extra/users/tom PROJECT MANAGER: Thomas Service,PhD,PE

QA Status yes, no (App. B , ISO 9000 , CGMP)

PROGRAM USE DESCRIPTION:

Perform two-dimensional axisymmetric finite element analysis of localized region at tank sidewall and base plate.

KEY WORDS: /prep7, /solv, /post1, plane42

Run No.	Description	Input File Name	Output File Name	Run Date::Time
1	two-dimensional axisymmetric finite element analysis of localized region at tank sidewall and base plate	Stp001.log	N/A	1/18/00 18:01

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1.0 INTRODUCTION AND BACKGROUND

This report summarizes the results of a finite element analysis, fracture mechanics analysis and field inspection of the Refueling Water Storage Tank (RWST) at the South Texas Project Nuclear Operating Company Unit 1. This evaluation was prompted because a radially oriented crack was detected by South Texas personnel in the base plate exterior to the tank. No circumferential crack indications have been identified in the vertical wall of the tank.

The objective of this analysis is to determine the critical crack size in the RWST under design basis loading conditions. This critical crack size calculation will allow the stability of the existing crack to be established in order to assure the structural integrity of the tank. The report identifies the apparent cause, cracking mechanism and related observations.

2.0 INPUT

Altran Corporation was provided with the original structural design analysis of the RWST performed in 1986 (Reference 1) and a copy of a liquid penetrant examination performed on site. (Attachment 1.) Additionally, Altran Corporation has inspected and performed field replication of the degraded area to determine the cracking mechanism.

3.0 METHODOLOGY

Altran has used EPRI proposed methodologies for the evaluation of through-wall cracking in austenitic piping (Reference 2.) Although the vessel in question is not piping, the evaluation still provides a conservative method to assess the stability of the observed crack.

In order to perform a fracture mechanics critical flaw size analysis information of the stress state in the region of the crack is required. The structural analysis performed in Reference 1 considers the stresses in the tank wall resulting from the hydrostatic head pressure of the water in the tank as well as dynamic seismic stress. The stresses in the base plate are not readily available for this report. Therefore, a two-dimension axisymmetric finite element analysis of the tank was performed to estimate the stresses in the base plate region and to confirm the stress state in the tank sidewall. These stresses are used to make critical crack size predictions using fracture mechanics principles.

A replication of the crack was made during an inspection of the tank. Replication consists of polishing the surface to be examined to a mirror finish, etching with an acid solution to reveal the microstructure and transferring the image to an acetate film for laboratory examination.

4.0 ANALYSIS AND RESULTS

4.1. Tank Geometry and Load Condition

The RWST is a 54' diameter 33' high storage tank fabricated from SA 240 Type 304 stainless steel. It was designed according to ASME Section III, Div 1, Class 2,

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Subsection NC, Subarticle NC-3800, 1974 Edition Including Winter of 1975 Addenda.

The design conditions as indicated in Reference 1 consist of:

Fluid ----- Dilute Boric Acid, (2,500 ppm) S.G. 1.0
Fluid Height ----- 32.39 feet
Temperature ----- 105°F
Internal Pressure ----- Atmospheric
External Pressure ----- Atmospheric
Wind Load ----- None
Seismic Loads ----- Category 1 per Spec 4Q019MS1044
Tank Radius ----- 324"
Tank Wall Thickness ----- 5/16" (at bottom of wall)
Bottom Plate Thickness - 1/4"

4.2. Summary of Original Analysis

The original design analysis report given in Reference 1 determines the stresses in the tank wall resulting from hydrostatic head pressure and addition stress due to seismic loads. The results of that analysis show that the maximum stress in the tank wall occurs at the bottom where it attaches to the base plate. Since this is near the location of the observed crack, these are the stresses of interest. The static hoop stress, σ_{H1} , was determined to be 14,560 psi and the dynamic hoop stress, σ_{H2} , due to seismic loads was determined to be 5,180 psi. Therefore the maximum hoop stress, σ_{Hmax} , in the shell at the bottom of the tank was determined to be 19,740 psi. The maximum stress in the longitudinal direction, σ_{Lmax} , at the same location was calculated to be 2,370 psi. However, since the observed crack is in the radial direction, longitudinal stresses will not contribute to propagation and thus only circumferential (or hoop) stresses will be considered.

4.3. Summary of Axisymmetric Finite Element Analysis

The original analysis only considered the stress state in the tank sidewall and not the base plate. Since the crack has been observed in the base plate it is necessary to determine the stress state in that region. This was done using finite element analysis, FEA. A two-dimensional axisymmetric finite element analysis was performed on a model of a localized region at the tank sidewall and base plate.

The model consists of a section of the base plate and a portion of the sidewall. Since the localized stresses at this joint are not affected by far field effects this simplified model is considered adequate. The boundary conditions consist of fixed vertical displacement of the base plate except for the region directly around the sidewall connection. Addition vertical constraint was placed at the base plate periphery to simulate gussets and anchor bolting. The region around the sidewall/base plate was allowed to displace in all directions to account for any bending introduced by the sidewall loads. These are considered conservative assumptions. The applied loads

consist of a uniform pressure applied to all internal elements, sidewall and bottom. Figure 1 shows the finite element plot of the model with the loads and boundary conditions. This pressure is equal to the maximum hydrostatic pressure resulting from the internal fluid as determined in Reference 1.

The results of the finite element analysis show that the hoop stress in the sidewall where it connects to the base plate is significantly less than the stress calculated in Reference 1. This is a result of the load carrying effects of the bottom plate. The hoop stress in the tank is shown in Figure 2.

The results of the finite element analysis show the linearized stress through the wall thickness where it locally attaches to the base plate is a 363 psi hoop stress. The corresponding localized hoop stress in the base plate linearized through the base thickness is 1,750 psi. To be conservative the maximum hoop stress in the side wall will be taken to be that calculated in Reference 1, $\sigma_{HWALL} = 19,740$ psi (19.74 ksi.) The maximum hoop stress in the base plate will be taken to be that calculated in the finite element analysis, $\sigma_{HBASE} = 1,750$ psi (1.75 ksi.)

4.4. Summary of Fracture Mechanics Analysis

4.4.1. Linear Elastic Fracture Mechanics (LEFM)

Fracture mechanics principles can be used to estimate the critical size of a flaw for it to remain stable. The methodology using linear elastic fracture mechanics, if applicable, consists of:

1. Determine stress state in the crack free configuration
2. Select appropriate flaw geometry and Calculate stress intensity factor, K_I
3. Determine fracture toughness, K_{IC}
4. Calculate critical flaw size.

Section XI of the ASME Boiler and Pressure Vessel Code, covers these types of analyses for components such as pressurized reactors and piping but it does not cover components such as tank base plates. However, it can be used as a guideline for conservative calculations of critical flaw sizes.

The flaw geometry in this case is considered a through thickness crack in a semi-infinite plate. This is reasonable because both the diameter and height of the RWST are considerably larger than the detected flaw. In this case the corresponding stress intensity, K_I , is (Reference 3,4):

$$K_I = 1.12 \sigma_H \sqrt{\pi a} \quad (1)$$

where 1.12 is the free surface correction factor, σ_H , is the applied hoop stress and, a , is the crack depth.

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Austenitic stainless steel is a very tough material. Reference 7 states: “*Extensive fracture toughness testing of type 304 and 316 stainless steels shows that they are extremely resistant to fracture. Both types exhibit a ductile fracture response under a wide variety conditions.*” As a result LEFM techniques are not directly applicable for prediction critical crack sizes because valid estimates of fracture toughness, K_{IC} , are not known. One published estimate for K_{IC} of AISI 304/304L stainless steel annealed plate and sheet is 200 ksi in^{1/2} as given in a NASA publication (Reference 6).

The critical crack size, a_{cr} , can be determined by rearranging Eq. (1) as:

$$a_{cr} = \left(\frac{K_{IC}}{1.12 \sigma_H} \right)^2 \frac{1}{\pi} \quad (2)$$

where σ_H is the maximum hoop stress assumed to be applied to the crack.

Equation (2) was used to calculate LEFM critical flaw sizes for the applied stresses determined in the base plate and sidewall and using a fracture toughness of 200 ksi in^{1/2}. Table 1 summarizes the results.

Table 1. Summary of Critical Flaw Size Calculations Based on LEFM.

<u>Location</u>	<u>σ_{Hmax}, ksi</u>	<u>K_{IC}, ksi in^{1/2}</u>	<u>a_{cr}, in</u>
Sidewall	19.74	200	26.0
Base Plate	1.75	200	>300

The results in Table 1 show that under the worse case assumptions of applied stress the critical flaw size for a through wall crack in the sidewall based on LEFM is 26”. The results also show that the base plate can sustain a through thickness crack of over 300” assuming the same estimates of fracture toughness.

However, because of the high toughness and ductile fracture response of SA240 Type 304 stainless steel, fracture predictions should also be made assuming a more realistic failure process of plastic collapse.

4.4.2. Plastic Collapse Analysis

SA 240 Type 304 stainless steel, as with most austenitic steels, have high toughness and ductility and predictions of failure under these conditions should also be made using limit load analyses assuming failure due to net section plastic collapse. The Electric Power Research Institute, EPRI Report No. NP-4690-SR entitled Evaluation of Flaws in Austenitic Steel Piping, Reference 2, outlines a procedure for making failure predictions under these conditions.

The hoop stress at failure, σ_{hf} , due to an axial flaw is given by:

$$\sigma_{hf} = \frac{\sigma_{yield}}{\left(1 + \left(\frac{1.61}{4Rt}\right)l^2\right)^{1/2}} \quad (3)$$

where σ_{yield} is the yield strength of the material conservatively taken to be 30,000 psi (Reference 7), R is the tank radius taken to be 324", t is the tank thickness taken to be 0.3125" and l is the total length of flaw that can be sustained. Assuming the hoop stress at failure is taken to be the maximum sidewall hoop stress given in Table 1, Equation (3) can be solved for the flaw length, l, to cause plastic collapse. Substituting the above parameters and solving for, l, gives a flaw size of 18" to cause plastic collapse. If this is an edge flaw then the total crack length would be 1/2 the size or 9". This is a conservative estimate of the size of a longitudinal through-wall sidewall crack that can be sustained by the tank.

4.4.3. Crack Growth Predictions

Cracks in austenitic stainless steels can grow under several mechanisms. One is the result of fatigue crack propagation whenever there is a cyclic stress state. The other crack growth mechanism is due to stress corrosion cracking.

Appendix C of Section XI of the ASME Code provides for the evaluation of flaws in austenitic piping. Article C-3210 covers flaw growth due to fatigue. The crack growth rate per stress cycle, da/dN, is given by:

$$\frac{da}{dN} = C_o (\Delta K_I)^n \quad (4)$$

where ΔK_I is the stress intensity factor cycle resulting from the applied stress cycle, n = 3.3 and the constant C_o is given by:

$$C_o = 10^{(-10.009 + 8.12 \times 10^{-4} T - 1.13 \times 10^{-6} T^2 + 1.02 \times 10^{-9} T^3)}$$

where T is temperature in degrees F. The number of on/off stress cycles required for a crack to grow from an initial size to a final size can be obtained by integrating Equation (4). The only stress cycle the tank experiences is when it is drained and refilled. This corresponds to an on/off stress cycle with the maximum stress assumed to be 19.74ksi as given in Table 1. Substituting this value into Eq. (1) gives the stress intensity factor cycle that can be substituted into Eq. (4) and assume a temperature of

105°F. Integrating Eq. (4) from an initial flaw size of 0.25" (assuming an edge crack in the sidewall equal to the thickness of the base plate) to a final flaw size of 1", the total number of cycles to for the crack to grow 1", can be shown to be 107,100. This means the tank can be filled and drained over 100,000 times for the crack to grow to a length of 1 inch.

Cracks can initiate and propagate under a stress corrosion mechanism. In order for this to occur there needs to be a stress driving force and an environment conducive for crack growth. Stainless steels are susceptible to chloride stress corrosion cracking providing there is a stress and the temperature is above about 125°F, (Reference 8.) Provided the temperature remains below 125°F, crack propagation under this mechanism will be small to negligible.

4.5. Field Inspection and Replication

A visual field inspection of the crack was performed by Altran Corporation. Figure 3 shows an overall photograph of the crack and Figure 4 shows a close-up photograph of the crack in the region of the base plate/sidewall weld. Figure 5 shows a side view of the edge of the base plate illustrating the through thickness crack. These photographs show that the crack has a jagged, irregular appearance. This morphology is consistent with a stress corrosion cracking mechanism.

The replications of the cracked area that were taken on site were brought back to Altran Corporation for laboratory analysis. They were examined using stereo and scanning electron microscopy.

Figure 6 shows a photograph taken in the stereomicroscope of the replica of the main crack shown in Figure 4. In this image, other cracks as well as branching cracks are visible. Figure 7 shows a scanning electron micrograph taken of a replica of the edge of the plate shown in Figure 5. This photograph shows the crack initiating from the bottom tank exterior of the plate and propagating up through the thickness. It also shows evidence of transgranular crack propagation and branching which is characteristic of chloride stress corrosion cracking in austenitic stainless steels.

The initiation and propagation of external Stress Corrosion Cracks is likely to have occurred in the presence of residual stresses as a result of initial fabrication welds or applied loads. It is also possible that residual stresses may have been relieved over time due to local yielding and crack initiation.

5.0 CONCLUSIONS

It can be concluded that a radial crack over 300 inches long through the thickness of the base plate at the perimeter of the RWST bottom will remain stable under design loading conditions. In addition, the constraint of the anchor bolts will also inhibit crack propagation in the base plate as well as intersection with other welded sections.

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The results of this analysis also show that the RWST can safely sustain a axial through wall crack in the sidewall in the region near the base plate estimated at 9" in length using very conservative assumptions and plastic collapse failure criteria.

The analysis showed that it would take over 100,000 on/off stress cycles for the crack to propagate by a fatigue mechanism from an initial length of 0.25" to a final length of 1".

The apparent cracking mechanism has been determined to be stress corrosion cracking initiating from the bottom of the tank near the periphery and propagating up through the base plate. However, further crack propagation under a stress corrosion mechanism will be small to negligible since the temperature of the RSWT remains under 125°F.

6.0 REFERENCES

1. Design Report 110015 Revision E. for South Texas Project Unit 1 Unit Refueling Water Storage Tank.
2. EPRI Report No. NP-4690-SR "Evaluation of Flaws in Austenitic Steel Piping", 1986
3. "Deformation and Fracture Mechanics of Engineering Materials, 4th ed." by R. W. Hertzberg, John Wiley & Sons NY NY 1996.
4. "Elementary engineering Fracture Mechanics, 4th ed." By David Broek, Martinum Nijhoff Publishers 1986.
5. ASME Section XI, 1980 through Winter 1981 Addenda
6. NASA/FLAGRO 2.0 Materials Constants published in NASA Publication JSC-22267A "Fatigue Crack Growth Computer Program NASA/FLAGRO Version 2.0 (Table G1)
7. ASM Handbook Volume 1, "Properties and Selection: Irons, Steels and High-Performance Alloys" page 866 Table 14, 1990.
8. "Principles and Prevention of Corrosion", by Denny Jones, page 256 Figure 8.16, Macmillan Publishing Co. NY NY 1992

7.0 PHOTOGRAPHS

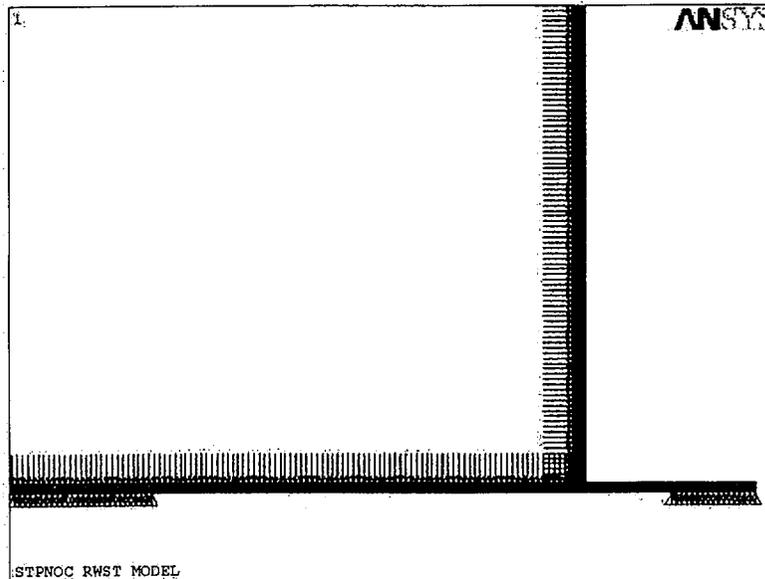


Figure 1. Axisymmetric Finite Element Model of Tank Sidewall and Base Plate.

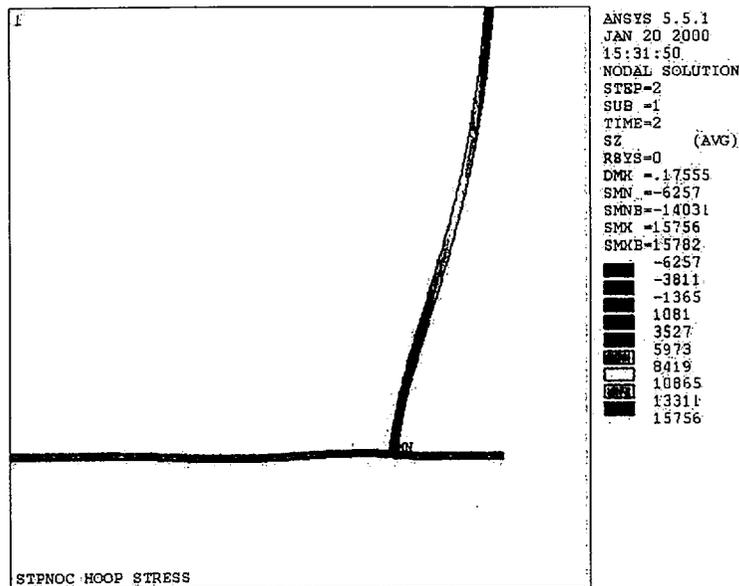


Figure 2. Hoop Stress Contours Near Base Plate Sidewall Joint.

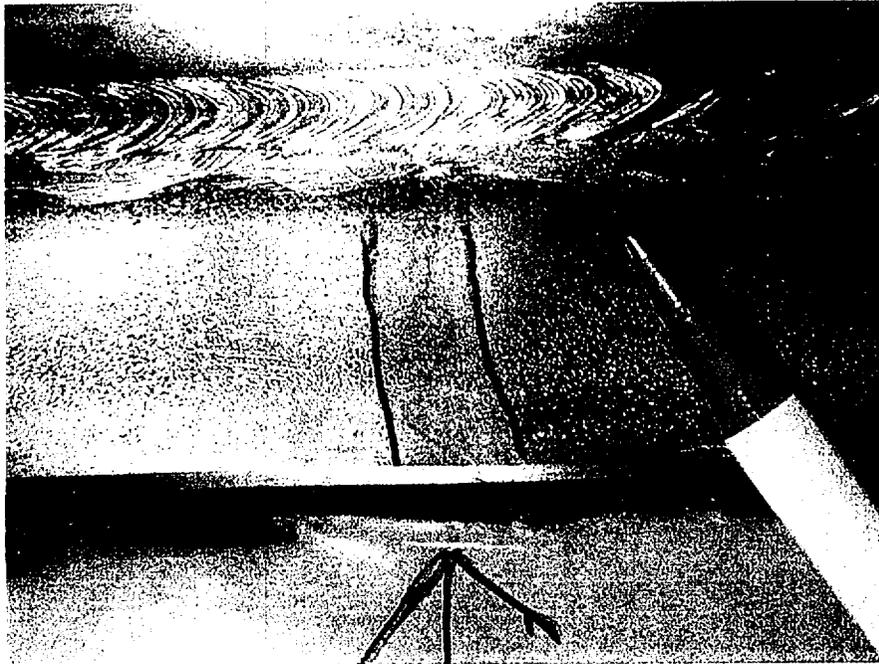


Figure 3. Photograph Showing Entire Crack.



Figure 4. Close-Up Photograph Showing Crack at Weld.

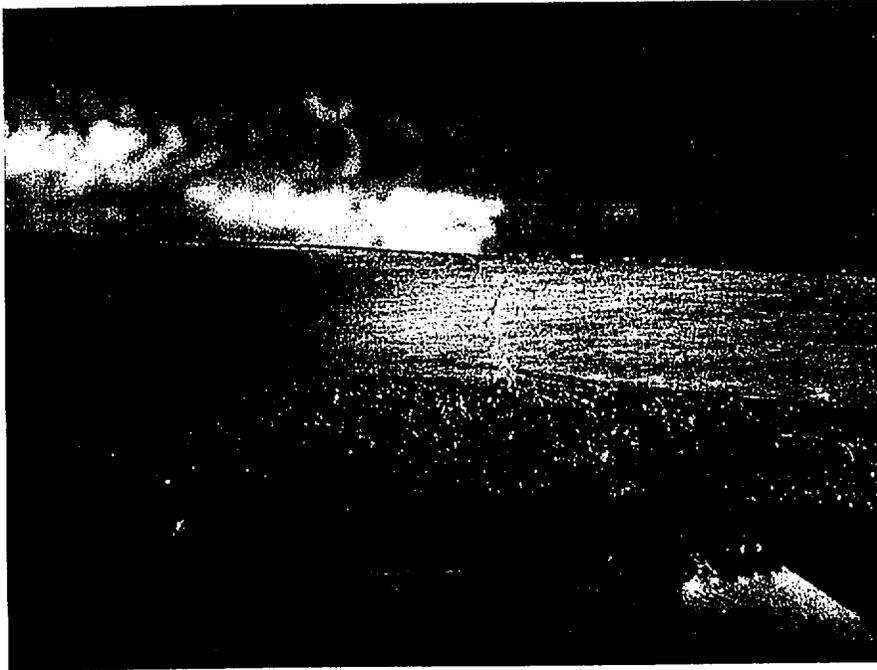


Figure 5. Photograph of Edge View of Base Plate Showing Through Thickness Crack.

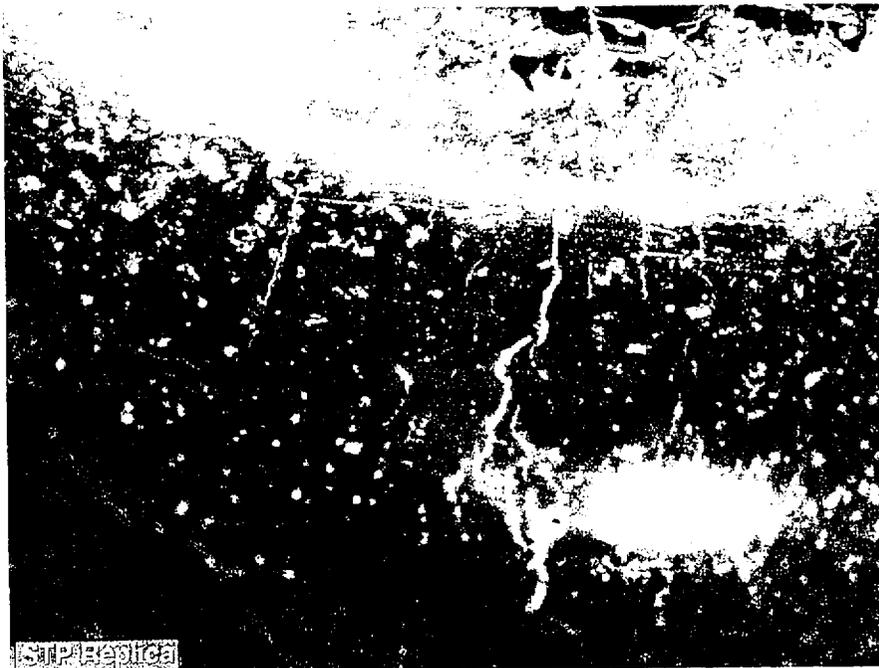
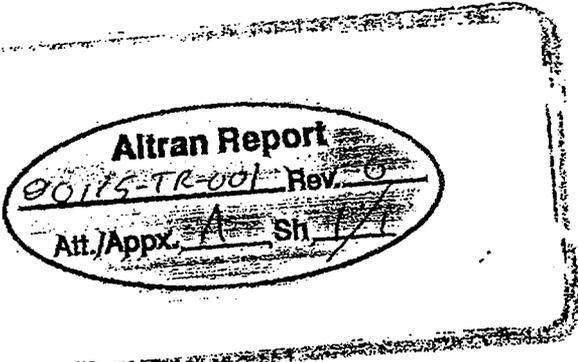
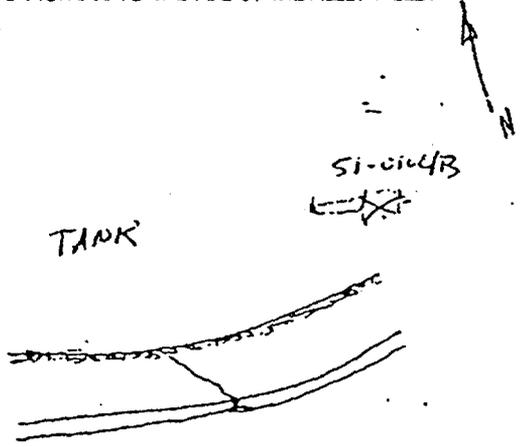


Figure 6. Photograph of Replica Taken from Area Shown in Figure 4.



Figure 7. Scanning Electron Photomicrograph of replica showing Cracking in the Edge of the Base Plate

RECORD NO. PT- 97 - 0247	0PQP05-ZA-0010			Deficiency Report N
SOLVENT REMOVEABLE LIQUID PENETRANT EXAMINATION				
Form 1	Liquid Penetrant Examination Record			Page 1 of 1
<input type="checkbox"/> ISI	<input type="checkbox"/> PSI	<input type="checkbox"/> Erosion/Corrosion	<input checked="" type="checkbox"/> Maintenance	<input type="checkbox"/> Info
COMPONENT DESCRIPTION / ID NO. REFUELING WATER STORAGE TANK		TAG/TPNS NO. 20121N1F101A	OUTAGE NO. MAINT	
Work Document No. N/A		PROCEDURE NO. OPQP05-ZA-0010	REV. 0	
UNIT NO. 1 BLDG. NO. MAB		ACCEPTANCE CRITERIA		
ROOM NO. 63 ELEVATION 10		Date of Examination: 9/19/97	Manhours: 2	
DWG NO.	COLOR		TYPE	BATCH NO.
MATERIAL SS	<input checked="" type="checkbox"/> CONTRAST <input type="checkbox"/> FLOURESCENT	PENETRANT	SKL-SP	96006K
		CLEANER	SKC-S	96A03K
		DEVELOPER	SKD-S2	95F01K
M&TE EQUIPMENT	CAL DUE DATE	SURFACE TEMP.		LIGHT LEVEL VERIFICATION
THERMOMETER 100-00520-082	1/28/98	78 °F		<input checked="" type="checkbox"/> ILLUMINATION - ADEQUATE
PROBE 100-00534-063	1/15/98			<input type="checkbox"/> ULTRAVIOLET - 800Mw/cm2 MIN
SURFACE CONDITION AS WELDED				
WELD NO./PART NO./SERIAL NO.		ACCEPT/REJECT	REMARKS	
TANK TO BASE PLATE FILLET		Reject	A FLAW WAS DETECTED ON THE BASE PLATE. THE FLAW EXTENDS FROM THE VERTICAL EDGE OF THE BASE PLATE AND ACROSS TO THE TOE OF THE FILLET WELD.	
WELD		Reject		
				
<input type="checkbox"/> SATISFACTORY		<input checked="" type="checkbox"/> UNSATISFACTORY		
INSPECTOR CLAY SUHLER	CERTIFICATE LEVEL II	DATE 9/19/07	SUPV/LEVEL III REVIEW	DATE
INSPECTOR	CERTIFICATE LEVEL	DATE	DED REVIEW ISI ONLY	DATE

ASME Section XI Appendix C Evaluation of Flaws in Austenitic Piping

T := 105 Temperature, F

S := 1.0 $K_{min}/K_{max}=0$

$$C := 10^{(-10.009 + 8.12 \cdot 10^{-4} \cdot T - 1.13 \cdot 10^{-6} \cdot T^2 + 1.02 \cdot 10^{-9} \cdot T^3)}$$

$$C = 1.161 \cdot 10^{-10}$$

$$C_o := C \cdot S \quad C_o = 1.161 \cdot 10^{-10}$$

n := 3.3

$\Delta\sigma := 19.74$ Stress Cycle, ksi Max Sidewall Stress

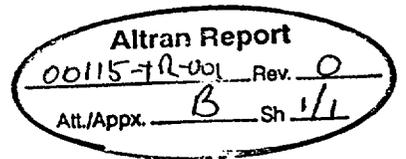
$a_i := 0.25$ Initial flaw size, in. Initial length of 0.25"

$a_f := 1.$ Final flaw size, in Final length of 1".

$$\Delta K := 1.12 \cdot \sqrt{\pi} \cdot \Delta\sigma$$

Cyclic Stress intensity Factor, ksi in^{1/2} *for ease of display
 \sqrt{a} is added below.*

$$\int_{a_i}^{a_f} \frac{1}{[\sqrt{a} \cdot (\Delta K)]^n \cdot C_o} da = 107096 \quad \text{Number of Cycles}$$



$$\Delta K := 1.12 \cdot \sqrt{\pi} \cdot \Delta\sigma \cdot \sqrt{a_f}$$

$$\Delta K = 39.187$$

THIS COMPUTER CALCULATION HAS BEEN CONFIRMED BY:	
<input checked="" type="checkbox"/>	DETAILED CHECKING OF ALL FORMULATION
<input type="checkbox"/>	COMPARISON TO AN IDENTICAL VERIFIED FILE IN
BY: <u>PME</u>	DATE: <u>1/24/00</u>



Laboratory Testing M&TE Index

Report No. 00115-TR-001 Rev.: 0 Sheet:

By: Thomas ServicePhD Date: 1/24/00 Chk: V. Christie Date: 1/24/00

The following laboratory test equipment control was used in preparation of the report.

M&TE Equipment	I.D. Number	Calibration Date	Calibration Due Date	Operator Name	Test Procedure
Optical Microscope	SMZ-U	6/9/99	6/30/2000	Van Christie	Imaging Purposes Only*
Cambridge Stereoscope 240 SFM	8009-11-08	N/A	N/A	Van Christie	Imaging Purposes Only*

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Att./Appx. C Sh 1/1

* All magnifications are approximate and are for informational purposes only.