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SUBJECT: Supplements 800415 interim deficiency rept re biological shield wall.Forwards agenda & presentation from 800610 meeting & discussion re frame mechanics evaluation.Sample fracture mechanic calculations encl.

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NIAGARA MOHAWK POWER CORPORATION/300 ERIE BOULEVARD WEST, SYRACUSE, N.Y. 13202/TELEPHONE (315) 474-1511

June 18, 1980

Office of Inspection and Enforcement
Region I
Attention: Mr. R. T. Carlson, Chief
Reactor Construction and Engineering
Support Branch
U. S. Nuclear Regulatory Commission
631 Park Avenue
King of Prussia, PA 19406

Dear Mr. Carlson:

Re: Nine Mile Point Unit 2
Docket No. 50-410

This letter supplements our April 15, 1980 10CFR 50.55(e) interim report on the Nine Mile Point Unit 2 biological shield wall. The attached agenda and presentation from the June 10, 1980 meeting with the staff of the Office of Nuclear Reactor Regulation regarding the Nine Mile Point Unit 2 biological shield wall deficiency are submitted for your information. This presentation is the same as the one made at your offices on May 7, 1980, except for the addition of the discussion regarding the fracture mechanics evaluation. The presentation made by our Architect/Engineer (Stone & Webster) regarding its Procurement Quality Assurance Program was also modified somewhat from the May 7, 1980 meeting.

Also enclosed are sample fracture mechanic calculations which show the methodology used in the analysis. A typical set of calculations will be available for review by your staff at our Architect/Engineer offices after July, 14 1980.

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It is Niagara Mohawk's understanding that the review and approval of our method of closure of this item is the responsibility of the Nuclear Regulatory Commission's Office of Inspection and Enforcement. The biological shield wall deficiency does not involve a deviation to the Preliminary Safety Analysis Report for Unit 2.

Very truly yours,

NIAGARA MOHAWK POWER CORPORATION

Gerald K. Rhode
Vice President
System Project Management

PEF:jk
Attachments
xc: Director of Inspection and Enforcement
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Director
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

AGENDA

Nine Mile Point Unit 2
Biological Shield Wall Meeting, June 10, 1980
NRC
Bethesda, Md.

Stone & Webster Attendees	NMPC Attendees
L. B. Hirst	S. F. Manno
C. E. Crocker	C. D. Terry
D. A. Boe	K. Ward
S. A. Ali	P. Francisco
I. Sprung	
R. G. Burns	R. Patch
R. H. Pinney	E. Feng
C. F. Reeves	
W. Diehl	
V. Zilberstein	

I. Introduction

A. Purpose of Meeting - NMPC/C. D. Terry
B. Statement of Problem - NMPC/C. D. Terry
C. Overview of Presentation - NMPC/C. D. Terry

II Biological Shield Wall Description

A. Functional Requirements and Physical Description - S&W/S. Ali
B. Design Criteria - S&W/S. Ali
C. Analytical Techniques - S&W/S. Ali
D. Method of Fabrication - S&W/S. Ali
E. Spec. Requirements - S&W/S. Ali
F. QA Program - S&W/R. Burns

III History of Events - NMPC/K. Ward

IV Metallurgical Discussion - S&W/D. Boe

V Closure Plan - S&W/C. E. Crocker

VI Engineering Evaluation

A. Stress - S&W/C. E. Crocker
B. Fracture Mechanics - S&W/I. Sprung
C. Summary of Evaluation Details - S&W/C. E. Crocker

VII Summary - NMPC/C. D. Terry

II BIOLOGICAL SHIELD WALL DESCRIPTION

A. Functional Requirements and Physical Description

The biological shield wall is a composite steel and plain high density concrete, cylindrical shell placed around the reactor pressure vessel.(Fig.1) The shield wall's main function is to provide radiation shielding and accommodate pipe restraint loads. It also provides anchorage support for floor beams, pipe supports and insulation and provides support for the star truss/stabilizer system.

General features of the biological shield wall are as follows:

a. The shield wall is approximately 20 inches thick, 28 foot - 2 inch I.D. and 48 foot - 4 inch in height. (Fig. 2)

b. The inside and outside steel shells are constructed of 1½ inch plates stiffened by horizontal and vertical ribs, also 1½ inch plate A537 Class 1 (Gr. 50) steel is used for steel shells and stiffeners.

c. The 1 foot 5½ inch plain concrete fill in between the two shells is "nonstructural" and is provided only to satisfy the shielding requirements.

d. The shield wall is anchored to the concrete reactor support pedestal at the base, and the top of the shield wall is supported from the containment wall by the star truss assembly. The support at the base allows for radial growth while restraining rotation and tangential movement.

e. Major pipe penetrations are sealed by steel doors which are designed to:

   1. Provide the required radiation shielding.

   2. Resist transient pressure loadings within the shield annulus.

B. Design Criteria

The BSW is designed in accordance with the AISC code for the normal operating load conditions. For the abnormal/extreme environmental load combinations, the allowable stresses are increased in accordance with the factors specified in the NMP2 PSAR.

The following major loads have been considered in the analysis and design of the BSW:

- Deadload and seismic loads

- Accident temperature cases consisting of the maximum temperature differentials between the inner and outer walls occurring as the result of a loss-of-coolant accident (LOCA).

- Accident pressure differential between the inner and outer walls occurring as the result of a LOCA.

- Pipe restraint loads occurring as the result of restraining pipes following a rupture.

- Jet impingement loads resulting when pressurized fluid from a ruptured pipe strikes the BSW.

C. Analytical Techniques

The structural analysis of the biological shield wall is performed by the finite element method using the computer program STRUDL. The shield wall is modeled using a 180° model with the appropriate boundary conditions for the symmetric and anti-symmetric loads. Analysis for general loading conditions are conducted using principles of superposition.

The inner and outer walls as well as the horizontal and vertical stiffeners are modeled using isoparametric elements. The stresses in the biological shield wall under normal operating conditions are very low. The conditions which control the design of the biological shield wall and under which the stresses approach the allowables are the accident conditions, such as accident temperature and pipe rupture loads. The stresses from this analysis are used in the engineering analysis to be discussed later.

D. Method of Fabrication

The biological shield wall is divided into three rings as shown in Fig. 4. The three rings are further subdivided into three 120° segments, a total of nine segments. These nine segments were fabricated in the shop and then shipped to the NMP2 site. These 120° segments were welded together along vertical seams to form the three complete rings at the site. The three rings will in turn be welded together along the horizontal seams to form the complete biological shield wall.

E. General Specification Requirements

- All work was performed under seller's QA program

- Welding was done in accordance with AWS D1.1

- The following options were provided to perform NDE of all full penetration welds:

  1. Radiographics or ultrasonic inspection with MT of root pass

  2. Progressive magnetic particle at 1/3, 2/3 and 3/3 weld joint thickness

The seller chose to employ UT along with MT of the root-pass

- AISC code of standard practice was invoked for workmanship requirements.

REACTOR BUILDING CONFIGURATION

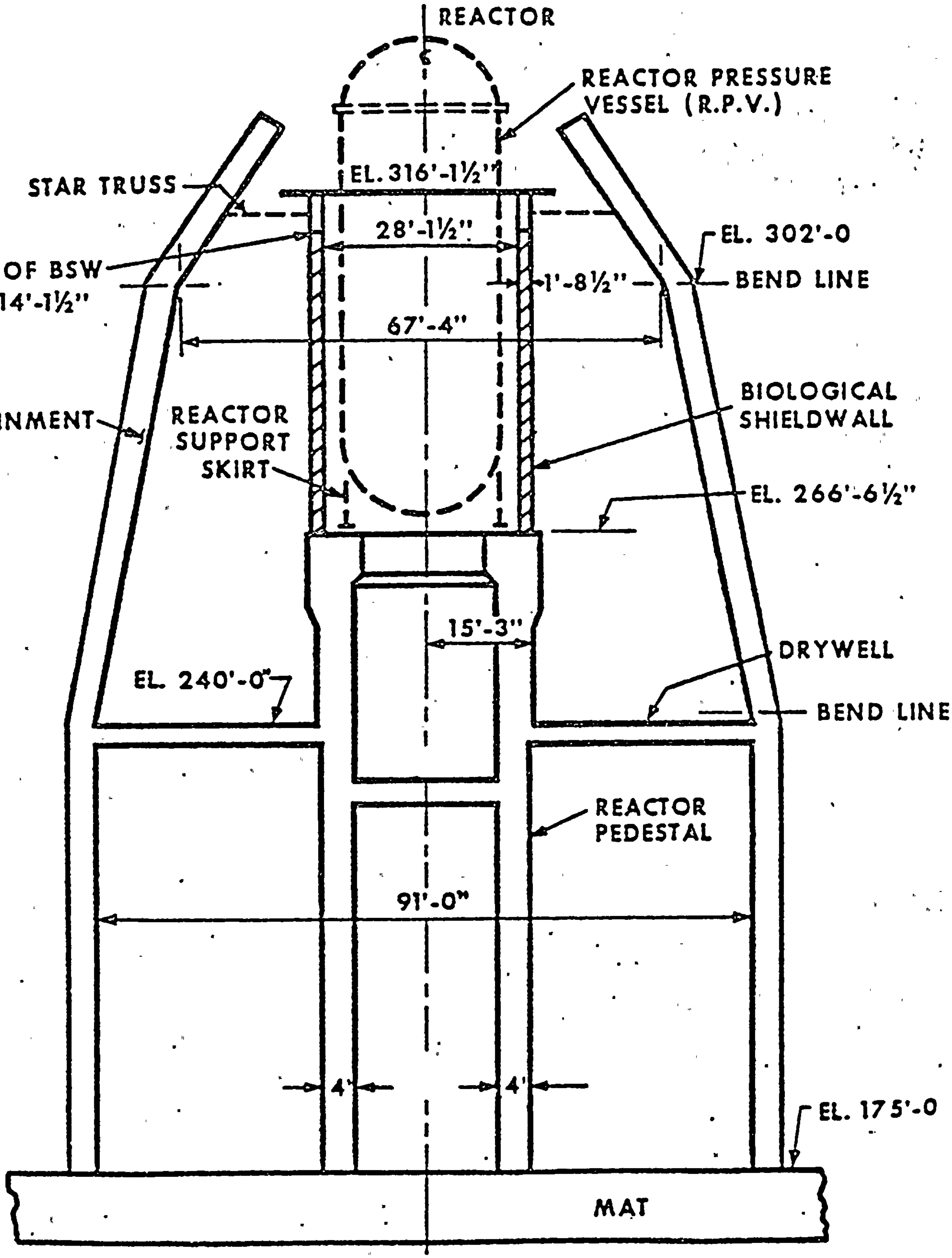


FIGURE 1

PLAN

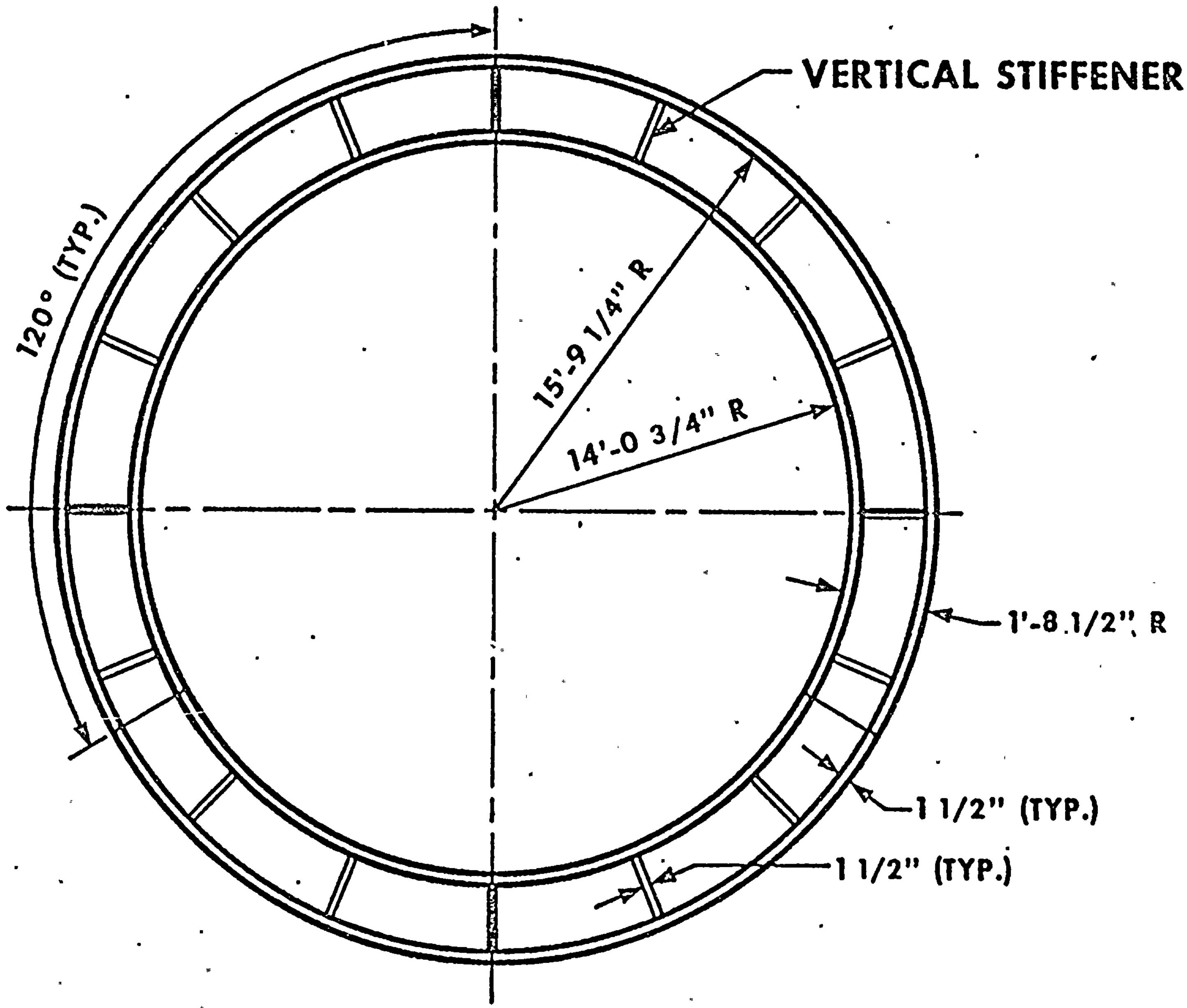


FIGURE 2

BASE DETAIL

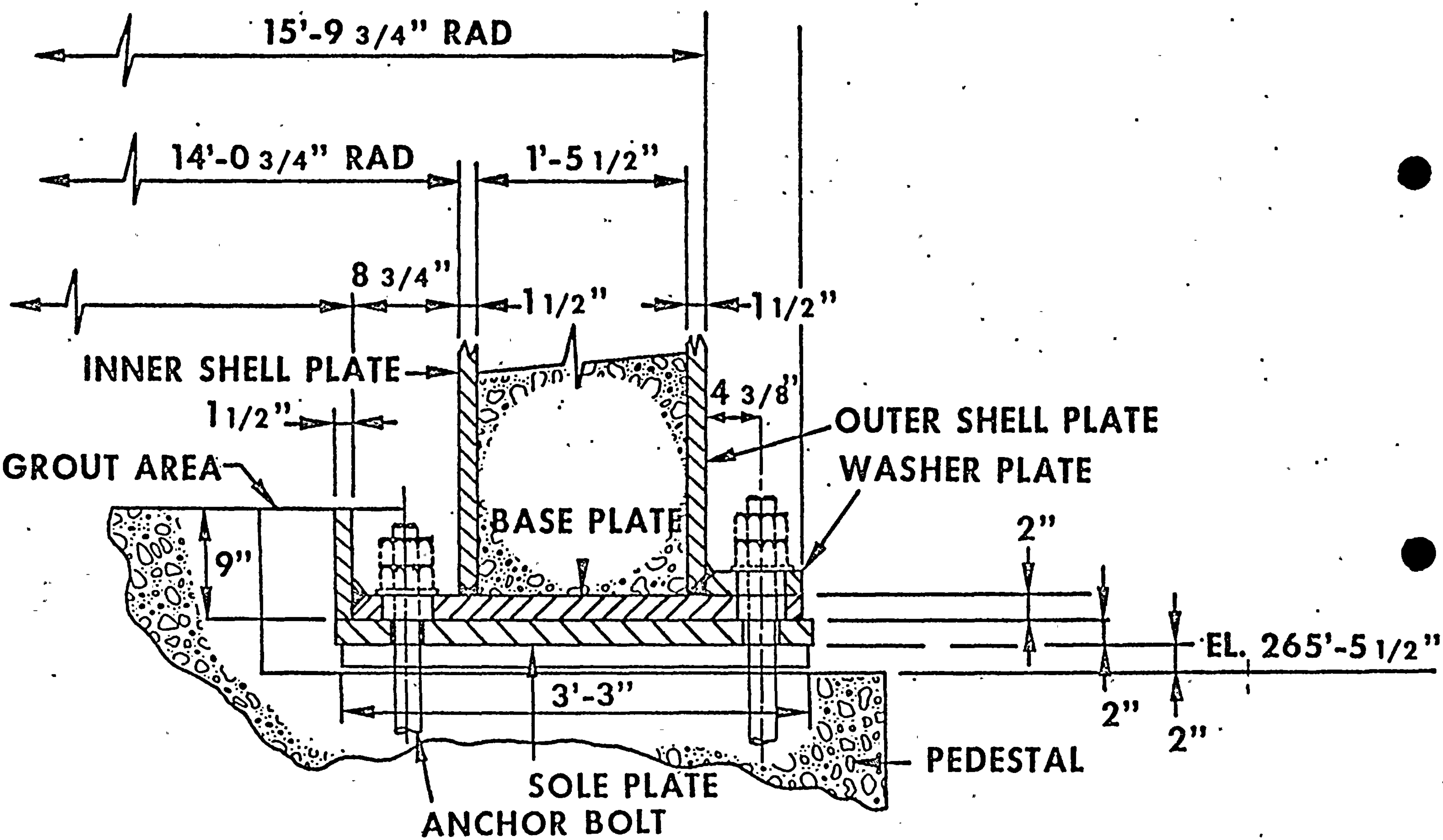


FIGURE 3

ELEVATION

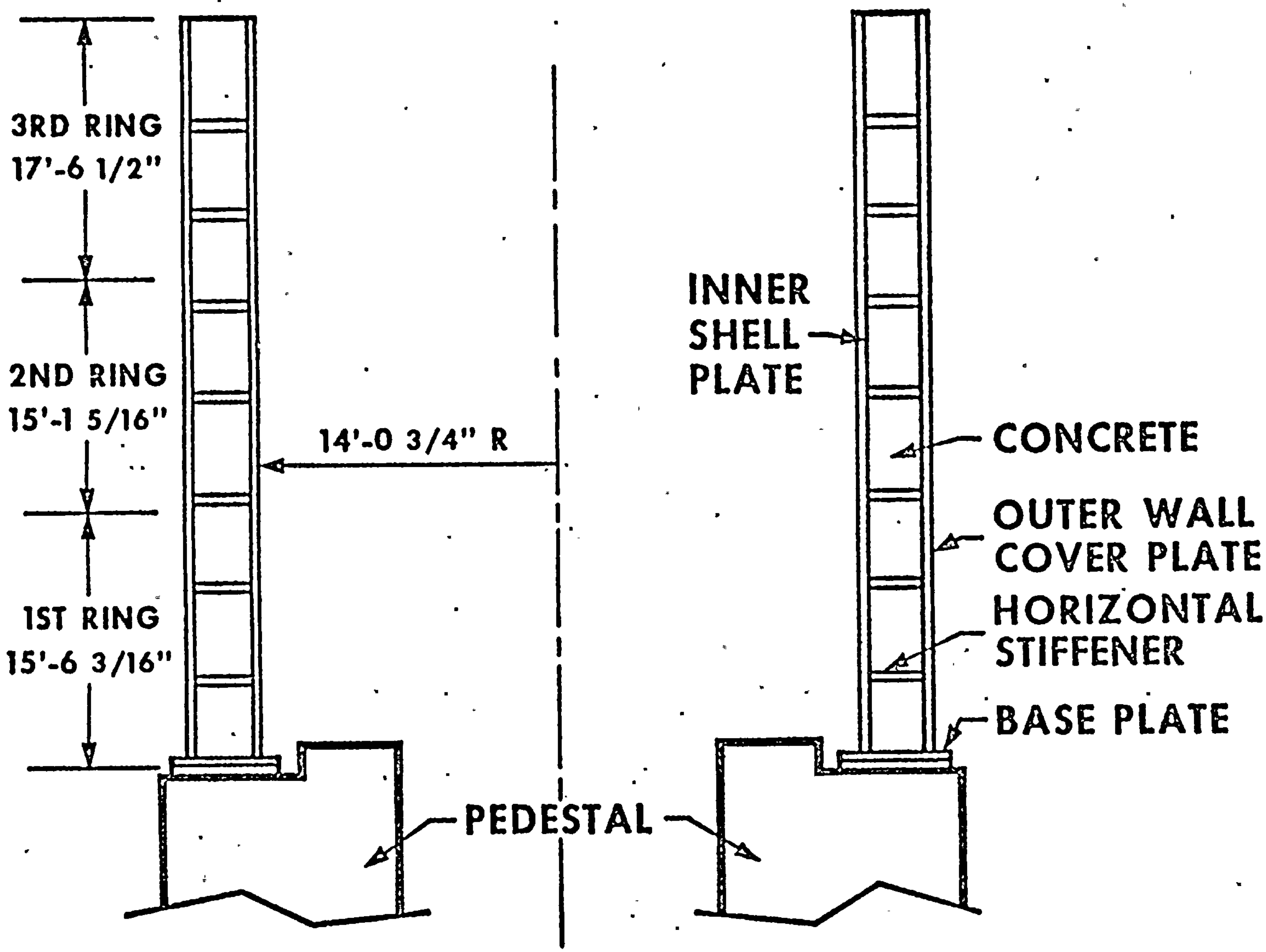


FIGURE 4

F. QA Program

The QA Program imposed by the specification requirements resulted in certain actions by both S&W and Cives (the Contractor).

Specification No. NMP2-S204G was reviewed and approved by S&W's QA Department (Quality Systems Division) to ensure the inclusion of appropriate QA/QC requirements.

The specification and associated shop test, inspection, and documentation (TID) report required, in summary, the following:

Cives

1. Compliance to Appendix B, 10CFR50
2. Submittal of QA program
3. Transmission of QA requirements to identified subcontractors
4. Conformance of NDT to AWS D1.1
5. Welding and NDT procedures submittal.

S&W

1. Qualify Cives as Seller by survey and audit
2. Perform inspection (over a 26-month period) covering 44 specific TID attributes
3. Of the 44 attributes, 11 specifically address weld quality (see attributes applied).

Attributes Applied

The following weld-related attributes were applied:

Welding Procedure
Electrode Control Procedure
Qualification of Welders
Weld Preparation
Weld Inspection
Random Check of Fabrication Completeness
Inspection of Surface Defects
NDT Test Oper Certifications
Procedure for NDT Inspection
NDT Inspection of Welds
Reports of NDT Tests

The above comprised a normal QA/PQA effort on this type of structure and we believe is consistent with a properly implemented activity.

QA/QC ACTIONS

NINE MILE 2 BIOLOGICAL SHIELD WALL

IV.F. Q.A. PROGRAM

S&W PREVENTIVE MEASURES

- REVIEW & APPROVAL OF SPECIFICATIONS BY QA
- REVIEW & APPROVAL OF CIVES NDT PROCEDURES
- VERIFICATION OF SPECIAL PROCESS PROCEDURE APPROVAL
- FABRICATOR SURVEY & QUALIFICATION

CIVES PREVENTIVE MEASURES

- COMPLIANCE TO 10CFR50, APPENDIX B
- PASS ALONG OF QA REQUIREMENTS TO SUBS
- NDT TO AWS D1.1
- NDT OPERATORS TO MEET ASNT-TC-1A

S&W INSPECTION MEASURES

- TEST, INSPECTION, DOCUMENTATION - 44 ATTRIBUTES
- 11 - ATTRIBUTES ADDRESS WELDING
- 3 - INSPECTORS, 26 - MONTHS, 1,300 - MAN-HOURS

CONCLUSION

- NORMAL MEASURES EMPLOYED
- PROBLEMS IDENTIFIED WERE RESPONDED TO
- PROGRAM MEASURES ADEQUATE

III. HISTORY OF EVENTS

- INITIAL PROBLEM WAS FIRST DISCOVERED AT TOE OF THE OUTER COVER PLATE TO BASE PLATE WELD DURING FIELD INSPECTION.

- SAMPLE OF WELD WAS SELECTED FOR UT TO VERIFY WELD WAS FREE OF DEFECTS.

- WHILE NO SIMILAR DEFECTS WERE DETECTED IN TOE AREA, INDICATIONS WERE FOUND IN THE ROOT AREA OF THE WELD WHICH PROMPTED 100% INSPECTION. AT THIS TIME THIS PROBLEM WAS REPORTED TO THE NRC AS A POTENTIAL 10CFR50.55(e).

- A SPECIAL TEST BLOCK WAS DEVELOPED SUCH THAT ANY REFLECTORS FROM THE BACKING BAR COULD BE PROPERLY IDENTIFIED.

- APPROXIMATELY 20% OF THE LENGTH OF THE WELD REQUIRED REPAIR.

- METALLURGICAL SAMPLE WAS REMOVED FROM OUTER COVER PLATE TO BASE PLATE WELD FOR ANALYSIS.

BASE DETAIL

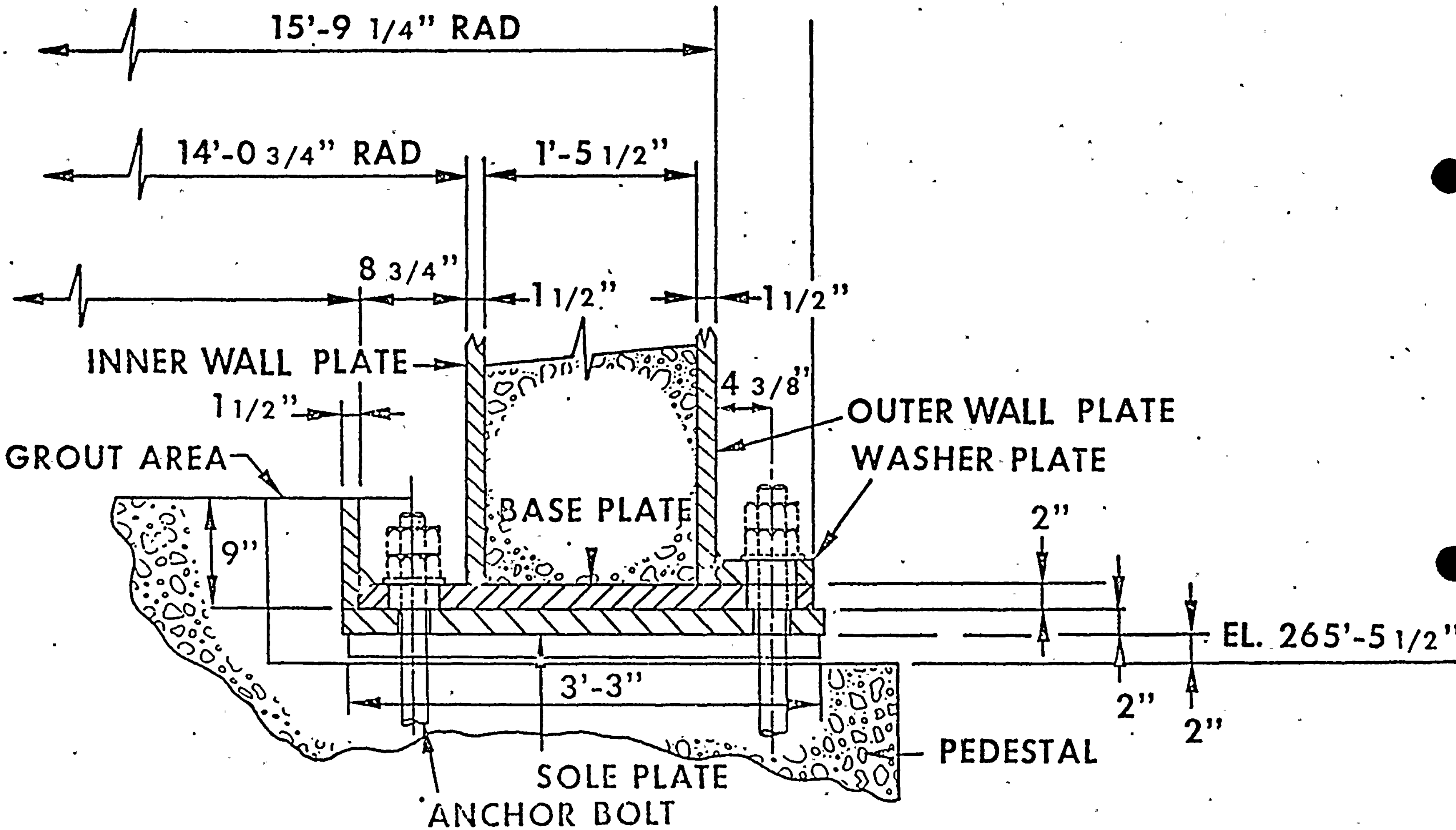


FIGURE 2

COVER PLATE TO BASE PLATE WELD

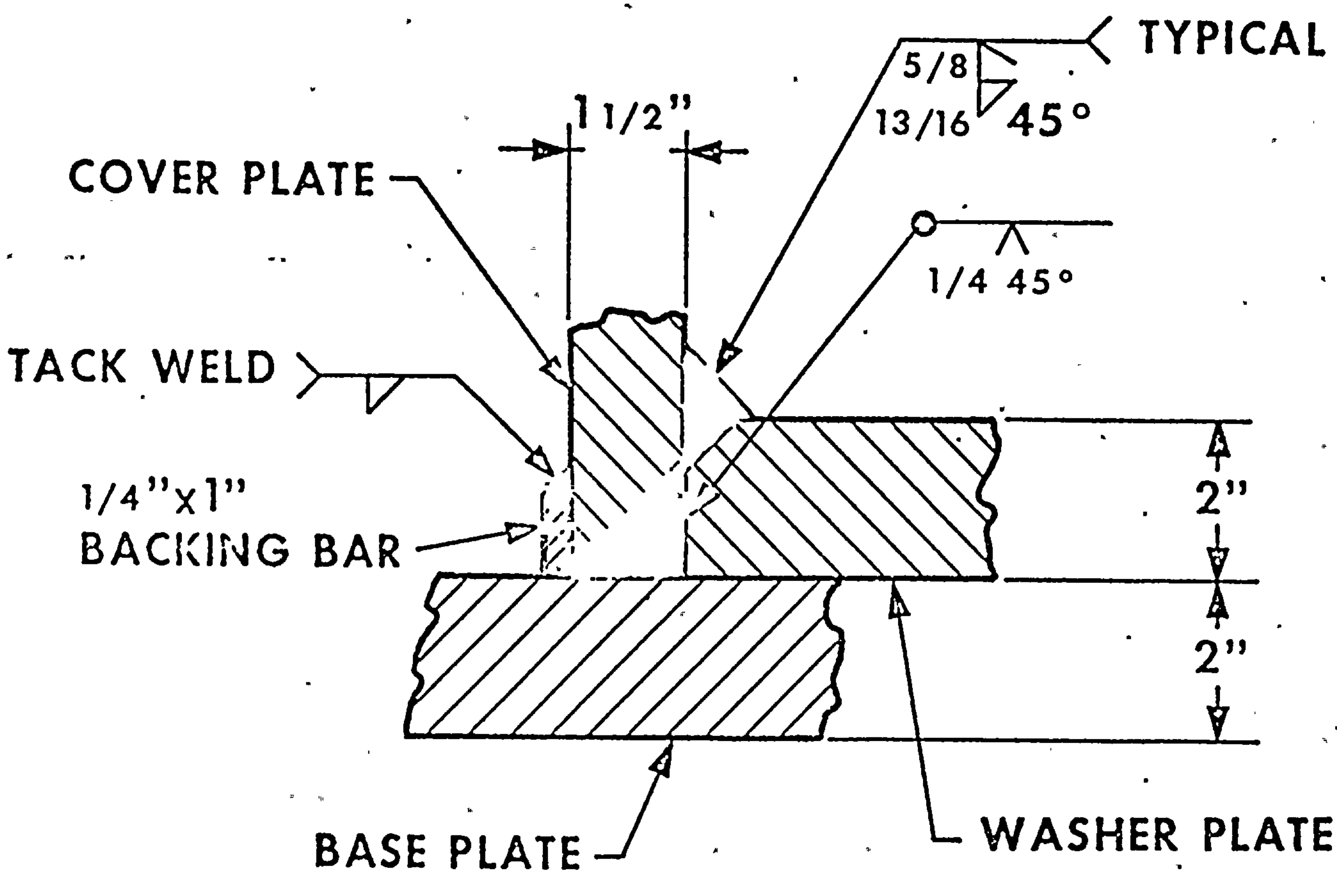


FIGURE 5

- VISUAL LINEAR INDICATIONS WERE FOUND IN HORIZONTAL STIFFENER TO INNER WALL WELDS DURING ONSITE INSPECTION OF THIRD RING SEGMENTS.

- INVESTIGATION CONDUCTED OF ROOT AREA BY MAGNETIC PARTICLE TESTING AND GRINDING ON ALL THREE RINGS.

- MT EXAMINATION YIELDED REJECT RATE OF APPROXIMATELY 22% ON RING 3 SEGMENTS. RINGS 1 AND 2 WERE ACCEPTABLE.

- HIGH RATE OF REJECTION OF THESE WELDS LEAD TO DECISION TO CONDUCT AN INVESTIGATION OF ALL WELD CONFIGURATIONS.

HORIZONTAL STIFFENER TO INSIDE AND OUTSIDE WALL PLATES

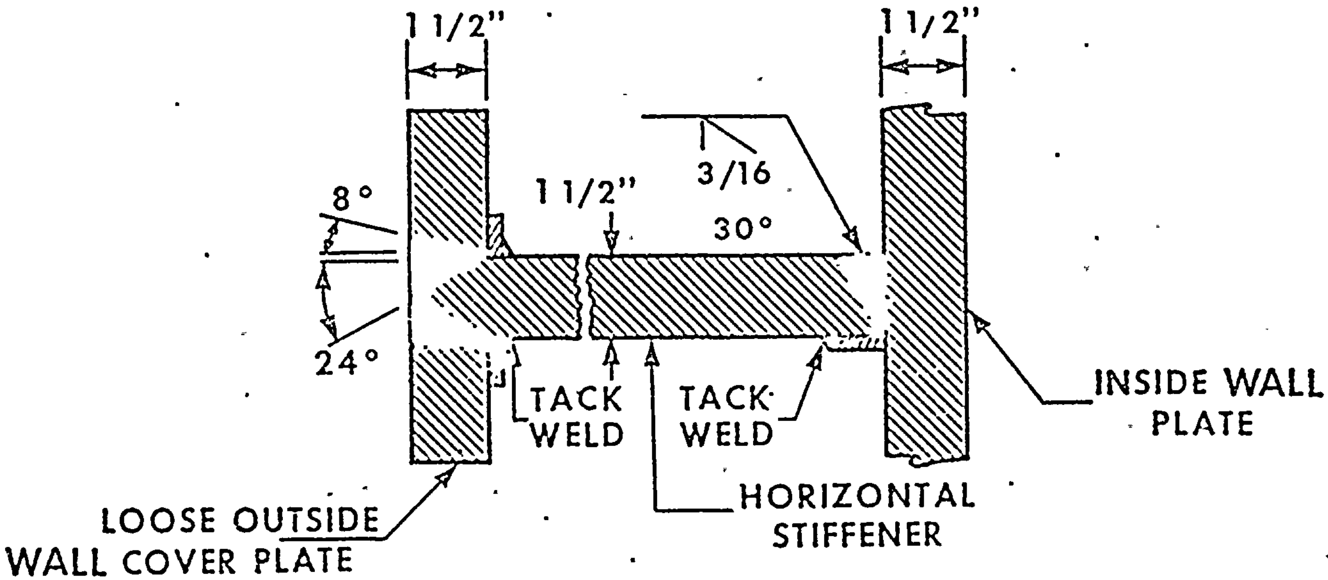


FIGURE 8

- SINCE MAJORITY OF WELDS WERE INACCESSIBLE TO A NORMAL AWS D1.1 UT INSPECTION, A SAMPLING PLAN WAS EMPLOYED TO ASSESS WELD QUALITY.

- ADDITIONALLY FOUR SAMPLES WERE TAKEN OF HORIZONTAL STIFFENER TO INNER WALL WELDS FROM RING 3.

- RESULTS OF SAMPLE PLAN DID NOT PROVIDE DESIRED CONFIDENCE LEVEL FOR QUALITY OF WELDS.

— DECISION TO ULTRASONICALLY EXAMINE ALL ACCESSIBLE SHOP WELDS 100% -

A. SPECIAL TECHNIQUE WAS DEVELOPED FOR ULTRASONIC EXAMINATION OF WELDS.

B. TECHNIQUES REVIEWED BY INDEPENDENT CONSULTANT AND ARE CONFIDENT OF ITS ACCEPTABILITY.

C. INNER WALL STATUS

D. COVER PLATE STATUS

E. STIFFENER TO STIFFENER STATUS

General Weld Quality

The welds that we have been discussing were made in the shop using the fluxed core process with gas shielding, or SMAW process. All welds examined metallurgically exhibited overall high quality. No cracking has been found in weld metal; all cracking has occurred in the HAZ, or else outside the HAZ in the base metal.

V CLOSURE PLAN

The resolution of the shield wall weld defects is outlined as follows:

1. A 100% UT inspection is being performed for accessible shop welds (.90% of all shop welds are accessible for UT). A standard AWS D1.1 UT is performed where access permits. Otherwise, a special UT in accordance with AWS D1.1 is performed.

2. Based on UT data, an engineering evaluation is performed to determine repairs required. The evaluation employs stress analysis and fracture mechanics to demonstrate acceptability of inconsequential defects. All PSAR commitments regarding loads, allowable stresses, and other technical requirements will be maintained. The UT and evaluation is in accordance with AWS D1.1 , Section 3.7.6.

3. As discussed, a metallurgical evaluation was performed on five specimens removed from the shield wall. Results of the evaluation are factored into our overall approach.

This program of UT, engineering evaluation, and metallurgical examination, all in accordance with AWS D1.1 and our PSAR commitments will ensure that the biological shield wall will be more than adequate to perform its intended design function.

The overall erection sequence to implement the approach outlined above is as follows:

1. Repair as required based on engineering evaluation

2. Attach cover plates

3. Fit-up and weld the three rings together

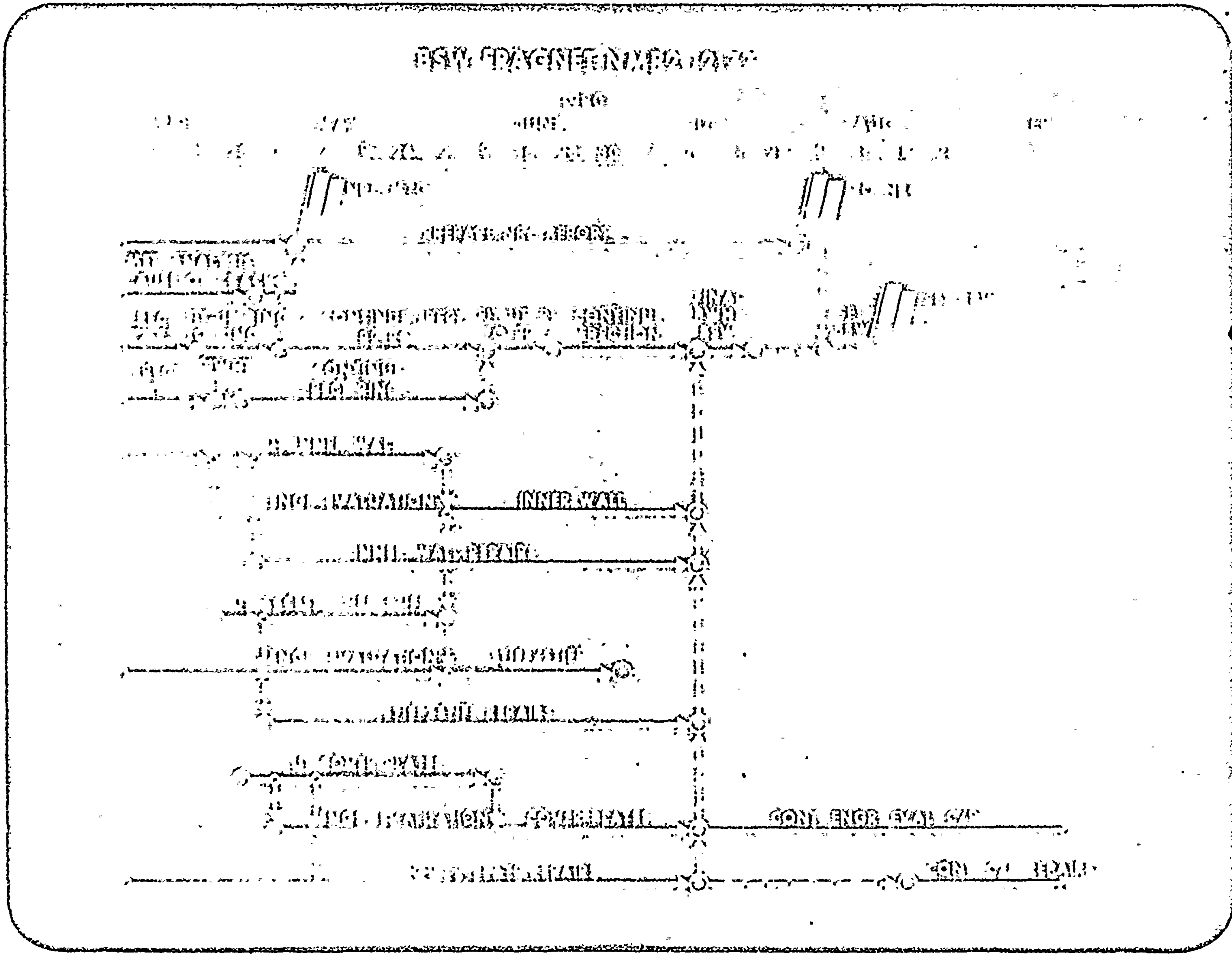
4. Perform final PWHT

5. Set BSW on pedestal without concrete

6. Complete remaining repairs, if any

7. Attach remaining cover plates and fill with concrete.

(Refer to Fragnet, Fig. 5)


INNER WALL

VI. ENGINEERING EVALUATION

A. Stress Analysis

Based on UT data, weld defect sizes, locations, and orientations are obtained for evaluation. Stresses in the vicinity of the defects are evaluated as a result of reduced weld area due to the defects. As mentioned, all PSAR commitments regarding allowable stresses are being maintained. Once it is shown that the stresses are at an acceptable level, the stress and defect information are evaluated for fracture mechanics considerations.

B. Fracture Mechanics Evaluation

In the industry today, a conservative fracture mechanics analysis is now a regular means of assuring the integrity of welded structures which realistically contain some discontinuities in the material, such as slag, porosity, lack of fusion, etc.

Such an analysis provides a sound basis for establishing acceptability criteria for the discontinuities and thus can eliminate unnecessary repairs.

Most structural steels when loaded under normal design conditions are ductile and the methods of linear elastic fracture mechanics (LEFM) are not applicable. Therefore, yielding fracture mechanics is used to calculate critical conditions (critical crack size and critical stress). In this analysis we use both LEFM and a technique by Dowling and Townley (Ref. 1). This method, known as Two-Criteria Approach, has been used by others (Ref. 2-7), and covers the spectrum of conditions from brittle fracture (where LEFM is applicable) to completely plastic failure (where some form of limit analysis has to be used). The structure is built of 537 Class 1 steel, which has excellent fracture toughness in the longitudinal direction. In cases where it is required, the directional properties such as in the through-thickness direction are considered.

For the purpose of this analysis, the variety of discontinuities which might be encountered in a welded structure can be reduced to two major types, namely surface and subsurface defects. The term "defect" is used here only for convenience and does not mean that a discontinuity under consideration is not acceptable.

It is assumed throughout the analysis that the applied stress is a tensile stress perpendicular to the defect, the applied loads are dynamic and there is no cyclic loading which could initiate fatigue cracking. In this analysis, surface and subsurface defects are defined as in ASME XI, Div. 1 (see Fig. 1).

In the case of a surface defect at the root of a weld, the stress intensity factor is given in Fig. 2.

The fracture criterion is given in Fig. 3. To be conservative, the dynamic fracture toughness K_{Id}, is used in this analysis. K_{Id} can be found from one of the known correlations between K_{Id} and the Charpy impact energy, C_V.

Also, we can plot the applied stress versus critical defect size and compare a reported defect size with the one on the plot (see Fig. 4).

For subsurface cracks the stress intensity factor is defined as in Fig. 5.

The above approach is essentially a LEFM method with some modifications. When this method is applied to non-brittle materials, it may give unrealistic results.

As mentioned before, the two-criteria method avoids this problem. The fracture (or critical) stress is calculated from the expression given in Fig. 6.

In conclusion, we would like to emphasize once again the fact that the fracture mechanics analysis is very conservative. We use conservative assumptions for the defect size and stresses plus we assume that all the defects are sharp, which for most of them is not the case. Thus, we believe the analysis provides additional assurance for the safety of the BSW structure.

C. Summary of Evaluation Details

For the evaluation, the welds are grouped into three configurations: inner wall to stiffener, cover plate to stiffener, and stiffener to stiffener. From a structural point of view, the most important welds are the inner wall to stiffener and the cover plate to stiffener welds. Details for each configuration are as follows:

1. Inner Wall to Stiffener

   A special UT in accordance with AWS D1.1 is performed for the entire inner wall. Defect sizes and locations are mapped, stresses are evaluated, and a fracture mechanics evaluation is performed. Based on the evaluation accept/repair decisions are made.

   See Table 1

2. Cover Plate to Stiffener

   A standard AWS D1.1 UT is performed for all cover plates. UT examination cannot reasonably provide conclusive information required to perform an engineering evaluation for defects located in the top 1" of the weld near the nose of the stiffener. Therefore, defects located in this area are repaired to a depth of 1". For defects located in other areas, a special UT in accordance with AWS D1.1 is performed, defect sizes and locations are mapped, stresses are evaluated, and a fracture mechanics evaluation is performed. Accept/repair decisions are made based on the evaluation.

   See Table 2

3. Stiffener to Stiffener

All accessible stiffener to stiffener welds are examined using standard AWS D1.1 where possible and a special UT in accordance with AWS D1.1 otherwise. Over 40% of all stiffener to stiffener welds are accessible for UT). Data from the stiffener to stiffener examination and inner wall to stiffener examination are used to predict the incidence of defect occurrence and effective loss of weld area. A special analysis is performed for each inaccessible stiffener, postulating that large amounts of weld area are removed for analysis purposes. With conservative assumptions is will be shown that adequate structural integrity exists. It is expected that all cases will be acceptable. However, in the case that structural integrity can not be demonstrated, the design will be revised to compensate.

See Table 3.

TABLE 1

Inner Wall to Stiffener UT Status - 6/5/80

Ring	% Compl.	No. of Indications	Total Length Indications (in)	% Indications (by length)
1	94	4	11 3/4	.1
2	97	2	30 1/8	.3
3	95	17	301 3/4	2.8

TABLE 2

Cover Plate to Stiffener UT Status - 6/5/80

Note: Status covers initial standard AWS D1.1 UT only

Ring	% Compl.	Length Rej. (in)	% Length Rej.
1	100	3,322	17
2	100	3,838	22
3	61	824	12

TABLE 3

Stiffener to Stiffener UT Status - 6/5/80

	Standard AWS D1.1			Special UT	
Ring	% Compl.	Length Rej. (in)	% Length Rej.	% Compl.	No. of Indications
1	0	--	--	0	--
2	0	--	--	5	0
3	73	54 3/8	2.5	28	0

REFERENCES

1. A. R. Dowling and C. H. A. Townley, "The Effect of Defects on Structural Failure: A Two-Criteria Approach", The International Journal of Pressure Vessels and Piping, 3, 2, 77-107, 1975.

2. G. G. Chell, "A Combined Linear Elastic and Post-Yield Fracture Mechanics Theory and Its Engineering Applications," Fracture Mechanics in Engineering Practice - Editor P. Stanley. Applied Science, London.

3. R. P. Harrison, "A Unified Approach to Failure Assessment of Engineering Structures," Same as 2.

4. A. Muscati and C. E. Turner, "Post-Yield Fracture Behavior of Shallow-Notched Alloy Steel Bars in Three Point Bending," Same as 2.

5. C.H.A. Townley, "The Integrity of Cracked Structures Under Thermal Loading," Same as 2.

6. R. L. Roche, "Analysis of Structures Containing Cracks - Some Comments on the J_1 Integral Criterion," The International Journal of Pressure Vessels and Piping, 7, 1979, P. 65.

7. J. M. Bloom, "Prediction of Ductile Tearing of Compact Fracture Specimens Using the R-6 Failure Assessment Diagram," The International Journal of Pressure Vessels and Piping, 8 (1980) 215-231.

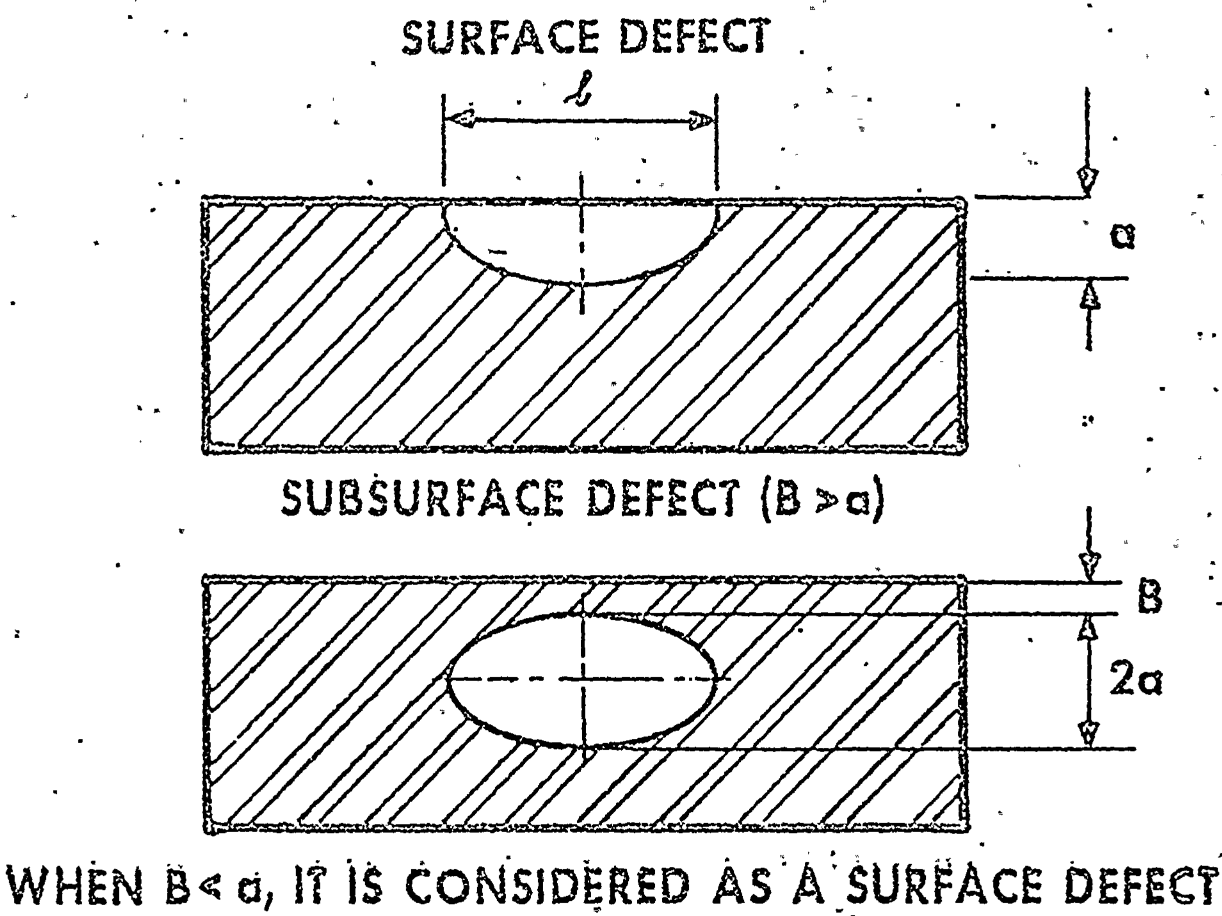

SURFACE DEFECT
ℓ
a
SUBSURFACE DEFECT (B > a)
B
2a
WHEN B < a, IT IS CONSIDERED AS A SURFACE DEFECT

FIGURE 1

SURFACE DEFECTS

$$K_I = F_S F_E F_W F_G F\left(a/a_N\right) S\sqrt{\pi a}$$

WHERE

a IS THE DEFECT SIZE

S IS THE STRESS

F_S = 1.12 IS THE SURFACE-ENERGY FACTOR

F_E IS THE SHAPE FACTOR

$F\left(a/a_N\right)$ AND F_G ARE THE GEOMETRY FACTORS

$$F_W = f\left(\frac{a}{t}\right)$$

FIGURE 2

FRACTURE CRITERION

$$K_I \geq K_{Id} \ (\text{or } K_{IC})$$

WHERE

K_{Id} (K_{IC}) IS THE FRACTURE TOUGHNESS

FIGURE 3

APPLIED STRESS VS. DEFECT SIZE FOR A GIVEN K_{Id}

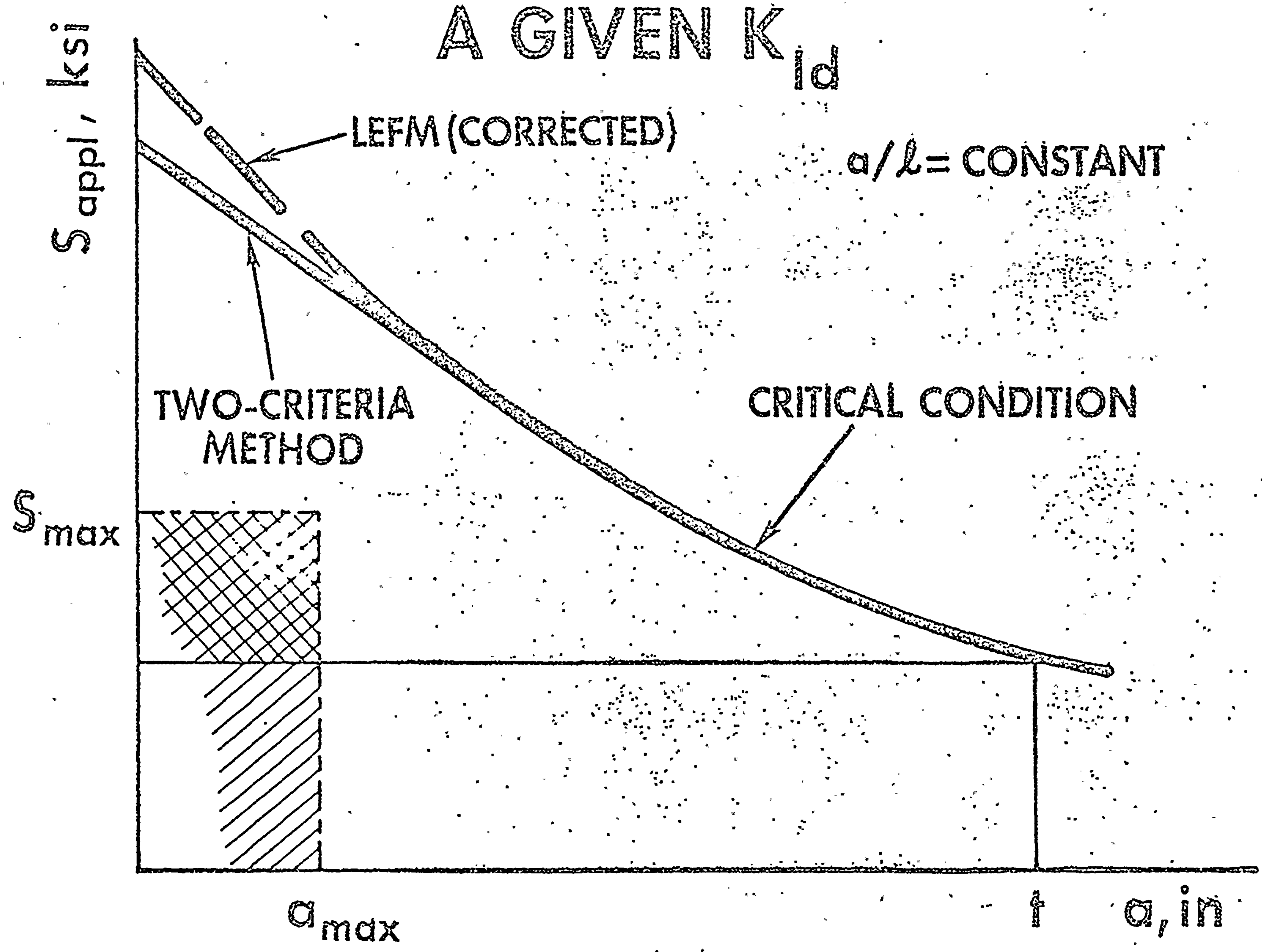


FIGURE 4

SUBSURFACE DEFECTS

$$K_I = M_m F_E S\sqrt{\pi a}$$

WHERE

$$M_m = F_S F_W$$

$$F_G F\left(a/a_N\right) = 1$$

FIGURE 5

TWO-CRITERIA METHOD

$$S_f = S_U \frac{2}{\pi} \cos^{-1}\left[\exp - \frac{\pi^2}{8} \cdot \left(\frac{S_K - S_{res}}{S_U^2}\right)^2\right]$$

WHERE

S_f = FRACTURE STRESS

S_U = ULTIMATE STRESS

S_K = STRESS CALCULATED FROM EQUATIONS SIMILAR TO THE LEFM RELATIONS

FIGURE 6

FRACTURE MECHANICS - SAMPLE CALCULATIONS

To illustrate the approach outlined in the report, two typical examples are given below. The first example evaluates the effect of the exclusion of one-eighth inch from the stiffener plate thickness. The second example is an evaluation of an indication discovered in the inner wall of the Ring 1.

A.1 Surface Defect at the Root of a Weld

The exclusion of one-eighth inch from the stiffener plate thickness in the stress analysis which essentially postulates the existence of an infinitely long one-eighth inch surface defect at the root of a backing bar weld required that a fracture mechanics evaluation of such a defect be performed. The location of the defect is shown in Figure A1.

A.1.1 LEFM Approach

The stress intensity factor for this case is given in Section VI, Figure 2 of the Fracture Mechanics presentation. The parameters in the equations are given below:

a. The surface-energy factor F_S = const = 1.12;

b. The shape factor

$$F_E = \frac{1}{\sqrt{Q}}$$

is defined in ASME XI. This factor can be represented as

$$F_E = \frac{1}{\sqrt{1 + 4.593(\frac{a}{l})^{1.65} - .212(\frac{S}{S_{ys}})^2}}$$

where l is defect length and S_{ys} is the yield strength of the material (S_{ys} = 50 ksi).

c. Factor $F(a/a_n)$ describes the stress distribution in the backing bar:

$$F(\frac{a}{a_N}) = \frac{2}{\pi} [\frac{a}{a_N} - \sqrt{(\frac{a}{a_N})^2 - 1} + \frac{\pi}{2} - \sin^{-1} \frac{a_N}{a}],$$

where a and a are shown in Figure A1.

d. Factor F_G accounts for the stress field gradient caused by changes in geometry of the stressed structure. In this case the factor applies to defects emanating from the root and the toe of T-welds. Analyses of such joints were performed in References A1 and A2. The most conservative of the values from these papers was used in this calculation. In this example, F_G = 1.328.

e. Factor F_W is the correction for finite thickness, t, of a plate:

$$F_W = \sqrt{\frac{2t}{\pi a} \tan \frac{\pi a}{2t}}$$

f. As shown in Figure A1, the defect size

$$a = \Delta a + a_N,$$

where Δa is the actual defect size and a_N is the stressed portion of the backing bar. For this particular case a_N = .09". Thus, in this example

$$a = .125 + .09 = .215".$$

g. The stress

$$S = S_{applied} + S_{res}$$

where $S_{applied}$ is the applied stress and S_{res} is the residual stress in the structure after postweld heat treatment (PWHT). The maximum design stress is used in this calculation as the applied stress so that $S_{applied}$ = 25 ksi. The residual stress after PWHT at 1100 F is assumed to be 10% of the yield strength, that is

$$S_{res} = .1S_{ys} = .1 \times 50 = 5 \text{ ksi}.$$

Finally, note that the defect is assumed to be infinitely long so that a/l = 0.

Thus

$$K_I = 1.12\, F_G F(\frac{a}{a_N})\, S\sqrt{\pi a} \sqrt{\frac{\frac{2t}{\pi a}\tan\frac{\pi a}{2t}}{1 + 4.593(\frac{a}{l})^{1.65} - .212(\frac{S}{S_{ys}})^2}} =$$

$$= 1.12 \times 1.328 \times .86 \times 30\sqrt{.215\pi}\sqrt{\frac{\frac{2 \times 1.5}{.215\pi}\tan\frac{.215\pi}{2 \times 1.5}}{1 + 4.593(0)^{1.65} - .212(\frac{25}{50})^2}} =$$

$$= 33.3 \text{ ksi } \sqrt{\text{in.}}$$

The fracture toughness of the material is calculated from the Sailors-Corten relation (Reference A3):

$$K_{Id} = 15.873\,(Cv)^{.375}$$

where Cv is the Charpy V-notch impact energy.

Although the postulated defect is apparently located in the HAZ where toughness in the through-thickness direction, according to Stone and Webster experimental data, is better than in the base metal, the base metal toughness is used here for the sake of conservatism. Based on the experimental Charpy impact tests performed at 90F and available published data (Reference A4), the Charpy energy at 100 F is:

$$C_V \geq 20 \text{ ft. lb.}$$

Using the minimum value of C_v, the fracture toughness in the through-thickness direction is calculated:

$$K_{Id} = 15.873(20)^{.375} = 48.8 \text{ ksi } \sqrt{\text{in.}}$$

Thus, $K_I = 33.3 < K_{Id} = 48.8$

The critical defect size evaluated from the LEFM equation on Figure 2

$$\Delta a_{cr} = .47".$$

A.1.2 Two-Criteria Approach

The critical applied stress is given by the equation in Section VI, Figure 6 of the Fracture Mechanics presentation. The parameters in this equation are:

a. The ultimate stress

$$S_u = S_{flow}\ (1-a/t) = \frac{S_{ys} + S_{ts}}{2}\ (1-a/t)$$

b. The critical stress, S_k, is calculated from the following LEFM relation:

$$S_k = \frac{K_{Id}\sqrt{1 + 4.593(\frac{a}{l})^{1.65}}}{\sqrt{2t[1.12 \cdot F_G\ F(\frac{a}{a_N})]^2 \tan\frac{\pi a_{cr}}{2t}}}.$$

The above relation can be derived from equation shown in Section VI, Figure 2 of the Fracture Mechanics presentation, except for the plastic zone correction which is not included here.

The critical defect size evaluated from the equation in Section VI, Figure 6 of the Fracture Mechanics presentation is:

$$\Delta a_{cr} = .42"$$

Using the lower of the two calculated values of Δa_{cr},

$$\Delta a_{cr} = .42"$$

we find that the ratio

$$\frac{\Delta a_{cr}}{\Delta a} = \frac{.42}{.125} = 3.36.$$

Therefore, a one-eighth inch defect at the root of a weld subjected to 25 ksi stress is acceptable.

A.2 Subsurface Defect in the Inner Wall of the Bioshield Wall

Another example illustrates an actual case of a reported indication in the inner wall of Ring 1. The indication was interpreted as a subsurface defect parallel to the surface of the inner wall (see Figure A2).

A.2.1 LEFM Approach

The stress intensity factor for this case is given in Section VI, Figure 5 of the Fracture Mechanics presentation. The parameters in this equation are:

a. Factor M_m is the correction factor for membrane stress. It is given in Figure A-3300-2 of ASME XI, Division 1, as a function of plate thickness and defect location. For this case, i.e. defect parallel to the plate surface, $M_m = 1$.

b. Factor F_E is the same as in the first example (see A1.1).

c. The stress, once again, includes both applied and residual stresses. The applied stress in this example is 16 ksi, and the residual stress, as in A1.1, is 5 ksi. Thus,

$$S = S_{applied} + S_{res} = 16 + 5 = 21 \text{ ksi.}$$

d. The defect size, a, for a subsurface defect, equals half the reported defect size. In other words, 2a = 1/8 and a = 1/16 in. Note that for conservatism, if the defect size is reported as less than 1/8 in. as it is here, it is assumed that 2a = 1/8 in.

e. The defect length, according to the UT report, l = 3/4 in.

Hence, a/l = .083.

Thus,

$$K_I = \frac{21\sqrt{\pi/16}}{\sqrt{1 + 4.593(.083)^{1.65} - .212\left(\frac{21}{50}\right)^2}} = 9.13 \text{ ksi } \sqrt{\text{in.}}$$

Since the fracture toughness of the material in the through-thickness direction at the minimum temperature when the stress might develop is:

$$K_{Id} = 48.8 \text{ ksi } \sqrt{\text{in}}$$

(see A1.1). $K_I \ll K_{Id}$

The critical defect size evaluated from LEFM equation in Section VI, Figure 5 of the Fracture Mechanics presentation, assuming that the ratio a/l is constant,

$$a_{cr} = 1/8 \text{ in.}$$

and

$$2a_{cr} = 3\ 1/2 \text{ in.} > t = 1\ 1/2 \text{ in. (plate thickness).}$$

A.2.2 Two Criteria Approach

The critical applied stress is given by the equation in Section VI, Figure 6 of the Fracture Mechanics presentation. The parameters in this equation are:

a. The ultimate stress:

$$S_u = S_{flow}\left(1 - \frac{a}{t}\right) = \frac{S_{ys} + S_{Ts}}{2}\left(1 - \frac{a}{2}\right)$$

Since the defect is parallel to the plate surface, a/t vanishes, and

$$S_u = \frac{S_{ys} + S_{Ts}}{2}$$

b. The critical LEFM stress, S_k, is calculated as follows:

$$S_k = \frac{K_{Id}\sqrt{1 + 4.593\left(\frac{a}{l}\right)^{1.65}}}{\sqrt{M_m^2\ \pi a_{cr} + .212\left(\frac{K_{Id}}{S_{ys}}\right)^2}}$$

The critical defect size evaluated from the equation in Figure 6 is:

$$a_{cr} = 1.7",$$

so that

$$2a_{cr} = 3.4" > t = 1\text{-}1/2" \text{ (plate thickness).}$$

Therefore, the one-eighth inch defect subjected to 16 ksi stress is acceptable.

REFERENCES:

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A3 R.H. Sailors and H.T. Corten, ASTM STP513, p. 164.

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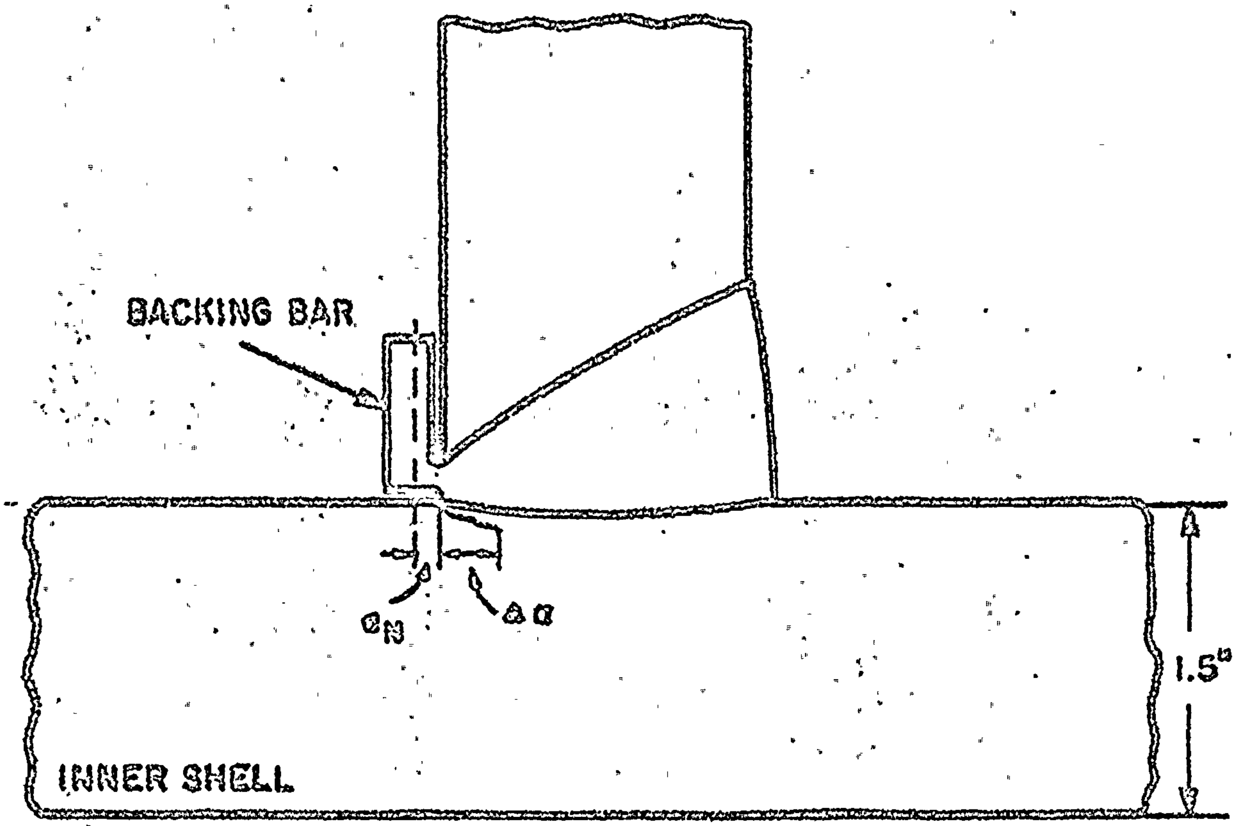

$$e = e_N + \Delta e$$

FIGURE A1

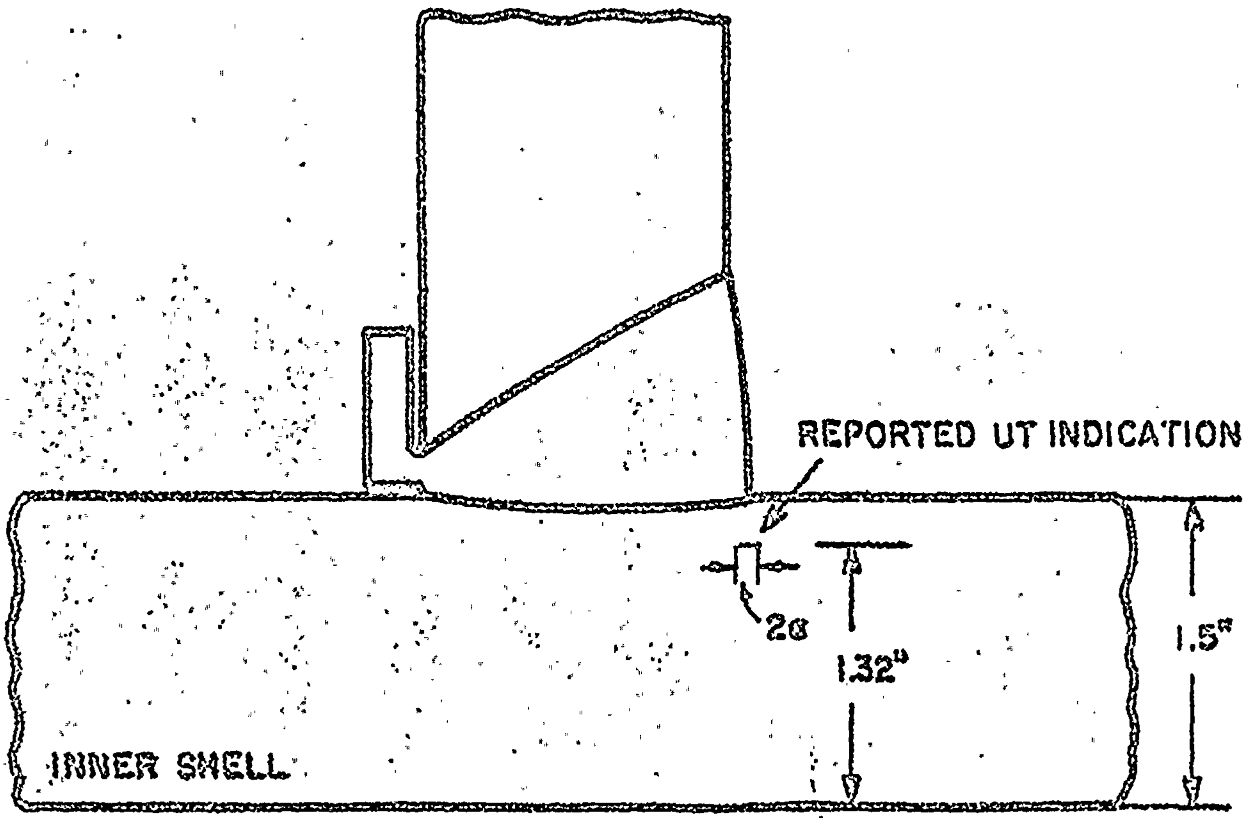

FIGURE A2