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February 28, 1986

Mr. Harold R. Denton, Director
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC. 20555

Subject: Braidwood Station Unit 1
Preservice Inspection (PSI) Disposition of
Indications for Loop 1 Steam Generator
and the Pressurizer
NRC Docket No. 50-456

Reference (a): May 24, 1985 K.A. Ainger Letter to H.R. Denton
(b): October 11, 1985 K.A. Ainger Letter to H.R. Denton

Dea Mr. Denton:

This is to inform you of the results of the preservice examination of the Braidwood Station Unit 1 steam generators and pressurizer vessels. Two unacceptable ultrasonic indications to ASME code Section XI were identified. One indication was found in Loop 1 steam generator and the other indication was located in the pressurizer. We believe that these indications are not cracks or lack of fusion but rather very small, innocuous slag inclusions formed during vessel fabrication. This conclusion has been reached by comparing Braidwood Station information against Byron Station PSI results of the steam generators and pressurizers.

Attempts to repair these indications involves some risk of reducing vessel integrity. We have conducted fracture mechanics which demonstrates that if the indications were inservice inspection flaws they would not grow to unacceptable sizes during plant life. We believe sufficient information exists at this time to conclude that repairs to Loop 1 steam generator and the pressurizer are not warranted. We are hereby requesting NRC concurrence with this position.

Included is information that addresses issues discussed with NRC during January 15, 1986 conference call. A timely review is requested as repairs to the vessels could affect the fuel load date.

B001
1/15

Please direct any questions that you or your staff may have to this office.

One signed original and fifteen copies of this letter and the enclosure are provided for your review.

Very truly yours,

Anthony Miosi

A. D. Miosi
Nuclear Licensing Administrator

ADM/klj

cc: J. Stevens (NRC)
1364K

ENCLOSURE

Braidwood Unit 1 Steam Generator/Pressurizer Preservice Inspection Disposition of Indications

Contents

Tables, Figures and Attachments

DISPOSITION OF ULTRASONIC INDICATIONS IDENTIFIED IN BRAIDWOOD UNIT 1 STEAM GENERATOR AND PRESSURIZER

1.0 INTRODUCTION

This report summarizes the evaluation and disposition of the Preservice Inspection (PSI) data from Braidwood Unit 1 steam generator and pressurizer shell welds. The PSI data shows two indications that exceed the acceptance criteria of ASME Code Section XI. One unacceptable indication was found in the upper shell-to-transition cone circumferential weld of the Loop 1 steam generator. Another unacceptable indication was identified in the upper middle shell-to-lower middle shell circumferential weld of the pressurizer. Nondestructive testing has characterized these indications as small innocuous slag inclusions of the same nature as the indications found in the vessels at Byron Units 1 and 2. We have concluded that the integrity of the vessels at Braidwood can be best preserved by not removing the indications.

2.0 DISCUSSION OF ULTRASONIC SIZING

The sizing method used in developing the data presented in this report is the recommended practice of ASME Section V, Article 4 as referenced by Section XI for vessel welds. The indication through wall dimensions and lengths are determined at the points where the observed signal falls to 50% of the calibrated distance amplitude correction curve (DAC). The DAC curve is established using the side-drilled holes in the calibration blocks shown in Figures 1a and 1b. These calibration blocks meet the requirements of Section V.

The ultrasonic procedures, equipment and calibration blocks used for the Braidwood Unit 1 preservice inspection (PSI) meet the Section XI, 1977 Edition with Addenda through Summer 1978 requirements as was applicable at Byron units 1 and 2. The calibration blocks are of the same material specification with the same size machined reflectors. At both plants the transducers used were 2.25 MHz with 0.5" x 1.0" element size.

Although it is commonly understood that this sizing methodology tends to over estimate the true size of ultrasonic reflectors, no attempts to apply correction factors have been made. Adjustment of through wall dimension based on beam spread effects have not been applied. Neither has any downsizing correction been applied based on the destructive versus nondestructive sizing comparisons observed during the evaluation of ten (10) similar indications at Byron Units 1 and 2.

As will be discussed in detail below, however, the tendency of the ultrasonic methodology employed to oversize indications of this nature is readily apparent.

3.0 DISCUSSION OF STEAM GENERATOR RESULTS

3.1 Ultrasonic Results:

The PSI data from Braidwood Unit 1 Steam Generator's shell welds shows one unacceptable indication in the upper shell-to-transition cone weld (weld #6) of the Loop 1 Steam Generator. This weld is part of the secondary side pressure boundary and is an ASME Class 2 weld. The location of the weld is identified in Figure 2. Since the acceptance criteria for Class 2 welds are still in preparation the rules of IWB-3500 were used for data evaluation. The acceptance standard for pressure retaining welds in vessels are found in paragraph IWB-3511 and the specific allowable indication sizes are found in Table IWB-3511-1.

The indication was detected using a 60 degree angle beam transducer. The maximum amplitude was 75%-80% of the distance amplitude correction curve. The indication is located between circumferential position 29 ft. - 11.7 in. and 30 ft.-0.9 in., making it 1.2 inches long. It is oriented parallel to and is approximately 1/4 inch from the weld centerline. The through-wall location as measured by Section XI ultrasonic methodology shows the indication located at 0.55 inch from the inner diameter (I.D.) surface and extending out to 1.00 inch from the I.D. surface. The weld thickness (t) at this location was measured as 3.95 in.

Using the Section XI sizing methodology the indication is classified as a subsurface indication. The through-wall dimension (2a) is 0.45 in., the length (l) is 1.20 in. and the separation from the I.D. surface is 0.55 in. The indication aspect ratio (a/l) is 0.19 giving an allowable subsurface a/t value of 3.5%. The a/t value of the indication is calculated as 5.7% which exceeds the acceptance standards of Table IWB-3511-1 (allowable a/t = 3.5%).

Additional investigations were performed to confirm the indication and to assist in determining the nature of the reflector source. A non-recordable (< 50% DAC) signal was noted when scanning from the opposing direction. More significantly, an indication was observed when scanning using a straight beam (0 degree) technique in the area of interest. The straight beam results confirm the location and subsurface nature of the indication. It is noted that detection of a straight beam signal is typical of a volumetric (inclusion or porosity) rather than a planar discontinuity.

3.2 Supplemental Non-destructive Examination:

Review of the original fabrication radiographs maintained in the Westinghouse archives did not reveal any evidence of a relevant indication. Additionally, a supplemental series of radiographs were made as part of this investigation. The radiographic technique employed was specifically designed to provide the highest sensitivity to detection of discontinuities at this location. This included placing a high energy Cobalt source outside the vessel wall and placing fine grain film on the inside surface. Since the indication is located somewhat closer to the I.D. surface than to the outer diameter (O.D.) surface, it was felt that this arrangement would provide highest sensitivity to planar discontinuities in the region of interest identified by ultrasonics. No indications were detected upon review of these radiographs. The procedure was repeated offsetting the source to provide for slightly angled shots and again no indications were found.

3.3 Comparison with the Ultrasonic Results at Byron 1 & 2

The ultrasonic investigation results of the indication described above are shown in Table 1. Also shown are the <u>ultrasonic</u> results of the indications investigated metallographically at Byron Unit 1 & 2.

Two indications from Byron Unit 1 (Weld 3 - Location 113 ccw; and Weld 3 - Location 93 ccw) and two indications from Byron Unit 2 (Weld 2 - Location 107 1/4 cw; and Weld 2 - Location 110 ccw) were removed as core samples and metallographically examined. Two sets of ultrasonic results are presented for each of the Byron Unit 1 indications representing the upper and lower range of ultrasonic sizing based on multiple examinations. The remaining are indications from Byron Unit 2 (Welds 5 and 6) that were physically measured during mechanical excavation from the I.D. surface.

The Braidwood Unit 1 indication shows ultrasonic data most similar to the Byron Unit 1 indication at Location 113 ccw. It is also somewhat similar to the Byron Unit 2 indication at Location 110 ccw. A few comparisons can be made from this data to highlight the basis for the conclusion that this indication is likely to be of even less concern than those physically sampled at Byron. It can be seen that the ultrasonic (U.T.) estimated through-wall extent of the indication (a/t ratio = 5.7%) is smaller than any of the sampled reflectors. The through-wall dimension (0.45 inches) and length (1.2 inches) are in the same range as is typical of the sampled reflectors. Additionally, the signal amplitude is in the lower end of the range of all of these reflectors. In one case it is a factor of three (10 dB) smaller than one of the core-sampled reflectors.

3.4 Comparison of U.T. Estimates with Physical Measurement Results at Byron Units 1 & 2:

Full reports of the metallographic investigations of the samples removed from Byron Units 1 & 2 have been provided in the referenced documents. The following is a brief summary of the results and a comparison to the indication detected in the Braidwood Unit 1 steam generator.

Attached Figures 4 and 5 show the results of the destructive examinations performed on Byron Units 1 & 2 core samples containing the defects. Comparison of the actual reflector sizes are plotted relative to the sizes estimated by the ultrasonic technique described previously. In all cases but one (described later) the ultrasonic size estimates are larger (i.e. plotted in the oversizing region) than the actual measured reflector size. It is also noted that the ultrasonic estimate of the indication in Braidwood Unit 1 falls within the range of values for the indications investigated at Byron.

The indications in Byron Unit 1, Weld 3 and Byron Unit 2, Weld 2 (shown as solid circles in Figures 4 and 5) were removed by core sampling and examined metallographically in the laboratory. In all cases the source of the reflectors were found to be embedded inclusions with evidence of slag from the welding process. The inclusions were typically found to lie in the boundaries between successive weld passes. All of the reflectors observed in the core samples had an actual through-wall dimension smaller than 0.200 inches resulting in a/t values less than 3.0%. In those cases the reflectors were all smaller than the U.T. estimates by at least a factor of two.

The remaining indications in Byron Unit 2, Welds 5 and 6 (shown as open circles in Figures 4 and 5) were excavated by mechanical means. In these cases none of the excavation areas revealed the indication to be open to the I.D. surface. This was determined by performance of surface examination (magnetic particle) before metal removal. In all cases but one, the depth of excavation at which the indication first appeared was measured to determine the distance of the indication from the I.D. surface for comparison with the U.T. data. The excavation then proceeded in 1/16 inch increments until the indication could no longer be detected with surface examination. Measurements were taken at the maximum excavation depth providing the value for the through-wall dimensions. All of the reflectors observed during excavation had actual through-wall dimensions smaller than 0.38 inches resulting in a/t values less than 4.5% with the exception of the indication where no measurement of the distance from the I.D. surface was made. In this case, the full through-wall dimension is conservatively given as if the indication extended to the I.D. The total through-wall dimension for this reflector was still less than 0.38 inches, however, the a/t value becomes exaggerated to 11.5% (essentially the same as the U.T. estimate, see Figure 5). This data point also represents the one case where the measured through-wall dimension slightly exceeds the U.T. estimate in Figure 4.

4.0 DISCUSSION OF PRESSURIZER RESULTS

4.1 Ultrasonic Results:

The PSI data from the Braidwood Unit 1 Pressurizer's shell welds shows one indication that exceeds the acceptance criteria of Section XI. The indication was found in the lower-to-upper intermmediate circumferential shell weld (weld #8C). The location of the weld is identified in Figure 3. This weld is part of the primary pressure boundary and is a ASME Class 1 weld. The acceptance standard for pressure retaining welds in Class 1 vessels are found in paragraph IWB-3511 and the specific allowable indication sizes are found in Table IWB-3511-1.

The indication was detected using both 45 and 60 degree angle beams. The maximum amplitude was 90% DAC for the 45 degree indication and 75% DAC for the 60 degree indication. The indication is located between circumferential position 6 ft. - 7.6 in. and 6 ft. - 8.55 in., making it 0.95 inches long. It is oriented parallel to and is approximately 1/2 inch from the weld centerline. The through-wall location as measured by Section XI ultrasonic methodology shows the indication located at 2.20 inches from the I.D. surface and extending out to 2.488 inches from the I.D. surface using the 45 degree data. The indication is of slightly smaller through-wall extent (0.200 inch) using the 60 degree data. The weld thickness (t) at this location was measured as 4.00 in.

Using the Section XI sizing methodology the indication is classified as a subsurface indication, and in fact is essentially located midway between the inner and outer surfaces. Using the 45 degree data, the through-wall dimension (2a) is 0.288 in., the length (l) is 0.95 in. The indication aspect ratio (a/l) is 0.15 giving an allowable subsurface a/t value of 3.2%. The a/t value of the indication is calculated as 3.6% which only marginally exceeds the acceptance standards of Table IWB-3511-1 (allowable a/t = 3.2%).

Using the 60 degree data, the through-wall dimension (2a) is 0.200 in., the length (l) is 1.00 in. The indication aspect ratio (a/l) is 0.10 giving an allowable subsurface a/t value of the indication is calculated as 2.5% which is acceptable to the standards of Table IWB-3511-1 (allowable a/t = 2.9%).

4.2 Supplemental Non-destructive Examination:

Review of the original fabrication radiographs maintained in Westinghouse archives identified no indications in the area of interest. Supplemental radiography of the pressurizer was not performed.

4.2 Comparison with the Ultrasonic Results at Byron 1 & 2

The ultrasonic investigation results of the indication detected in the Pressurizer are also shown in Table 1. The through-wall dimension and length of this indication fall within the same range of values as the indications from the slag inclusions in the Byron 1 and 2 Steam Generators. In fact, the through-wall dimension estimate is toward the lower range of these values. The U.T. estimated through-wall extent of the indication (a/t ratio = 3.6%) is significantly smaller than any of the other indications.

5.0 <u>CHARACTERIZATION OF INDICATIONS</u>

All of the above evidence supports a conclusion that the reflector sources are a small innocuous slag inclusion of the same nature as several found in the Byron Steam Generators. The following points summarize the evidence to support this conclusion.

5.1 Steam Generator Indication:

* The location within the weld is essentially identical to the small welding-induced inclusions found in the core samples taken from Byron Units 1 & 2.

* The ultrasonic estimate of a/t is 5.7% which is smaller than any ultrasonic estimate of the Byron indications investigated by sampling or excavation.

* The indication amplitude is consistant with, and in some cases significantly smaller than, the Byron indications investigated by sampling or excavation.

* The indication through-wall dimension is consistant with the Byron indications investigated by sampling or excavation.

* The indication data shows the reflector to be subsurface.

* The indication is detectable with straight (0 degree) beam examination, typical of a volumetric rather than a planar discontinuity.

* No evidence of cracking or lack of fusion is detectable by the extensive radiography performed.

5.2 Pressurizer Indication:

* The location within the weld is essentially identical to the small welding-induced inclusions found in the core samples taken from Byron Units 1 and 2 Steam Generators except that it is significantly farther from the I.D. surface.

* The ultrasonic estimate of a/t is 3.6% which is significantly smaller than any of the Byron indications investigated by sampling or excavation.

* The indication amplitude is consistant with the Byron indications investigated by sampling or excavation.

* The indication through-wall dimension is consistant with the Byron indications investigated by sampling or excavation.

* The indication data shows the reflector to be subsurface.

6.0 BYRON AND BRAIDWOOD COMPONENT FABRICATION

6.1 Manufacturing Sequence of Byron and Braidwood Components

The steam generators and pressurizers at Braidwood Station are essentially identical to those components at Byron Station. Both sites utilize Westinghouse Model D4 and D5 steam generators. The only major differences between these two models exist in the internal design. All four generating units have Westinghouse Model D Series 84 pressurizers. The Byron and Braidwood steam generators and pressurizers were manufactured within a five (5) year period with procedures developed to meet the requirements of ASME Section III 1971 Edition amended by various addenda. The manufacturing sequence of the Byron and Braidwood steam generators and pressurizers is provided in Table 2.

6.2 Description of Steam Generator Shell Fabrication:

Byron and Braidwood steam generator shell courses are made from SA 533 Grade A, Class II Mn-Mo type steel plate. The forgings such as the tube sheet, trunnions, manways, etc. are made of SA 508 Class II as modified by Code Case 1528. The longitudinal seams were flame cut to a $7^{o}/5^{o}$ bevel and closed in the forming roll on a 3/4 inch square bar that became the backup bar. Shielded Metal Arc Welding (SMAW) was utilized to seal the backup bar in preparation for Sub Arc Welding (SAW) of the longitudinal seams. Upon completion of the SAW, the backup bar was removed by automatic arc air. The I.D. area was then ground, inspected and back-welded using SAW. The circumferential welds were made in the same way except in some cases, the I.D. weld was not accessible for SAW. In these cases SMAW was used to back-fill the weld after back chip. Weld #6 is one case where the back welding was manual.

6.3 Post Weld Heat Treatment of Steam Generator Welds

All welding procedure qualifications were performed with a post weld heat (PWHT) at 1125 $\pm$ 25^{o}F for twenty-four (24) hours which qualifies for thirty (30) hours of total PWHT time. The upper shell-to-transition cone closure weld (weld #6) of the Braidwood 1 Loop 1 steam generator received PWHT for four (4) hours, two (2) minutes at a temperature of 1125 $\pm$ 25 ^{o}F.

7.0 FRACTURE MECHANICS ANALYSIS OF UNACCEPTABLE INDICATIONS

Section XI allows analytical evaluation of flaw indications for acceptability when the indications are identified during inservice inspections. During the preservice inspection of the Byron Unit 2 steam generators and pressurizer, fracture mechanics analyses of the vessels were developed to determine the acceptability of preservice indications at Byron which are characteristic of those at Braidwood.These analyses are in the form of handbook charts and were developed in accordance with paragraph IWB-3600 of Section XI, 1980 Edition. The Byron analyses can also be used to determine the acceptability of the Braidwood indications since the designs of the Byron and Braidwood vessels are essentially identical. The steam generator and pressurizer analyses are provided respectively in Attachments A and B. In Section 5 of each attachment are the specific evaluation charts for the Braidwood indications. These charts show that the Braidwood indications, if assumed to be inservice flaws, will not grow to unacceptable sizes during plant life. Per the requirements of Section XI, repair of the component welds would be unnecessary, if the indications were identified during an inservice inspection.

8.0 ADDITIONAL DISCUSSION

A conference call was held on January 15, 1986 with the Nuclear Regulatory Commission (NRC) to discuss the preservice inspection of the Braidwood Unit 1 steam generators and pressurizer. During that call the NRC requested the following information.

8.1 Steam Generator Water Level:

The Braidwood Unit 1 steam generator operating water level range is shown on Figure 2. At 0% (557°F, saturated), the water level is approximately 29 inches ($\pm$ 5%) below the upper shell-to-transition cone weld (weld #6). At 100% power (557°F, saturated), the water level is approximately 80 inches ($\pm$ 5%) above weld #6. Therefore, during normal plant operation the inner diameter surface of weld #6 is covered with water.

8.2 Copper Content in Feedwater System:

Copper and copper alloys in components of feedwater systems are known to promote corrosion. Components of the feedwater system at Braidwood contain no significant amounts of copper or copper alloys. Tubing of all feedwater system heat exchangers and main condensers are made of Type 304 stainless steel. Therefore, copper corrosion in the Braidwood feedwater systems will not occur.

9.0 CONCLUSION

As discussed in Sections 3.0 and 4.0 of this report, the preservice inspection of Braidwood Unit 1 steam generators and pressurizer has identified two ultrasonic indications that exceed the requirements of ASME Section XI. The indications are believed to be very small, innocuous slag inclusions formed during the fabrication of the vessels. They are not believed to be cracks or lack of fusion. This conclusion is supported by the following:

1. Metallurgical investigation of Byron weld samples identified the presence of trapped slag inclusions with actual dimensions much smaller than those predicted by ultrasonic techniques.

2. The designs of Braidwood steam generators and pressurizers are essentially identical to the Byron steam generators and pressurizers. Components at both sites were manufactured with similar procedures within a five year period.

3. Similar ultrasonic examination techniques were used for preservice inspections at Byron and Braidwood.

4. Ultrasonic and radiographic characteristics of the Braidwood indications are similar to those of the Byron indications.

The current condition of the Braidwood Unit 1 components will provide a sufficient level of plant safety when the plant becomes operational. The presence of small slag inclusions will not significantly affect the integrity of the vessels. Fracture mechanics analyses have demonstrated that, if the indications were inservice inspection flaws, they would not grow to unacceptable sizes during plant life. Based on Byron experience, the actual dimensions of the indications are most likely acceptable to Section XI requirements.

Section XI requires the removal of unacceptable indications identified in preservice inspections. However, removal of the indications does not guarantee an increase in the integrity of the components. The location of the indications at Braidwood makes their removal very difficult. Core sampling is impossible due to unusual geometry of the steam generator transition cone weld and the pressurizer cladding. The indications can be excavated, however, weld repair will be necessary due to the distance of the indications from the inner diameter (I.D.) weld surface. Welding at the I.D. surfaces may result in additional slag inclusions in weld metal interfaces. An attempt to repair these indications involves some risk of reducing vessel integrity. Furthermore, cladding repair in the pressurizer would mean additional hardship. For these reasons additional repairs are undesireable. Plant safety can be preserved by avoiding removal of the two innocuous indications.

TABLE - 1

COMPARISON OF BRAIDWOOD UNIT 1 STEAM GENERATOR AND PRESSURIZER SHELL U.T. RESULTS WITH BYRON UNITS 1 AND 2 U.T. RESULT FOR INDICATIONS REMOVE BY CORE SAMPLE OR GRINDING

Plant	Component	Weld No.	Location	% DAC	Thickness	Dist. from I.D.	Thru-wall	Length	a/l	a/t	Surf /Sub
Braidwood 1	S/G Loop 1	6	30 '	80%	3.95	0.550	0.450	1.20	0.19	5.7%	Sub
	PZR	8	6'-9.3"	90%	4.00	2.190	0.288	0.95	0.15	3.6%	Sub
Byron 1	S/G Loop 1	3	113 ccw	58%	3.10	0.570	0.370	0.75	0.25	5.8%	Sub
	-same ind.	3	113 ccw	51%	3.10	0.000	0.420	1.62	0.26	13.4%	Surf
	S/G Loop 1	3	93 ccw	120%	3.10	0.000	1.000	2.94	0.49	32.5%	Surf
	-same ind.	3	93 ccw	240%	3.10	0.000	0.370	1.00	0.09	8.4%	Surf
Byron 2	S/G Loop 3	2	107 1/4 cw	71%	3.30	0.000	0.240	0.88	0.27	7.3%	Surf
	S/G Loop 1	2	110 ccw	77%	3.20	0.160	0.530	0.88	0.30	8.3%	Sub
	S/G Loop 2	5	212 3/4 cw	81%	3.11	0.050	0.370	1.00	0.42	12.4%	Surf
	S/G Loop 1	6	110 1/2 cw	86%	3.92	0.020	0.430	0.75	0.60	11.2%	Surf
	S/G Loop 3	6	139 1/4 cw	130%	3.88	0.000	0.450	3.50	0.13	11.3%	Surf
	S/G Loop 2	6	229 cw	64%	4.06	0.000	0.240	0.75	0.32	6.0%	Surf
	S/G Loop 4	6	40 5/8 ccw	200%	3.91	0.000	0.510	3.25	0.16	12.8%	Surf
	S/G Loop 3	6	42 1/2 ccw	77%	3.89	0.000	0.330	1.00	0.33	8.3%	Surf

TABLE 2

LISTING OF THE MANUFACTURING SEQUENCE OF THE STEAM GENERATORS AND PRESSURIZERS FOR BYRON UNITS 1 AND 2 AND BRAIDWOOD UNITS 1 AND 2

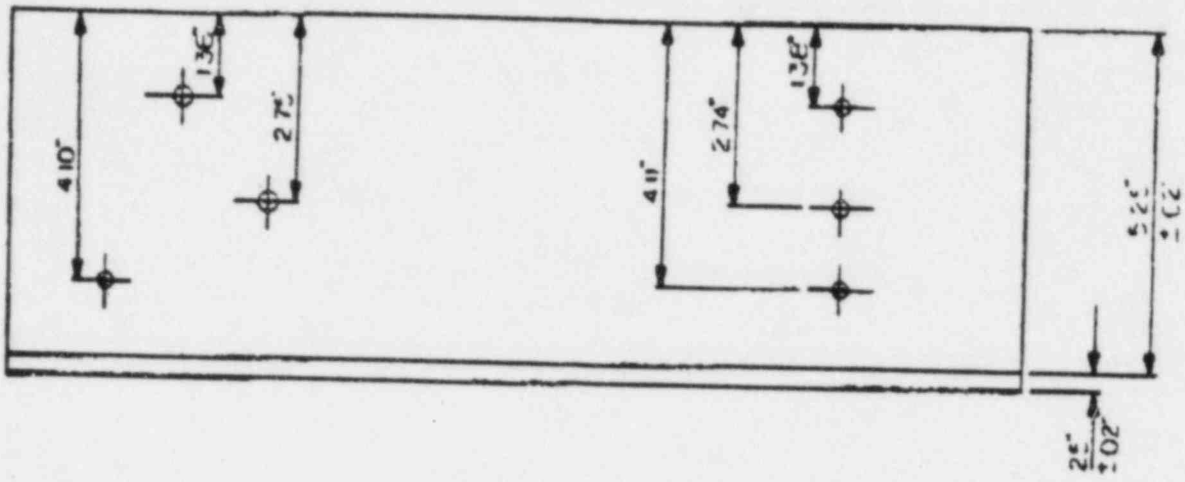
Plant	Component and S/N	Year Built	West. Quality Release Date (month/year)	ASME SEC.III Edition-Addenda
BYRON 1	S/G 1731	1977	7/77	1971-S72 & W74
"	S/G 1732	1977	7/77	1971-S72 & W74
"	S/G 1733	1977	7/77	1971-S72 & W74
"	S/G 1734	1977	7/77	1971-S72 & W74
"	PZR 1721	1976	10/76	1971-S73
BYRON 2	S/G 2095	1980	1/80	1971-S72 & W74
"	S/G 2096	1980	2/80	1971-S72 & W74
"	S/G 2097	1980	2/80	1971-S72 & W74
"	S/G 2098	1980	1/80	1971-S72 & W74
"	PZR 1941	1977	5/77	1971-S73
BRAIDWOOD 1	S/G 1711	1976	9/76	1971-S72
"	S/G 1712	1976	9/76	1971-S72
"	S/G 1713	1976	10/76	1971-S72
"	S/G 1714	1976	10/76	1971-S72
"	PZR 2101	1978	9/78	1971-S73
BRAIDWOOD 2	S/G 2111	1980*	10/80	1971-S72 & W74
"	S/G 2112	1980*	10/80	1971-S72 & W74
"	S/G 2113	1980*	11/80	1971-S72 & W74
"	S/G 2114	1980*	11/80	1971-S72 & W74
"	PZR 2121	1979*	9/79	1971-S73

* Year built was obtained from the code data form, this item was no longer recorded when the form was completed for Braidwood Unit 2.

BLOCK NO - BWD-61

SYSTEMS USE - PRIMARY SIDE OF STEAM GENERATOR CHANNEL AREA TO TUBE SHEET

DESCRIPTION - SA-216 GR WCC WITH STAINLESS STEEL CLAD 308L-16 & 309L-16 HT # 0530 & 8539 17 13/16" x 6 1/8" x 5 1/2" WITH 1/4" SIDE DRILLED HOLES



BLOCK NO - BWD-62

SYSTEMS USE - SECONDARY SIDE OF STEAM GENERATOR

DESCRIPTION - SA-533 GR A CL 2 24" x 8 1/2" x 3.95" WITH 1/4" SIDE DRILLED HOLES ℄ OF HOLES WERE MEASURED FROM THE O.D. SO THAT THEY WERE PARALLEL WITH I.D. SURFACE

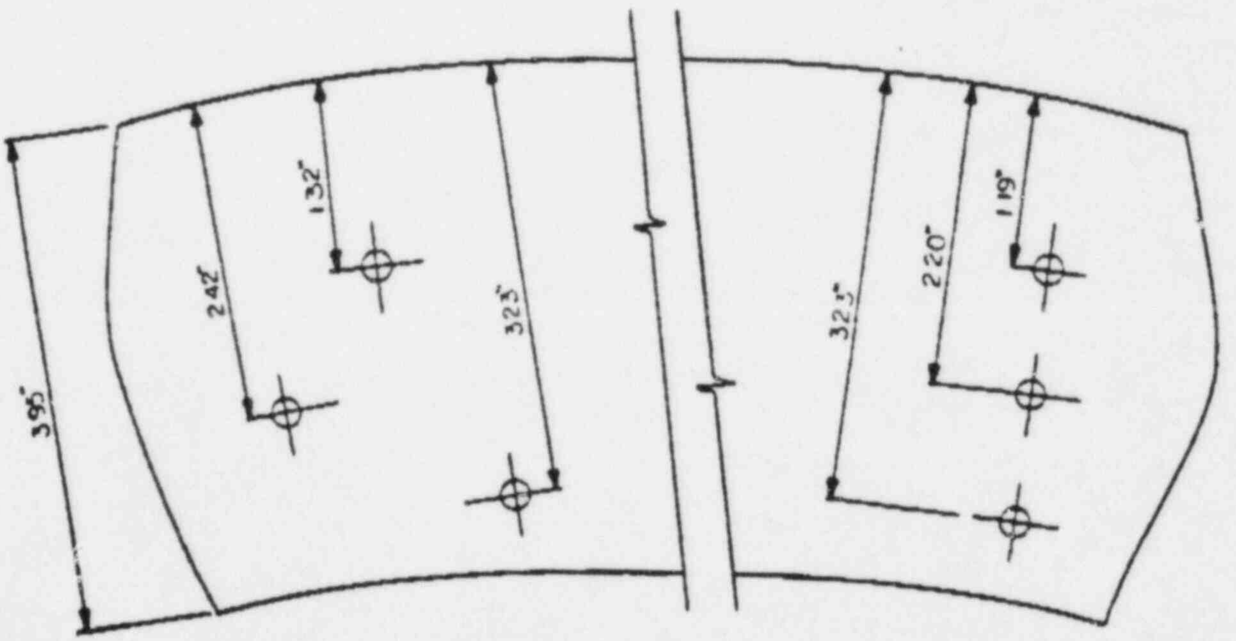


FIGURE 1a

BLOCK NO. - BWD-71 - UNIT 1 PRESSURIZER

SYSTEMS USE - PRESSURIZER SHELL WELDS
AND SHELL TO HEAD WELDS

DESCRIPTION - PZR 1721 SA-533 TYPE A CL. 2
HT. # 45498 WITH STAINLESS STE
CLAD T 10429
NAMEPLATE 10457
15" X 15" X 3.15" WITH 3/16" SIDE
DRILLED HOLES.

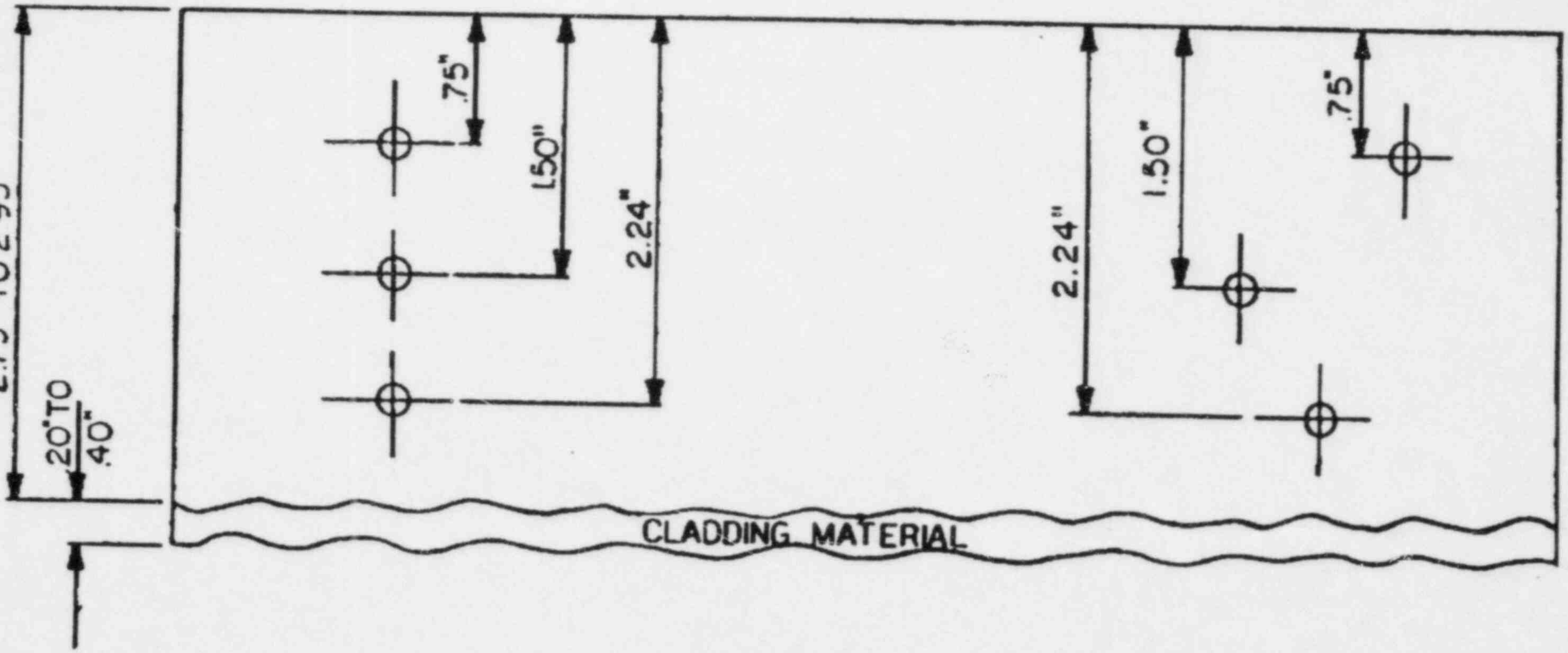
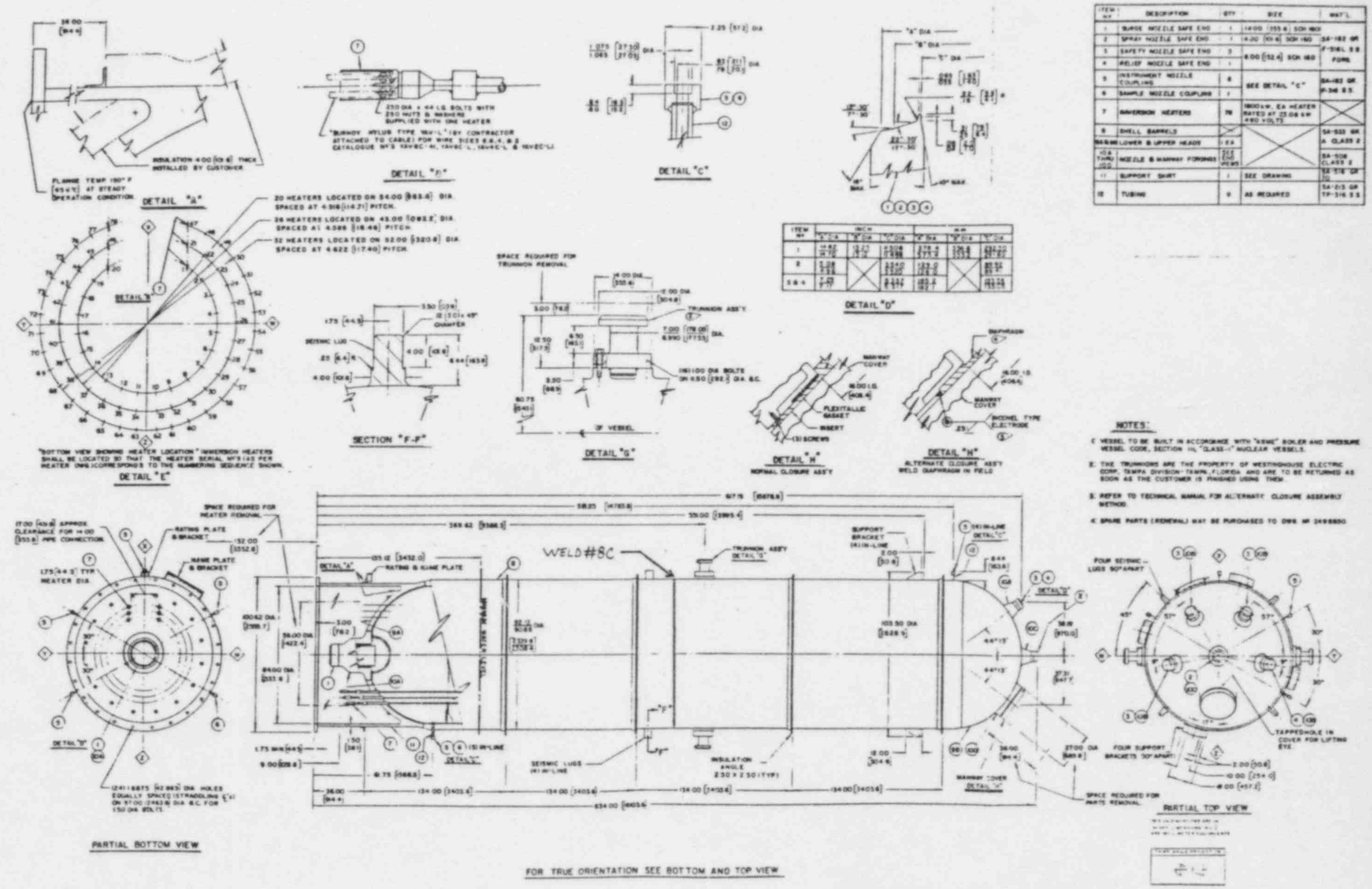
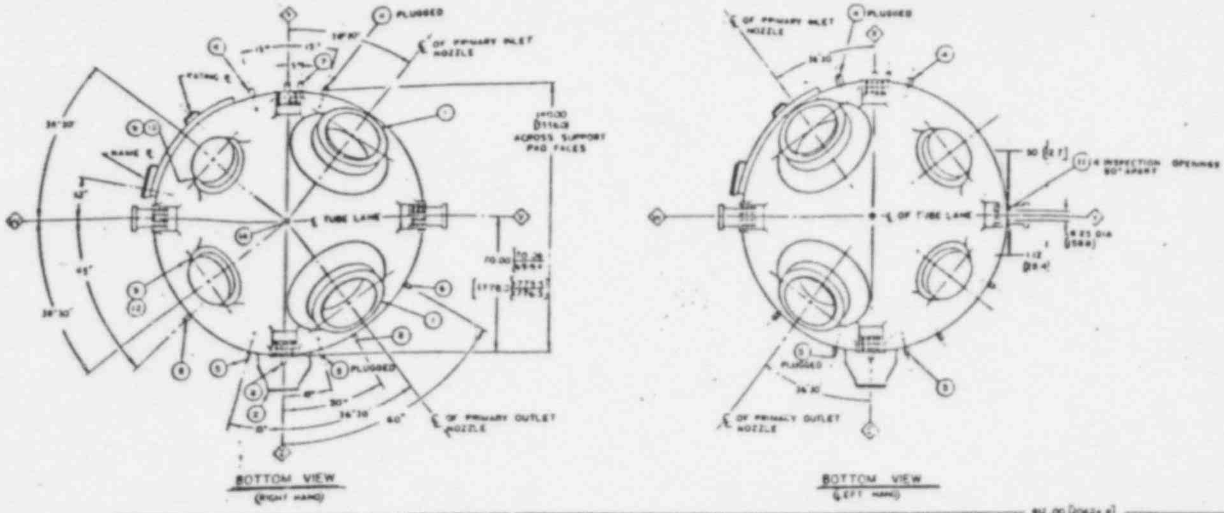


FIGURE 1b

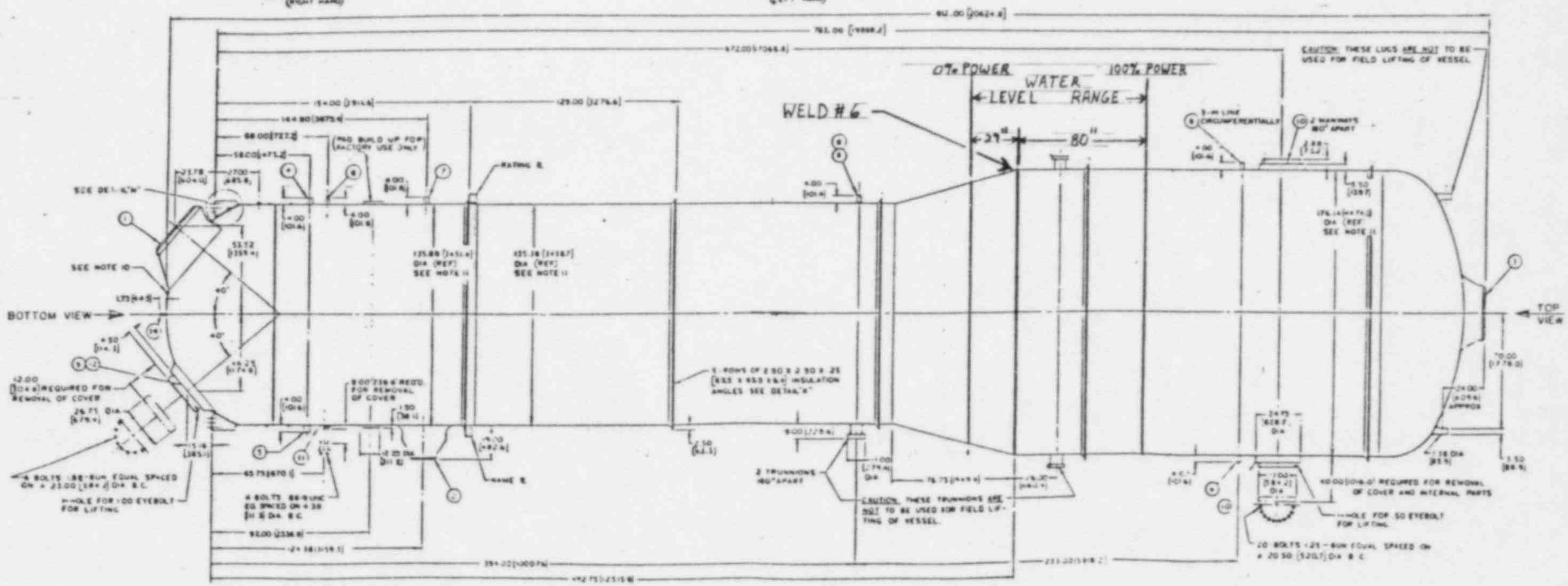


ITEM NO.	DESCRIPTION	QTY	SIZE	MAT'L
1	SURGE NOZZLE SAFE END	1	14.00 [355.6] SCH 160	SA-182 GR F-316L S.S. FORG.
2	SPRAY NOZZLE SAFE END	1	4.00 [101.6] SCH 160	
3	SAFETY NOZZLE SAFE END	3	6.00 [152.4] SCH 160	
4	RELIEF NOZZLE SAFE END	1		
5	INSTRUMENT NOZZLE COUPLING	6	SEE DETAIL "C"	SA-182 GR F-316 S.S.
6	SAMPLE NOZZLE COUPLING	1		
7	IMMERSION HEATERS	78	1800 kW, EA HEATER RATED AT 23.08 kW 480 VOLTS	
8	SHELL BARRELS			SA-533 GR A CLASS 2
9A & 9B	LOWER & UPPER HEADS	1 EA		
10A THRU 10G	NOZZLE & MANWAY FORGINGS	SEE END VIEWS		SA-508 CLASS 2
11	SUPPORT SKIRT	1	SEE DRAWING	SA-516 GR 70
12	TUBING	9	AS REQUIRED	SA-213 GR TP-316 S.S.

FIGURE 3

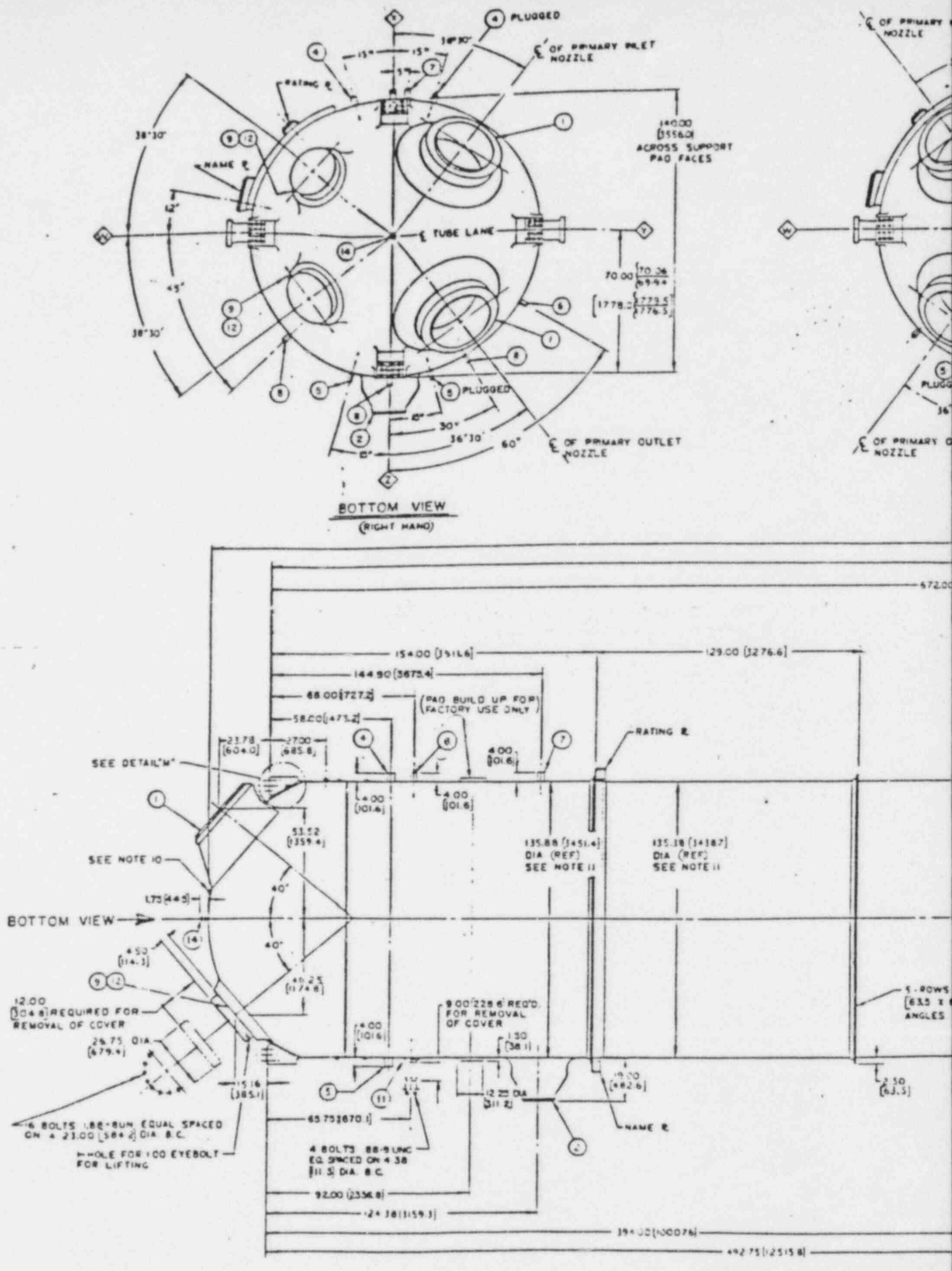


	TITLE	QTY	MATL SPEC	DET.	SIZE
1	PRIMARY COOLANT NOZZLE	2	SA216 WCC WITH [illegible]	"A"	31.00 [787.4] I.D.
2	FEEDWATER INLET NOZZLE	1	SA 508 CL.2	"L"	16.00 [406.4] O.D.
3	STEAM OUTLET NOZZLE	1	SA 508 CL.2	"E"	32.00 [812.8] O.D.
4	BOTTOM BLOWDOWN	2	SA 508 CL.1	"M"	2.00 PIPE CONN
5	SECONDARY SIDE SHELL DRAIN	1	SA 508 CL.1	"M"	1.00 PIPE CONN
6	WIDE RANGE WATER LEVEL TAP	3	SA 508 CL.1	"F"	.75 PIPE CONN
7	SAMPLING TAP	1	SA 508 CL.1	"F"	2.00 PIPE CONN
8	NARROW RANGE WATER LEVEL TAP	6	SA 508 CL.1	"F"	.75 PIPE CONN
9	PRIMARY MANWAY	2	SA 216 GR WCC	"C&D"	16.00 [406.4] I.D.
10	SECONDARY MANWAY	2	SA 508 CL.2	"B"	16.00 [406.4] I.D.
11	INSPECTION OPENING *	4	———	"B"	2.00 [50.8]
12	PRIMARY INSERT	2	SA 240 TYPE 304	"C"	20.50 [520.7] I.D.
13	PRIMARY DIAPHRAGM	2	SB 168	"D"	18.09 [459.5] O.D.
14	PRIMARY SIDE HEAD DRAIN	1	SA 182 GR F 316L	"L"	.38 PIPE CONN



FOR TRUE ORIENTATION SEE BOTTOM & TOP VIEWS

FIGURE 2



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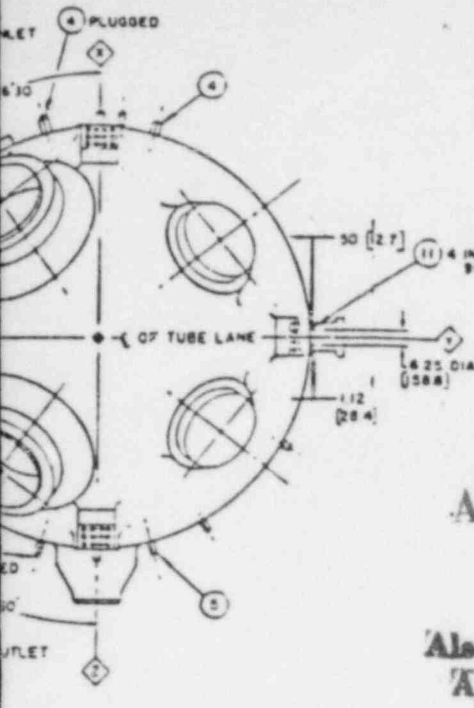
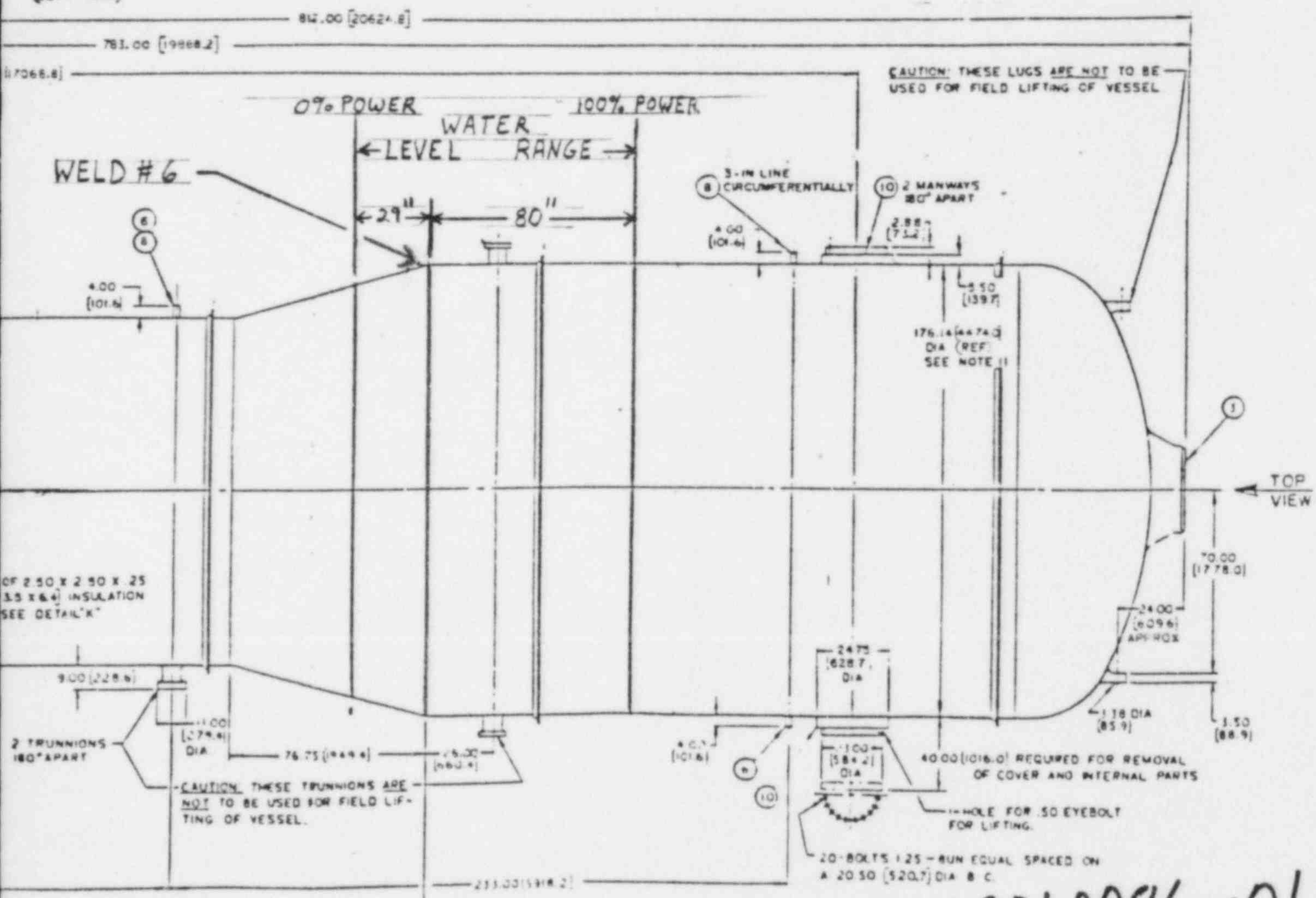


BOTTOM VIEW
(LEFT HAND)

TI
APERTURE
CARD

Also Available On
Aperture Card

	TITLE	QTY	MATL SPEC	DET	SIZE
1	PRIMARY COOLANT NOZZLE	2	SA216 WCC WITH [illegible] 308L S.S. ENDS	"A"	31.00 [787.4] I.D.
2	FEEDWATER INLET NOZZLE	1	SA 508 CL.2	"G"	16.00 [406.4] O.D.
3	STEAM OUTLET NOZZLE	1	SA 508 CL.2	"E"	32.00 [812.8] O.D.
4	BOTTOM BLOWDOWN	2	SA 508 CL.1	"H"	2.00 PIPE CONN
5	SECONDARY SIDE SHELL DRAIN	1	SA508 CL.1	"H"	1.00 PIPE CONN
6	WIDE RANGE WATER LEVEL TAP	3	SA508 CL.1	"F"	.75 PIPE CONN
7	SAMPLING TAP	1	SA508 CL.1	"F"	2.00 PIPE CONN
8	NARROW RANGE WATER LEVEL TAP	6	SA508 CL.1	"F"	.75 PIPE CONN
9	PRIMARY MANWAY	2	SA 216 GR WCC	"B"	16.00 [406.4] I.D.
10	SECONDARY MANWAY	2	SA508 CL.2	"B"	16.00 [406.4] I.D.
11	INSPECTION OPENING *	4	———	"B"	2.00 [50.8]
12	PRIMARY INSERT	2	SA240 TYPE 304	"C"	20.50 [520.7] I.D.
13	PRIMARY DIAPHRAGM	2	SB168	"D"	18.09 [459.5] O.D.
14	PRIMARY SIDE HEAD DRAIN	1	SA182 GR F 316L	"L"	.38 PIPE CONN



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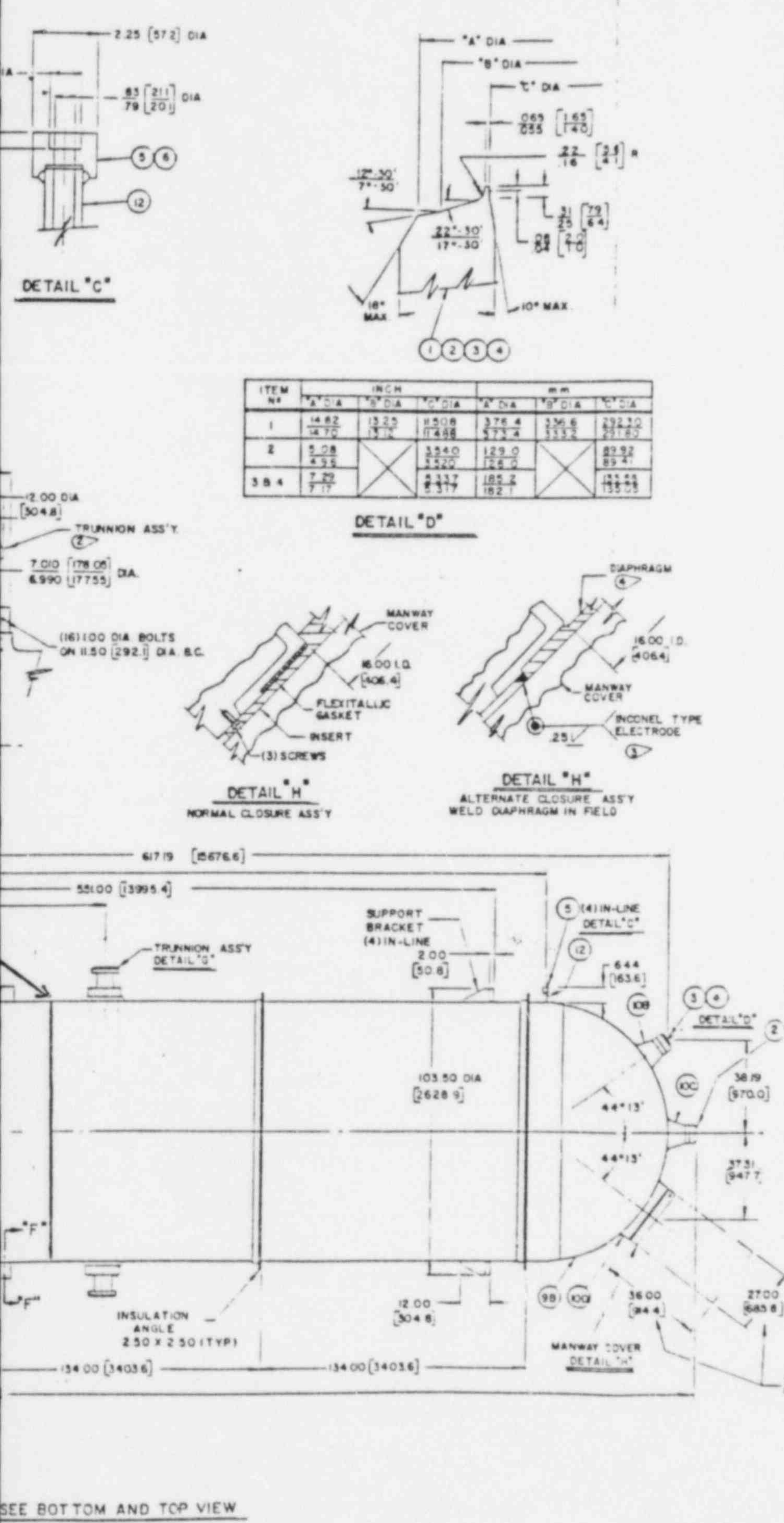
E BOTTOM & TOP VIEWS

FIGURE 2

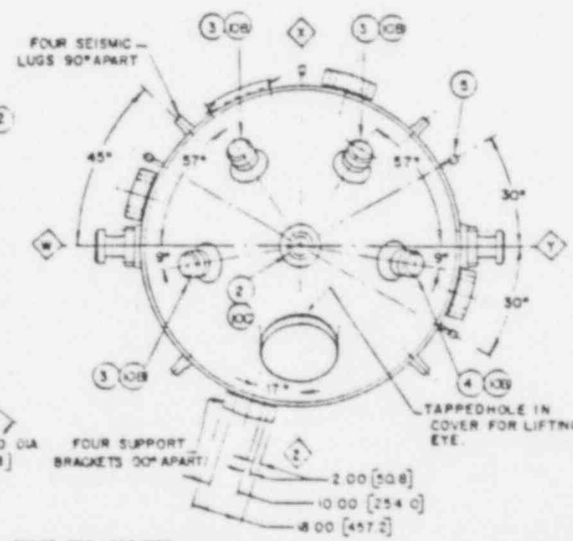


ITEM Nº	INCH			mm		
	"A" DIA	"B" DIA	"C" DIA	"A" DIA	"B" DIA	"C" DIA
1	14.82 / 14.70	13.25 / 13.12	11.508 / 11.488	376.4 / 373.4	336.6 / 333.2	292.30 / 291.80
2	5.08 / 4.95		3.540 / 3.520	129.0 / 126.0		89.92 / 89.41
3 & 4	7.29 / 7.17		5.337 / 5.317	185.2 / 182.1		135.55 / 135.05

ITEM Nº	DESCRIPTION	QTY	SIZE	MAT'L
1	SURGE NOZZLE SAFE END	1	14.00 [355.6] SCH 160	SA-182 GR. F-316L S.S. FORG.
2	SPRAY NOZZLE SAFE END	1	4.00 [101.6] SCH 160	
3	SAFETY NOZZLE SAFE END	3	6.00 [152.4] SCH 160	
4	RELIEF NOZZLE SAFE END	1		
5	INSTRUMENT NOZZLE COUPLING	6	SEE DETAIL "C"	SA-182 GR. F-316 S.S.
6	SAMPLE NOZZLE COUPLING	1		
7	IMMERSION HEATERS	78	1800 kW, EA HEATER RATED AT 23.08 kW 480 VOLTS	
8	SHELL BARRELS			SA-533 GR. A CLASS 2
9A & 9B	LOWER & UPPER HEADS	1 EA		
10A THRU 10D	NOZZLE & MANWAY FORGINGS	SEE END VIEWS		SA-508 CLASS 2
11	SUPPORT SKIRT	1	SEE DRAWING	SA-516 GR. 70
12	TUBING	9	AS REQUIRED	SA-213 GR. TP-316 S.S.

NOTES:

1. VESSEL TO BE BUILT IN ACCORDANCE WITH "ASME" BOILER AND PRESSURE VESSEL CODE, SECTION III, "CLASS-1" NUCLEAR VESSELS.
2. THE TRUNNIONS ARE THE PROPERTY OF WESTINGHOUSE ELECTRIC CORP., TAMPA DIVISION-TAMPA, FLORIDA AND ARE TO BE RETURNED AS SOON AS THE CUSTOMER IS FINISHED USING THEM.
3. REFER TO TECHNICAL MANUAL FOR ALTERNATE CLOSURE ASSEMBLY METHOD.
4. SPARE PARTS (RENEWAL) MAY BE PURCHASED TO DWG. Nº 2498850.



PARTIAL TOP VIEW

FIGURE 3

8603060086-02

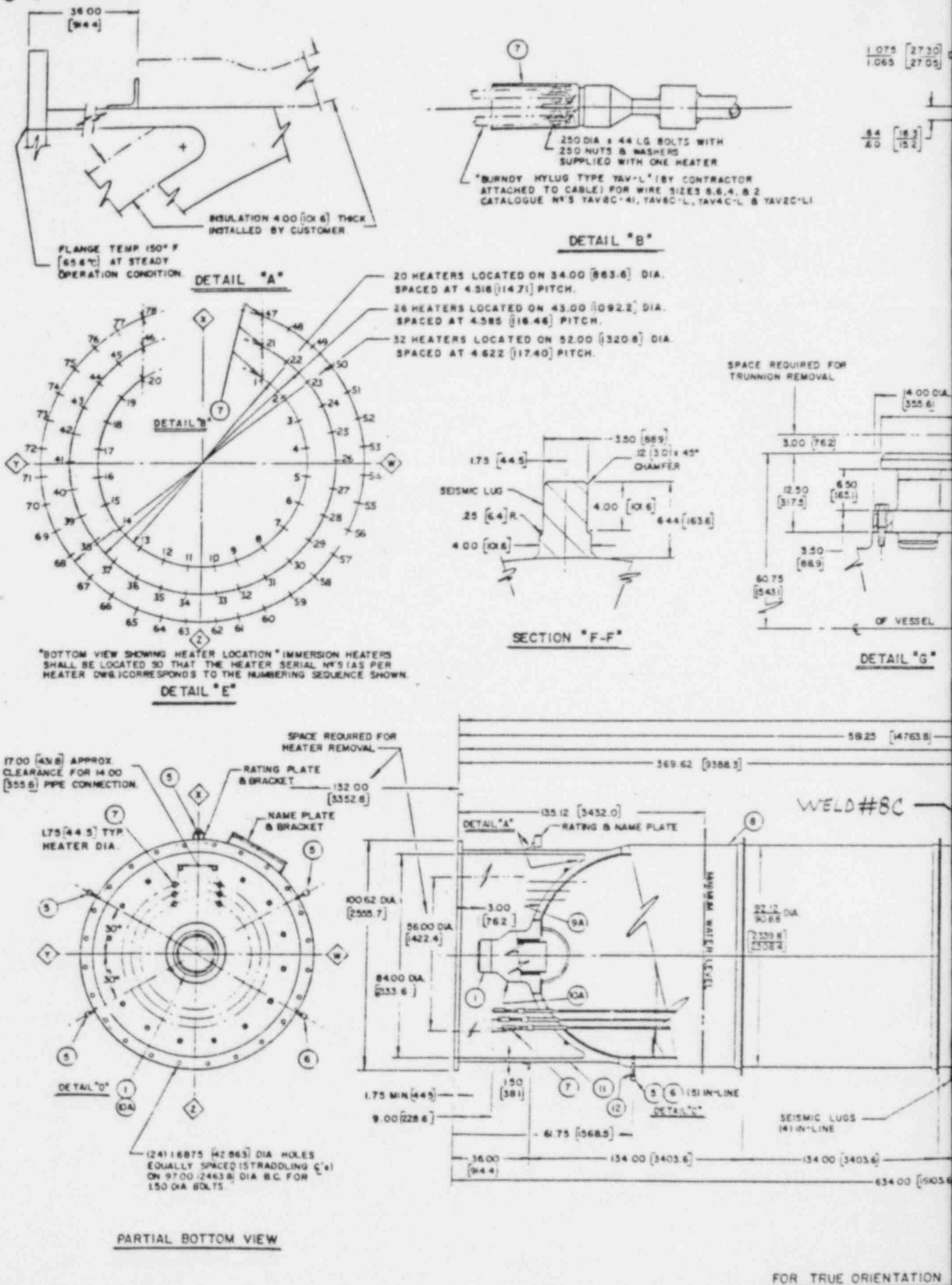


FIGURE - 4

COMPARISON OF ULTRASONIC ESTIMATED VERSUS PHYSICALLY MEASURED THROUGH WALL DIMENSIONS OF STEAM GENERATOR SHELL WELD INDICATIONS AT BYRON UNITS 1 AND 2

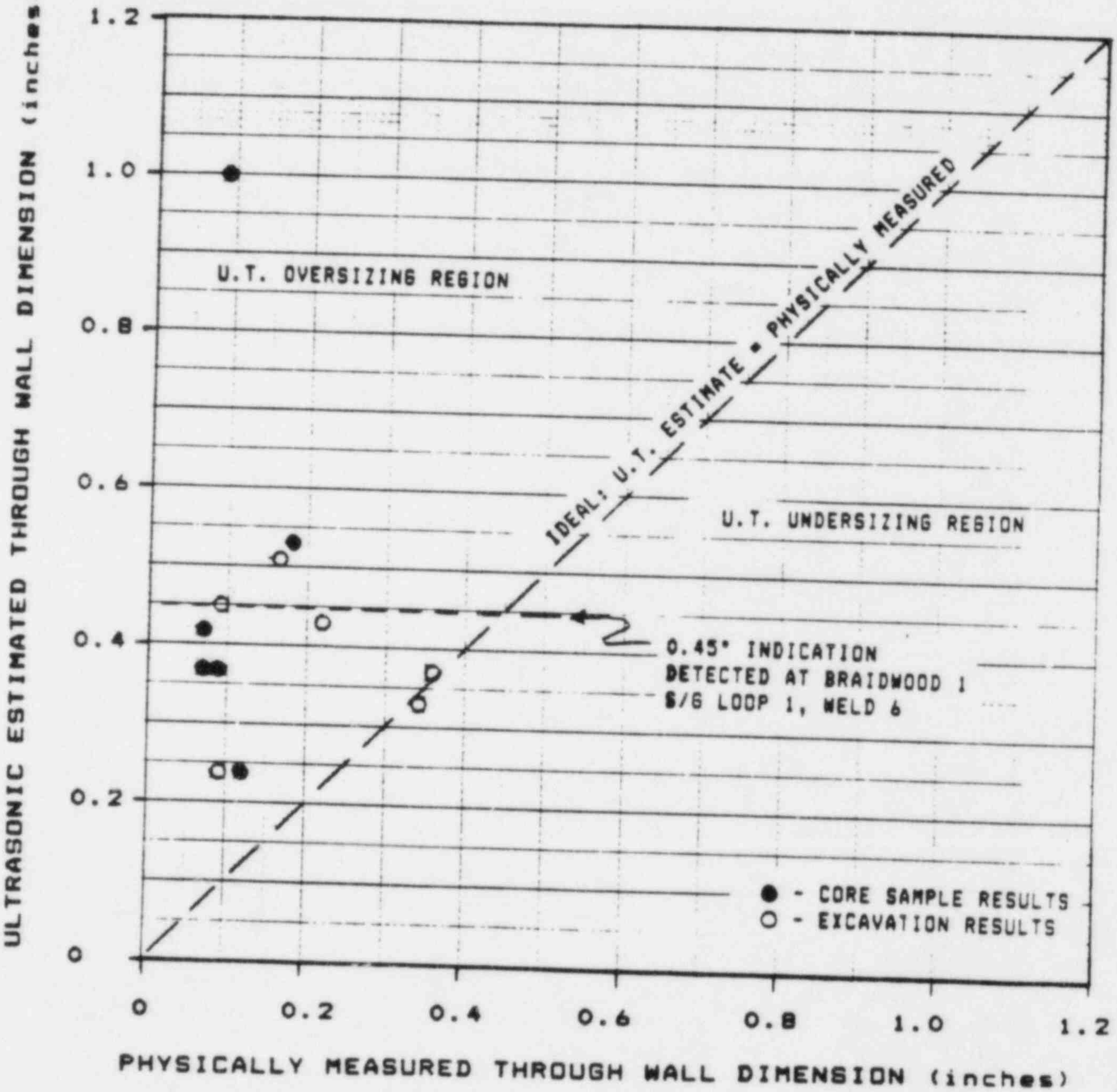
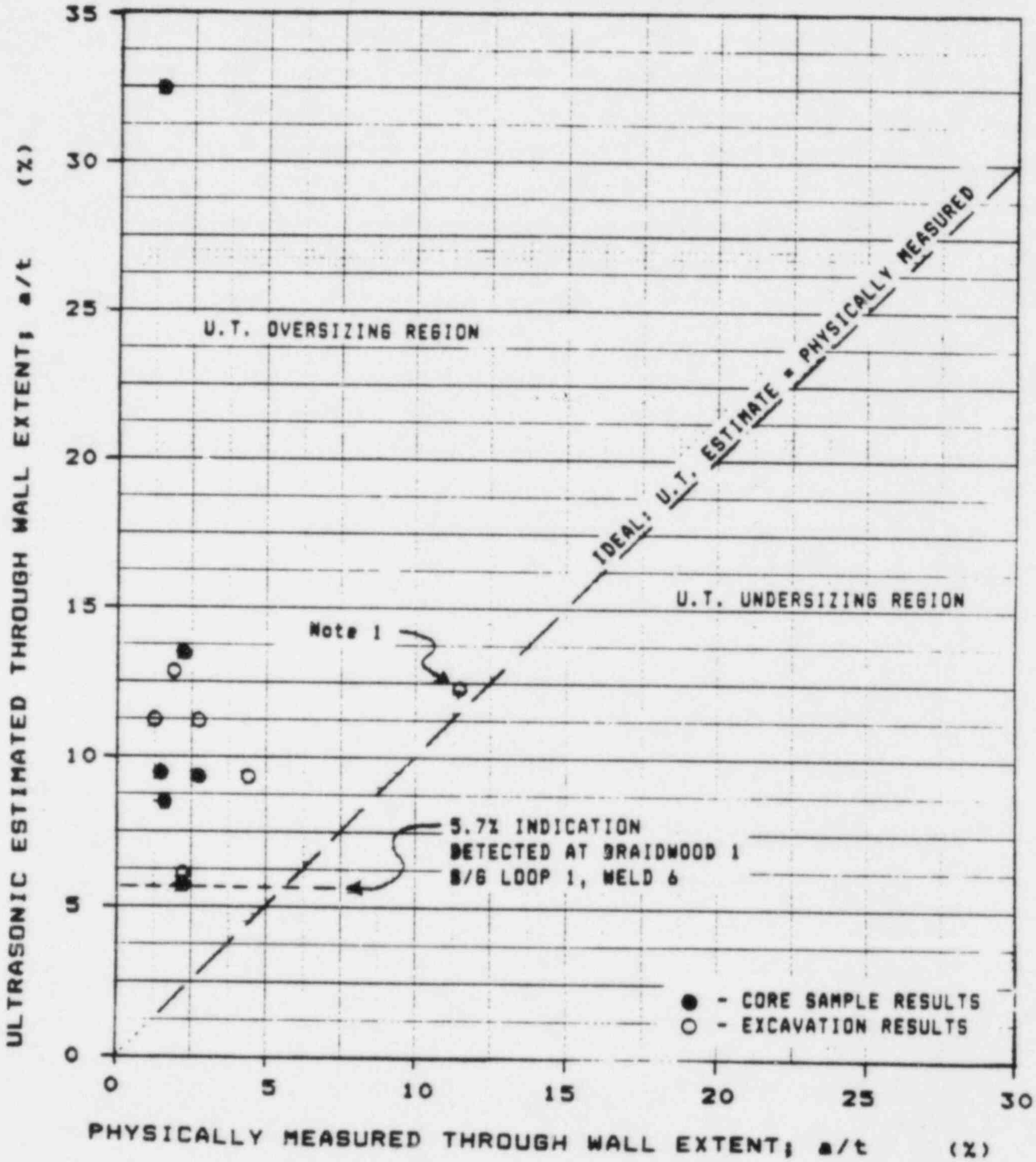


FIGURE - 5

COMPARISON OF ULTRASONIC ESTIMATED VERSUS PHYSICALLY MEASURED THROUGH WALL EXTENT (a/t) OF STEAM GENERATOR SHELL WELD INDICATIONS AT BYRON UNITS 1 AND 2



Note 1 : Dimension from I.D. to beginning of indication was not measure during excavation

ATTACHMENT A

STEAM GENERATOR FRACTURE MECHANICS

FLAW EVALUATION HANDBOOK CHARTS FOR BYRON UNIT 2 STEAM GENERATORS

1. INTRODUCTION

During inspections of the Byron Unit 2 steam generators, a number of indications were discovered. These evaluation are believed to be slag however for completeness a series of flaw evaluations have been carried out to determine the size of indications which are acceptable by the rules of Section XI, paragraph IWB 3600. These evaluations should prove useful for assessment of the results of future inservice inspections.

The results of these evaluations have been developed in the form of handbook charts, presented separately for each of the following regions of the steam generator:

- o Tubesheet to channel head weld region (seam SGC-01)
- o Tubesheet to stub barrel weld region (SGC-02)
- o Stub barrel intermediate seam (SGC-03)
- o Lower shell to cone weld region (SGC-05)
- o Upper shell to cone weld region (SGC-06)
- o Upper shell to dome weld region (SGC-08)
- o Feedwater nozzle to shell weld region (SGN-02)

The geometry of the Byron Unit 2 Model D-5 steam generators is shown schematically in Figure 1-1. All of the regions for which evaluation charts have been developed are identified in this figure by weld seam number. The weld seam number is also identified in parentheses in the above list.

The flaw evaluation charts have been developed based on direct application of the criteria of IWB 3600. The notation used for surface and embedded flaws is shown in Figure 1-2.

There are two alternative sets of flaw acceptance criteria for continued service without repair in paragraph IWB-3600 of ASME Code Section XI [1]. Namely,

1. Acceptance Criteria Based on Flaw Size (IWB-3611)
2. Acceptance Criteria Based on Stress Intensity Factor (IWB-3612)

Both criteria are comparable in accuracy for thick sections, and the acceptance criteria (2) have been assessed by past experience to be generally less restrictive for thin sections, and for outside surface flaws in many cases. In all cases, the most beneficial criteria has been used, generally criteria (2).

CRITERIA.BASED ON FLAW SIZE

The code acceptance criteria stated in IWB-3611 of Section XI are:

$a_f \leq .1\, a_c$ For normal conditions (upset & test conditions inclusive)

and $a_f \leq .5\, a_i$ For faulted conditions (emergency condition inclusive)

where

a_f = The maximum size to which the detected flaw is calculated to grow at the end of 40 years design life, or till the next inspection time.

a_c = The minimum critical flaw size under normal operating conditions (upset and test conditions inclusive)

a_i = The minimum critical flaw size for initiation of nonarresting growth under postulated faulted conditions. (emergency conditions inclusive)

To determine whether a flaw is acceptable for continued service without repair, both requirements must be met simultaneously. However, both criteria have been considered in advance before the charts were constructed. Only the most restrictive results were used in the charts.

CRITERIA BASED ON STRESS INTENSITY FACTOR

As mentioned in the preceeding paragraphs, the criteria used for the construction of the charts in this handbook are from the least restrictive of IWB 3611 or IWB 3612 of Section XI.

The term stress intensity factor (K_I) is defined as the driving force on a crack. It is a function of the size of the crack and the applied stresses, as well as the overall geometry of the structure. In contrast, the fracture toughness (K_{Ia}, K_{Ic}) is a measure of the resistance of the material to propagation of a crack. It is a material property, and a function of temperature.

The criteria are stated in IWB 3612:

$K_I \le \frac{K_{Ia}}{\sqrt{10}}$ For normal conditions (upset & test conditions inclusive)

$K_I \le \frac{K_{Ic}}{\sqrt{2}}$ For faulted conditions (emergency conditions inclusive)

where

K_I = The maximum applied stress intensity factor for the flaw size a_f to which a detected flaw will grow, during the conditions under consideration, at the end of design life, or to the next inspection.

K_{Ia} = Fracture toughness based on crack arrest for the corresponding crack tip temperature.

K_{Ic} = Fracture toughness based on fracture initiation for the corresponding crack tip temperature.

To determine whether a flaw is acceptable for continued service without repair, both criteria must be met simultaneously. However, both criteria have been considered in advance before the charts were constructed. Only the most restrictive results were used in the charts.

PRIMARY STRESS LIMITS

In addition to satisfying the fracture criteria, it is required that the primary stress limits of Section III, paragraph NB 3000 be satisfied. A local area reduction of the pressure retaining membrane must be used, equal to the area of the indication, and the stresses increased to reflect the smaller cross section. All the flaw acceptance tables provided in this handbook have included this consideration.

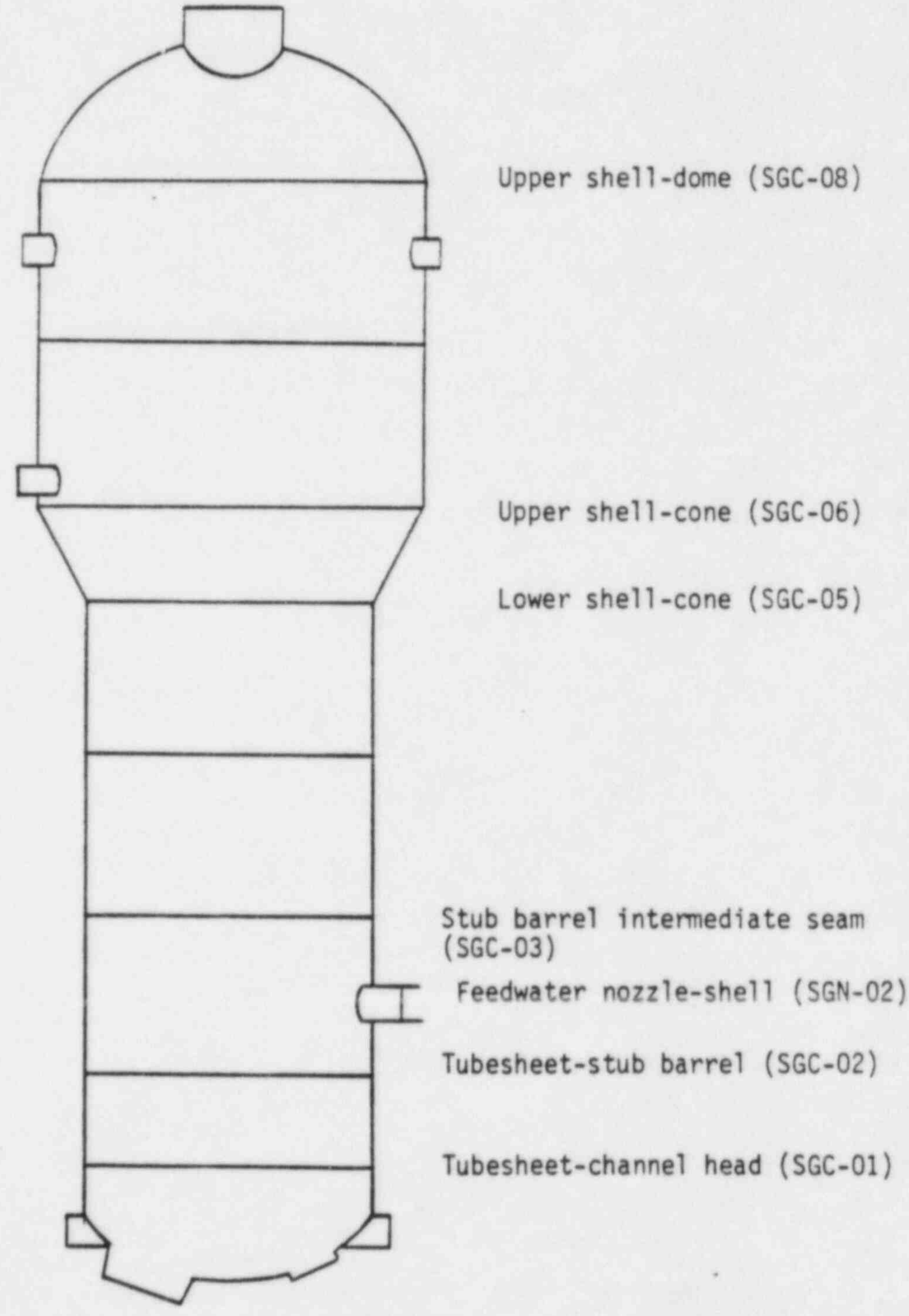
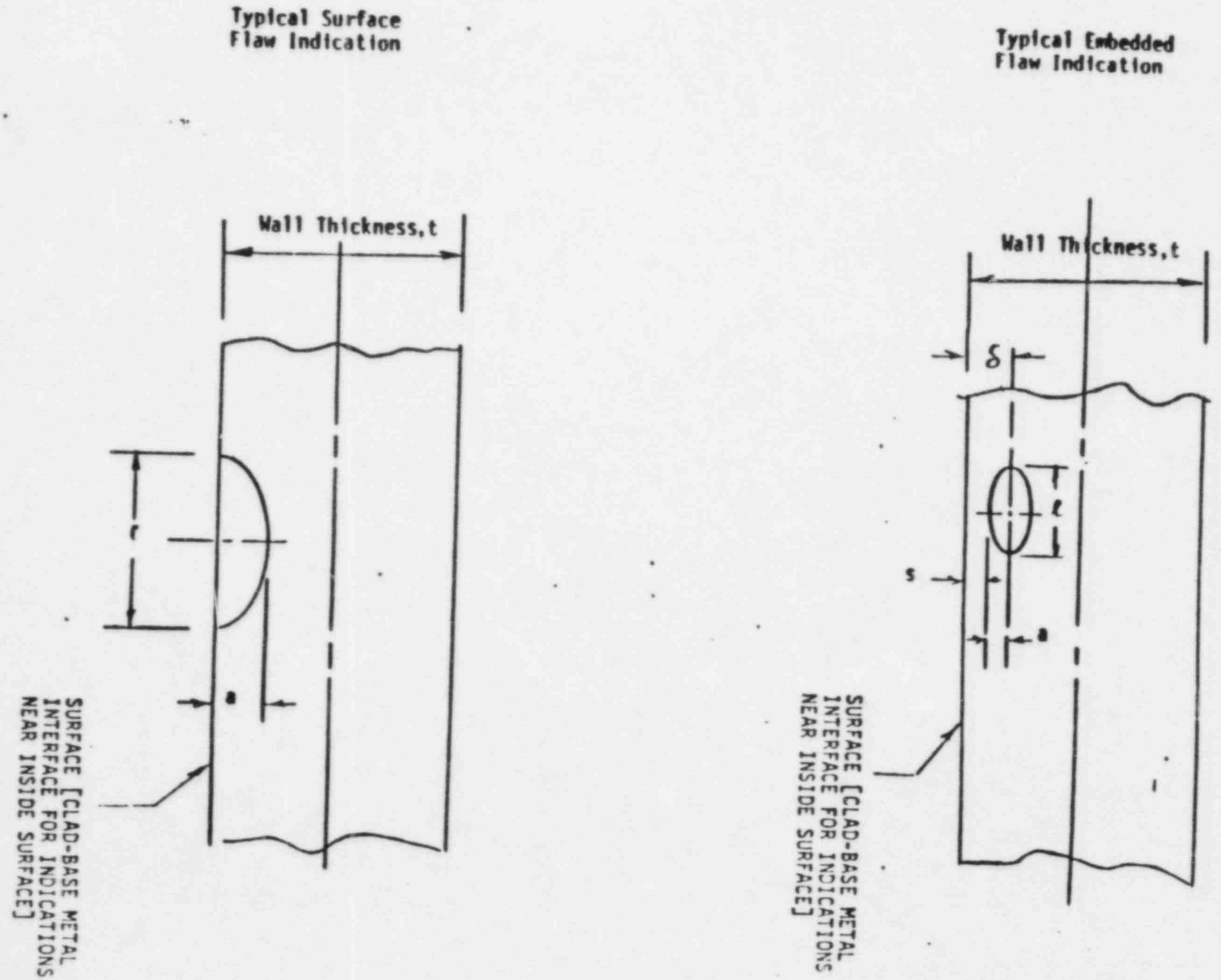


Figure 1-1 Schematic of Byron Unit 2 Model D-5 Steam Generator

FIGURE 1-2 Typical Notation of Surface and Embedded Flaw Indications



2. LOAD CONDITIONS, FRACTURE ANALYSIS METHODS AND MATERIAL PROPERTIES

TRANSIENTS FOR THE STEAM GENERATOR

The design transients for the Byron Unit 2 steam generators are listed in Table 2-1. Both the minimum critical flaw sizes, such as a_c under normal operating conditions, or a_i under faulted conditions for criteria (1) of IWB-3611, and the stress intensity factors, K_I, for criteria (2) of IWB-3612, are a function of the stresses at the cross-section where the flaw of interest is located, along with the material properties. Therefore, the first step for the evaluation of a flaw indication is to determine the appropriate limiting load conditions for the location of interest.

The key parameters used in the evaluation of any indications discovered during inservice inspection are the critical depths, first, that for the governing normal, upset, and test conditions and second, that for the governing emergency and faulted conditions.

It should be noted here that the flaw evaluation charts have been constructed based on all the operational transients for the steam generators. The pressure tests have been purposely omitted from the chart construction, because the severity of these tests can be mitigated by increasing the test temperature. Separate charts have been constructed to enable determination of hydrotest and leak test temperatures to ensure required margins of IWB 3600 are maintained.

STRESS INTENSITY FACTOR CALCULATIONS

One of the key elements of the critical flaw size calculations is the determination of the driving force or stress intensity factor (K_I). This was done using expressions available from the literature. In all cases the stress intensity factor for the critical flaw size calculations utilized a representation of the actual stress profile rather than a linearization. This was necessary to provide the most accurate determination possible of the critical flaw size, and is particularly important for consideration of emergency and faulted conditions, where the stress profile is generally nonlinear and often very steep. The stress profile was represented by a cubic polynomial:

$$\sigma(x) = A_0 + A_1 \frac{x}{t} + A_2 \left(\frac{x}{t}\right)^2 + A_3 \left(\frac{x}{t}\right)^3$$

where x is the coordinate distance into the wall

t = wall thickness

σ = stress perpendicular to the plane of the crack

For the surface flaw with length six times its depth, the stress intensity factor expression of McGowan and Raymund [2] was used.

The stress intensity factor K_I (ϕ) can be calculated anywhere along the crack front. The point of maximum crack depth is represented by $\phi = 0$. The following expression is used for calculating K_I (ϕ):

$$K_I(\phi) = \frac{\sqrt{\pi a}}{Q} \left(\cos^2\phi + \frac{a^2}{c^2} \sin^2\phi\right)^{1/4} \left(A_0 H_0 + \frac{2}{\pi} \frac{a}{t} A_1 H_1 + \frac{1}{2} \frac{a^2}{t^2} A_2 H_2 + \frac{4}{3\pi} \frac{a^3}{t^3} A_3 H_3\right)$$

The magnification factors $H_0(\phi)$, $H_1(\phi)$, $H_2(\phi)$ and $H_3(\phi)$ are obtained by the procedure outlined in Reference [2].

The stress intensity factor calculation for a semi-circular surface flaw, (aspect ratio 2:1) was carried out using the expressions developed by Raju and Newman [3]. Their expression utilizes the same cubic representation of the stress profile and gives precisely the same result as the expression of McGowan and Raymund for the 6:1 aspect ratio flaw, and the form of the equation is similar to that of McGowan and Raymund above.

The stress intensity factor expression used for a continuous surface flaw was that developed by Buchalet and Bamford [4]. Again the stress profile is represented as a cubic polynomial, as shown above, and these coefficients as well as the magnification factors are combined in the expression for K_I below:

$$K_I = \sqrt{\pi a}\,[A_0 F_1 + \frac{2a}{\pi} A_1 F_2 + \frac{a^2}{2} A_2 F_3 + \frac{4}{3\pi} a^3 A_3 F_4]$$

where F_1, F_2, F_3, F_4 are magnification factors, available in [4].

The stress intensity factor calculation for an embedded flaw was taken from work by Shah and Kobayashi [5] which is applicable to an embedded flaw in an infinite medium, subjected to an arbitrary stress profile. This expression has been shown to be applicable to embedded flaws in a thick-walled pressure vessel in a recent paper by Lee and Bamford [6].

FRACTURE TOUGHNESS

The other key element in the determination of critical flaw sizes is the fracture toughness of the material. The fracture toughness has been taken directly from the reference curves of Appendix A, Section XI. In the transition temperature region, these curves can be represented by the following equations:

$$K_{Ic} = 33.2 + 2.806 \exp. [0.02 (T-RT_{NDT} + 100°F)]$$

$$K_{Ia} = 26.8 + 1.233 \exp. [0.0145 (T-RT_{NDT} + 160°F)]$$

where K_{IC} and K_{IA} are in ksi$\sqrt{\text{in}}$.

The upper shelf temperature regime requires utilization of a shelf toughness which is not specified in the ASME Code. A value of 200 ksi√in has been used here. This value is consistent with general practice in such evaluations, as shown for example in reference [7], which provides the background and technical basis of Appendix A of Section XI.

The other key element in the determination of the fracture toughness is the value of RT_{NDT}, which is a parameter determined from Charpy V-notch and drop-weight tests. For this analysis, it was assumed that the RT_{NDT} is 10°F for the weld, and 40°F for the heat affected zone and base material. The tube sheet material is SA-508 Cl. 2a and the vessel material is SA-533 Gr. A, Cl. 2. These RT_{NDT} values are considered to be an upper bound for base and weld material in steam generators based on earlier work and the guarantees which are available from fabricators.

CRITICAL FLAW SIZE DETERMINATION

The applied stress intensity factor (K_I) and the material fracture toughness values (K_{Ia} and K_{Ic}) were used to determine the allowable flaw size values used to construct the handbook charts. For normal, upset and test conditions, the critical flaw size a_c is determined as the depth at which the applied stress intensity factor K_I exceeds the arrest fracture toughness K_{Ia}.

For emergency and faulted conditions the minimum flaw size for crack initiation is obtained from the first intersection of the applied stress intensity factor (K_I) curve with the static fracture toughness (K_{Ic}) curve.

TABLE 2-1 STEAM GENERATOR TRANSIENTS - BYRON UNIT 2

NUMBER	TRANSIENT IDENTIFICATION	# Cycles
1	Heatup and Cooldown *	200
	Turbine Roll Test	20
		220
2	Plant loading and unloading *	13200
	Unit loading	1500
	Small Step load increase	2000
		16700
3	Inadvertent RCS Depressurization *	20
	Control Rod Drop	80
	Large Step Load Decrease	200
	Partial Loss of Flow	80
	Inadvertent S.I. Actuation	60
	Loss of Power	40
	Inadvertent Startup of Inactive Loop	10
	Normal Loop Shutdown	80
		650
4	Reactor trip C *	10
	Reactor trip A	230
	Reactor trip B	160
		400
5	Excessive feedwater flow *	30
6	Bypass Line tempering *	20
	Valve failure	
	Normal loop startup	70
		90
7	Excessive bypass flow *	40
	Feedwater cycling	2000
		2040
8	Primary side leak test * (primary at 2485 psig, secondary at 885 psig)	200
9	Secondary side leak test* (primary at 615 psig, secondary at 1285 psig)	80
10	Primary side hydrotest* (primary at 3106 psig, secondary at 0 psig)	10
11	Secondary side hydrotest* (primary at 0 psig, secondary at 1481 psig)	10
12	Tube leak test D* (primary at 0 psig, secondary at 840 psig)	80
13	Tube leak test C* (primary at 0 psig, secondary at 600 psig)	120
14	Tube leak test B* (primary at 0 psig, secondary at 400 psig)	200
15	Tube leak test A* (primary at 0 psig, secondary at 200 psig)	800

*Governing Transients

3. FATIGUE CRACK GROWTH

In applying code acceptance criteria as introduced in Section 1, the final flaw size a_f used in criteria (1) is defined as the minimum flaw size to which the detected flaw is calculated to grow at the end of the design life, or until the next inspection time. In this handbook, ten-, twenty-, thirty-, and forty-year inspection periods are assumed.

These crack growth calculations have been carried out for all the regions of the Byron Unit 2 steam generators for which evaluation charts have been constructed. This section will examine the calculations, and provide the methodology used as well as the assumptions.

The crack growth calculations carried out were rather extensive, because a range of flaw shapes have been considered, to encompass the range of flaw shapes which could be encountered in service.

ANALYSIS METHODOLOGY

The fatigue crack growth analysis procedure involves postulating an initial flaw at specific regions and predicting the growth of that flaw due to an imposed series of loading transients. The input required for a fatigue crack growth analysis is basically the information necessary to calculate the parameter ΔK_I which depends on crack and structure geometry and the range of applied stresses in the area where the crack exists. Once ΔK_I is calculated, the growth due to that particular stress cycle can be calculated by equations given below and in Figure 3-1. This increment of growth is then added to the original crack size, and the analysis proceeds to the next transient. The procedure is continued in this manner until all the transients known to occur in the period of evaluation have been analyzed.

The transients considered in the analysis are all the design transients contained in the steam generator equipment specification, as shown in Section 2, Table 2-1. These transients are spread equally over the design lifetime of the vessel, with the exception that the preoperational tests are considered first. Faulted conditions are not considered because their frequency of occurrence is too low to affect fatigue crack growth.

Crack growth calculations were carried out for a range of flaw depths, and three basic types. The first type was a surface flaw with length equal to six times its depth, and whose analysis was previously reported. The second was a continuous surface flaw, which represents a worst case for surface flaws, and the third was an embedded flaw, with length equal to three times its width. For all cases the flaw was assumed to maintain a constant shape as it grew.

STRESS INTENSITY FACTOR EXPRESSIONS

Stress intensity factors were calculated from methods available in the literature for each of the flaw types analyzed. The surface flaw with aspect ratio 6:1 was analyzed using an expressure developed by McGowan and Raymund [2] where the stress intensity factor K is calculated from the actual stress profile through the wall at the location of interest.

The maximum and minimum stress profiles corresponding to each transient are represented by a third order polynomial, such that:

$$\sigma (X) = A_0 + A_1 \frac{X}{t} + A_2 \frac{X^2}{t^2} + A_3 \frac{X^3}{t^3}$$

The stress intensity factor K_I (ϕ) can be calculated anywhere along the crack front. The point of maximum crack depth is represented by $\phi = 0$. The following expression is used for calculating K_I (ϕ).

$$K_I(\phi) = \frac{\sqrt{\pi a}}{Q} (\cos^2\phi + \frac{a^2}{c^2} \sin^2\phi)^{1/4} (A_0 H_0 + \frac{2}{\pi} \frac{a}{t} A_1 H_1$$

$$+ \frac{1}{2} \frac{a^2}{t^2} A_2 H_2 + \frac{4}{3\pi} \frac{a^3}{t^3} A_3 H_3)$$

The magnification factors $H_0(\phi)$, $H_1(\phi)$, $H_2(\phi)$ and $H_3(\phi)$ are obtained by the procedure outlined in reference [2].

The stress intensity factor for a continuous surface flaw was calculated using an expression for an edge cracked plate [8]. The stress distribution is linearized through the wall thickness to determine membrane and bending stress and the applied K is calculated from:

$$K_I = \sigma_m Y_m \sqrt{a} + \sigma_B Y_B \sqrt{a}$$

The magnification factors Y_m and Y_B are taken from [8] and a is the crack depth.

For embedded flaws the stress intensity factor is much lower than for a surface flaw of equivalent size. This, combined with the fact that the fatigue crack growth rate for embedded flaws is much lower, leads to the conclusion that fatigue crack growth from embedded flaws is generally very low. For these cases, the stress intensity factor provided in Appendix A of Section XI was used directly, which requires linearizing the stress, as discussed above. For these cases the flaw shape was set with length equal to three times the width, and the eccentricity was set at 2.5, which corresponds to a flaw near the inside surface of the vessel. This flaw shape provides a conservative, worst case calculation of stress intensity factor for embedded flaws.

In regions where crack growth for embedded flaws exceeded one percent in 40 years, the crack growth results were factored directly into the embedded flaw evaluation charts.

CRACK GROWTH RATE REFERENCE CURVES

The crack growth rate curves used in the analyses were taken directly from Appendix A of Section XI of the ASME Code. Water environment curves were used for all inside surface flaws, and the air environment curve was used for embedded flaws and outside surface flaws.

For water environments the reference crack growth curves are shown in Fig. 3-1, and growth rate is a function of both the applied stress intensity factor range, and the R ratio (K_{min}/K_{max}) for the transient.

For R<0.25

$$(\Delta K_I < 19 \text{ ksi}\sqrt{\text{in}}) \ \frac{da}{dN} = (1.02 \times 10^{-6}) \ \Delta K_I^{5.95}$$

$$(\Delta K_I > 19 \text{ ksi}\sqrt{\text{in}}) \ \frac{da}{dN} = (1.01 \times 10^{-3}) \ \Delta K_I^{1.95}$$

where $\frac{da}{dN}$ = Crack Growth rate, micro-inches/cycle.

For R>0.65

$$(\Delta K_I < 12 \text{ ksi}\sqrt{\text{in}}) \ \frac{da}{dN} = (1.20 \times 10^{-5}) \ \Delta K_I^{5.95}$$

$$(\Delta K_I > 12 \text{ ksi}\sqrt{\text{in}}) \ \frac{da}{dN} = (2.52 \times 10^{-1}) \ \Delta K_I^{1.95}$$

For R ratio between these two extremes, interpolation is recommended.

The crack growth rate reference curve for air environments is a single curve, with growth rate being only a function of applied ΔK. This reference curve is also shown in Figure 3-1.

$$\frac{da}{dN} = (0.0267 \times 10^{-3}) \ \Delta K_I^{3.726}$$

where, $\frac{da}{dN}$ = Crack growth rate, micro-inches/cycle

ΔK_I = stress intensity factor range, ksi$\sqrt{\text{in}}$

$= (K_{Imax} - K_{Imin})$

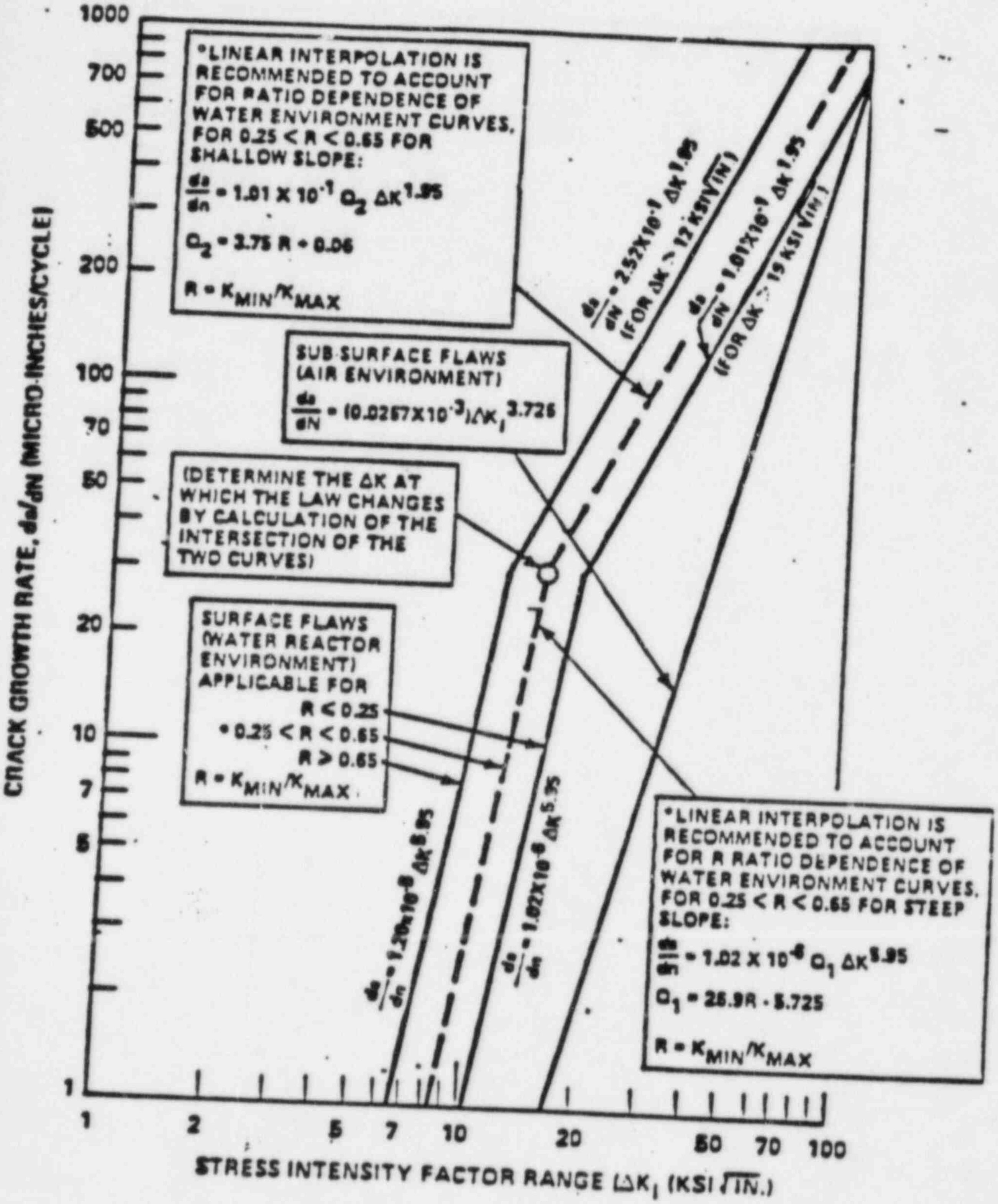


FIG. 3-1 REFERENCE FATIGUE CRACK GROWTH CURVES FOR CARBON AND LOW ALLOY FERRITIC STEELS

4. USE OF THE FLAW EVALUATION CHARTS

EVALUATION PROCEDURE

The evaluation procedures contained in ASME Section XI are clearly specified in paragraph IWB-3600. Use of the evaluation charts herein follows these procedures directly, but the steps are greatly simplified.

Once the indication is discovered, it must be characterized as to its location, length (ℓ) and depth dimension (a for surface flaws, 2a for embedded flaws), including its distance from the inside surface (S) for embedded indications. This characterization is discussed in further detail in paragraph IWA 3000 of Section XI.

The following parameters must be calculated from the above dimensions to use the charts (see Figure 1-2):

- o Flaw Shape parameter, $\frac{a}{\ell}$
- o Flaw depth parameter, $\frac{a}{t}$
- o Surface proximity parameter (for embedded flaws only), $\frac{\delta}{t}$

where

- t = wall thickness of region where indication is located
- ℓ = length of indication
- a = depth of surface flaw; or half depth of embedded flaw in the width direction
- δ = distance from flaw centerline to surface (for embedded flaws only) ($\delta = s + a$)
- S = smallest distance from edge of embedded flaw to surface

Once the above parameters have been determined and the determination made as to whether the indication is embedded or surface, then the two parameters may be plotted directly on the appropriate evaluation chart. Its location on the chart determines its acceptability immediately.

Although the use of the handbook charts is conceptually straight forward, experience in their development and use has led to a number of observations which will be helpful.

Surface Flaws

An example handbook chart for surface flaws is shown in Figure 4-1. The flaw indication parameters (whose calculation is described above) may be plotted directly on the chart to determine acceptability. The lower curve shown (labelled code allowable limit) is simply the acceptance standard from IWB 3500, which is tabulated in Section XI. If the plotted point falls below this line, the indication is acceptable without analytical justification having been required. If the plotted point falls between the code allowable limit line and the lines labelled "upper limits of acceptance by analysis" it is acceptable by virtue of its meeting the requirements of IWB 3600, which allow acceptance by fracture analysis. (Flaws between these lines would, however, require future monitoring per IWB 2420 of Section XI.) The analysis used to develop these lines is documented in this report. There are four of these lines shown in the charts, labelled 10, 20, 30, 40 years. The years indicate for how long the acceptance limit applies from the date that a flaw indication is discovered, based on fatigue crack growth calculations.

As may be seen in Figure 4-1, the chart gives results for surface flaw shapes up to a semi-circular flaw ($a/\ell = 0.5$). For the unlikely occurrence of flaws which the value of a/ℓ exceeds 0.5, the limits on acceptance for $a/\ell = 0.5$ should be used. The upper limits of acceptance have been set at (a maximum of) twenty percent of the wall thickness in all cases.

Embedded flaws

An example evaluation chart for embedded flaws is shown in Figure 4-2. The heavy diagonal line in the figure can be used directly to determine whether the indication should be characterized as an embedded flaw or whether it is sufficiently close to the surface that it must be considered as a surface flaw (by the rules of Section XI). If the flaw parameters produce a plotted point below the heavy diagonal line, it is acceptable by analysis. If it is above the line, it must be considered a surface flaw and evaluated using the surface flaw chart in Figure 4-1.

The standards for flaw acceptance without analysis cannot be shown in the embedded flaw charts because of their generality. Therefore, they have been plotted separately in Figure 4-3. Note the change in standards with the 1980 code, when the standards became a function of the proximity to the surface, S.

Detailed examples of the use of the charts for both surface and embedded flaws are presented in the following sections.

Surface flaw Example

Suppose an indication has been discovered which is a surface flaw and has the following characterized dimensions:

$$a = 0.12"$$
$$\ell = 1.2"$$
$$t = 3.13"$$

The flaw parameters for the use of the charts are

$$\frac{a}{t} = 0.0383 \; (3.83\%)$$

$$\frac{a}{\ell} = 0.10$$

Plotting these parameters on Figure 4.1 it is quickly seen that the indication is acceptable by analysis. To justify operation without repair it is necessary to submit this plot along with the Technical Basis document [1] to the regulatory authorities.

Embedded Flaw Example

A circumferential embedded flaw of 0.24 x 5.00", located within 0.2817" from the surface, was detected. Determine whether this flaw should be considered as an embedded flaw.

$2a = 0.8138"$

$S = 0.2817"$

$\delta = S + a = 0.2817 + 1/2\ (0.8138) = 0.6886"$

$t = 3.13"$

$\ell = 5.0"$

and,

$a = 1/2 \times 0.8138"$

$= 0.4069"$

Using Figure 4-2:

$$\frac{a}{t} = \frac{0.4069}{3.13} = 0.13$$

$$\frac{\delta}{t} = \frac{0.6886}{3.13} = 0.22$$

Since the plotted point (x) is below diagonal line, the flaw is considered embedded. The flaw is not acceptable, however, since the upper limit for allowable flaws was set at a/t = 12.5%, which corresponds to a total wall penetration ($\frac{2a}{t}$) of 25%.

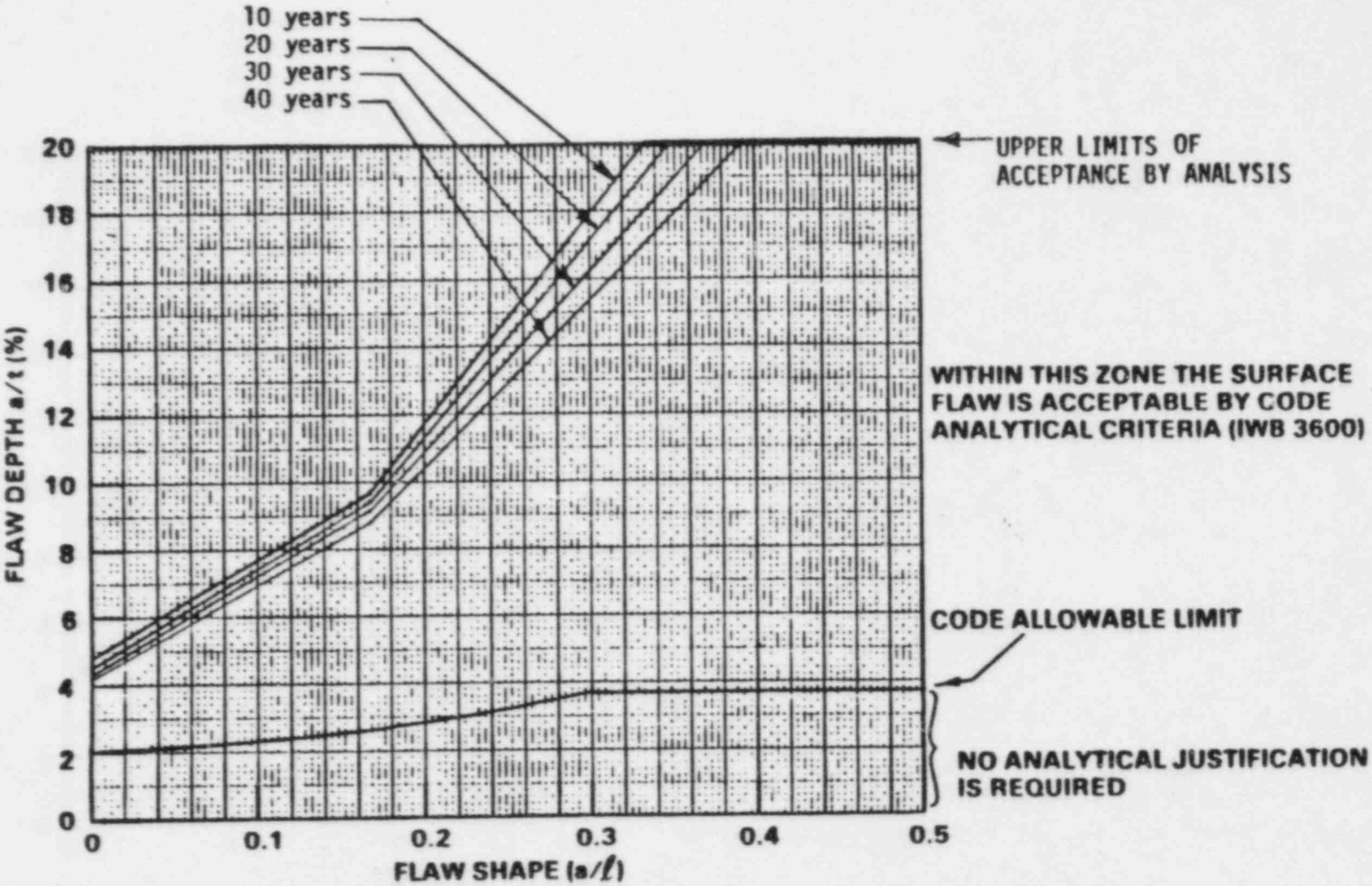


FIGURE 4-1 Flaw Evaluation Chart for Circumferential Surface Flaw in the Tube Sheet to Stub Barrel Weld Region

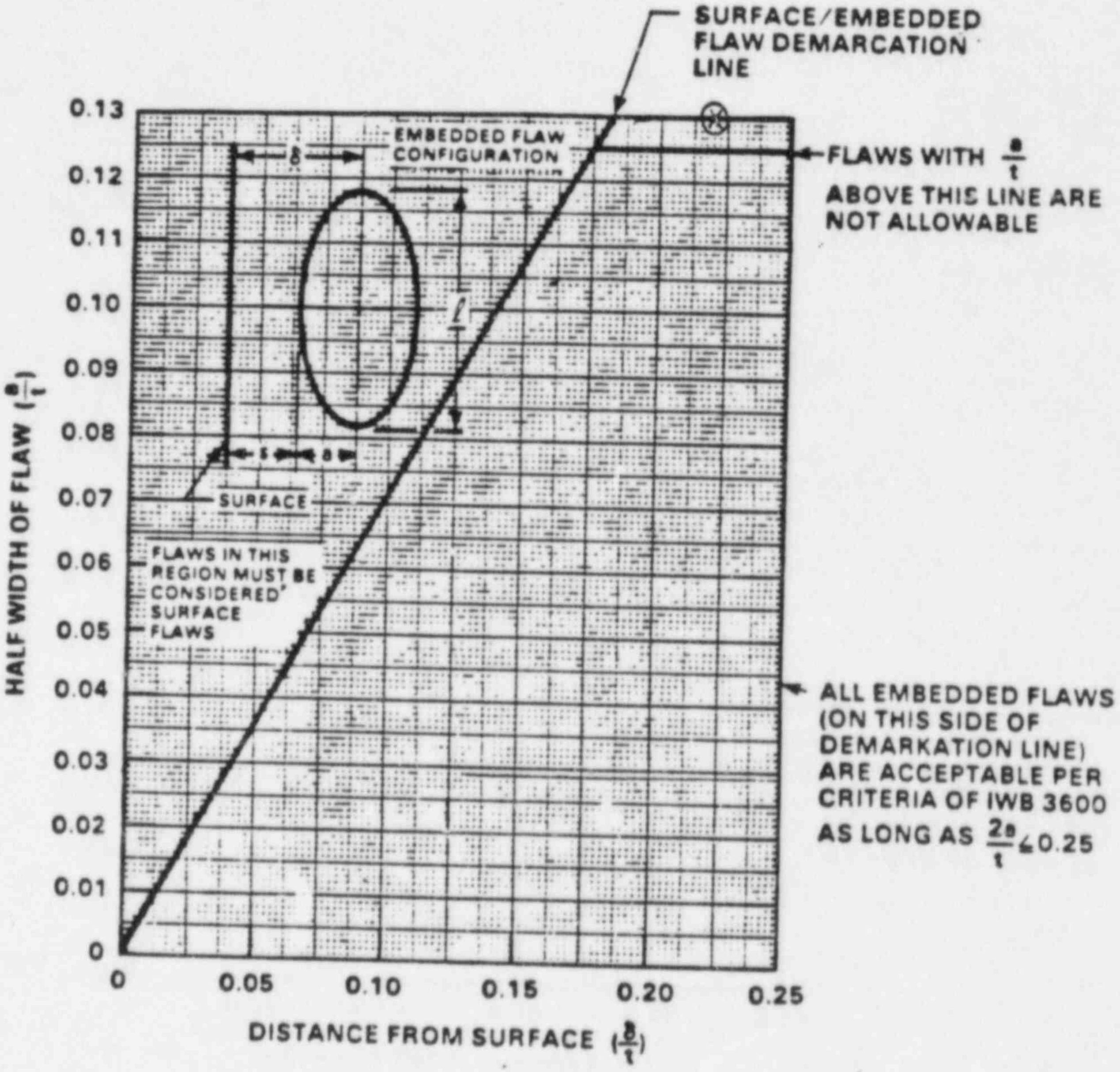


Figure 4-2 Inside Surface Flaw Evaluatin Charts - Circumferential Flaws in Tubesheet to stub barrel weld region (SGC-02)

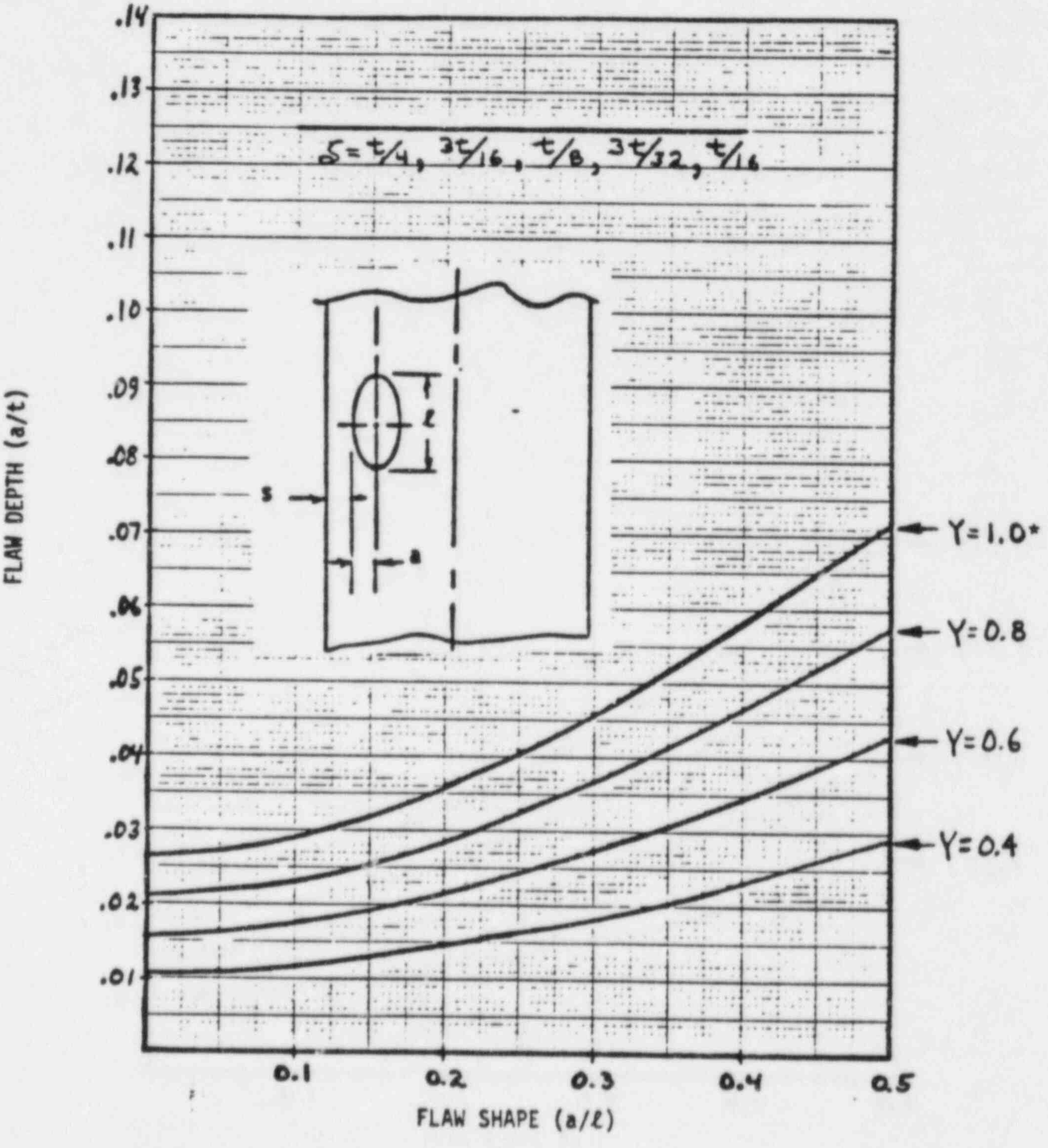


FIGURE 4-3 Acceptance Standards for Embedded Flaws, from Table IWB-3511-1

*Only Y = 1.0 curve applies to ASME Codes prior to 1980 Edition.

5. HANDBOOK CHARTS FOR BRAIDWOOD UNIT 1 STEAM GENERATOR

In this section flaw evaluation charts are provided for each of the regions of interest for the Braidwood Unit 1 model D-4 steam generators, as shown in Figure 5-1. The charts are provided in the following order:

- Upper shell to cone weld region (SGC-06)

Instructions and examples for use of the charts are contained in Section 4.

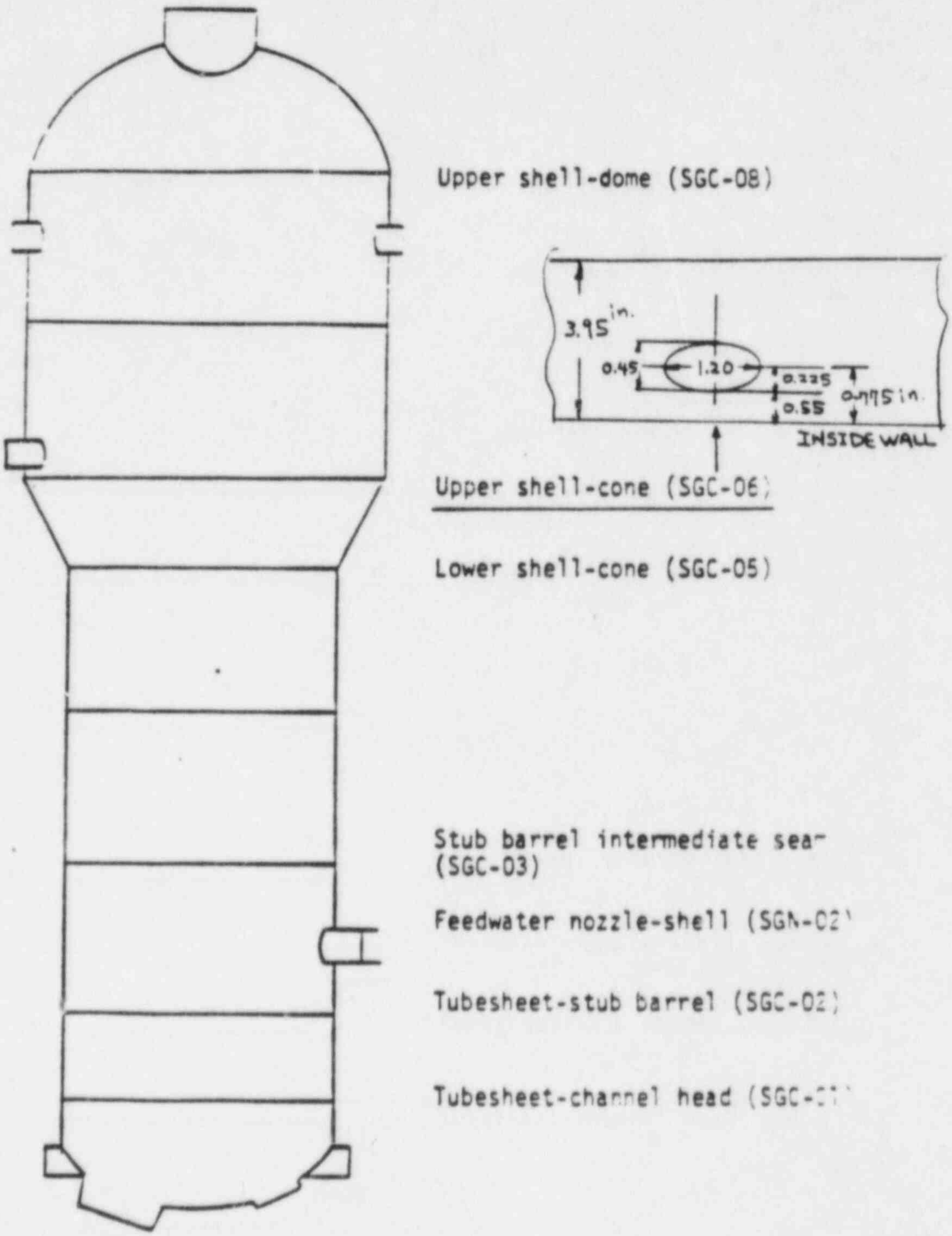


Figure 5-1 Schematic of Braidwood Unit 1 Steam Generator

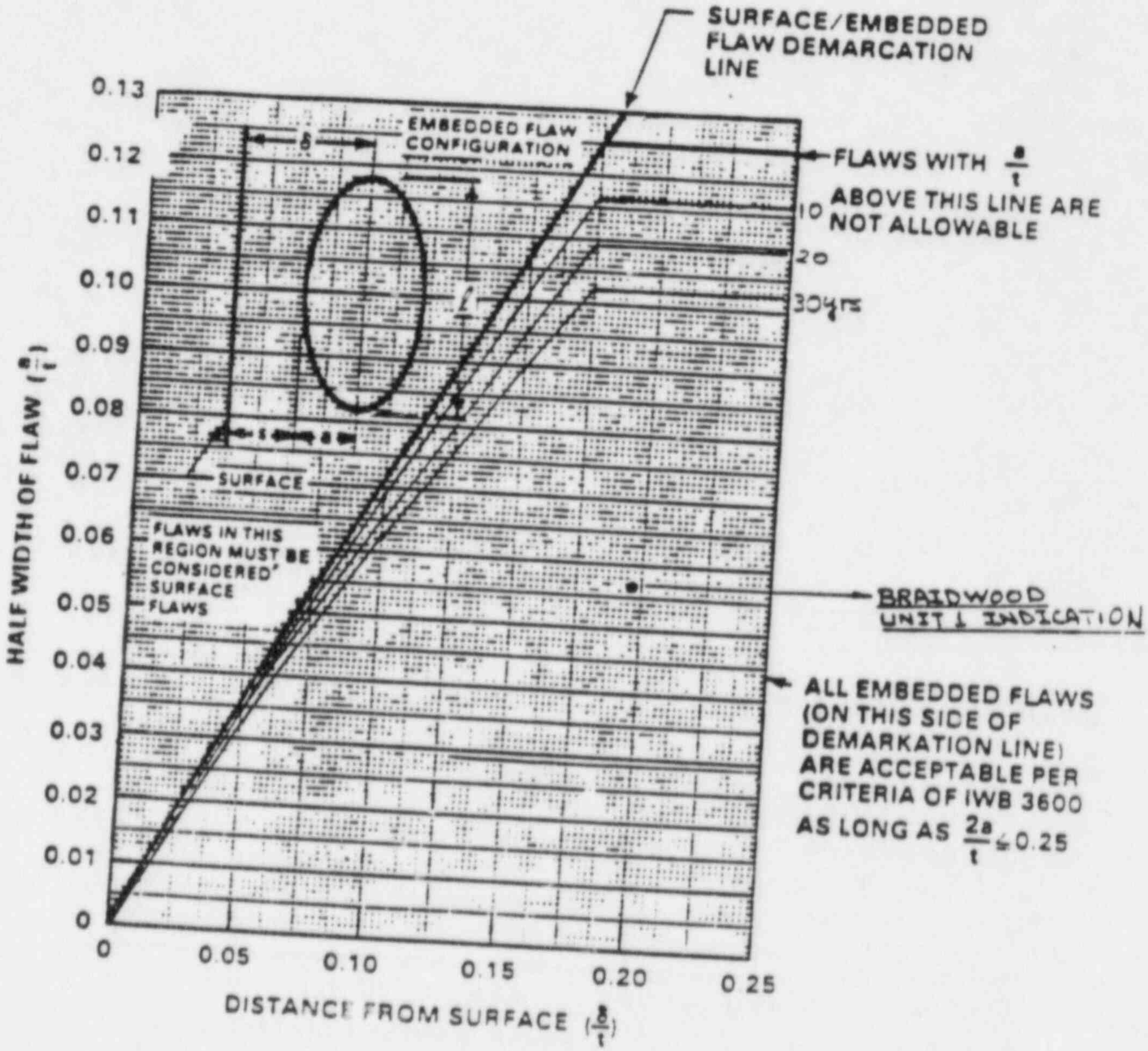


Fig. 2 Plotting of the Braidwood Unit 1 Indication in Embedded Flaw Evaluation Handbook of Byron Unit 2 S.G. at Welding Section SGC6

ATTACHMENT B

PRESSURIZER FRACTURE MECHANICS

FLAW EVALUATION HANDBOOK CHARTS FOR BYRON UNIT 2 PRESSURIZER

1. INTRODUCTION

During inspections of the Byron Unit 2, pressurizer a number of indications were discovered. These evaluation are believed to be slag however for completeness a series of flaw evaluations have been carried out to determine the size of indications which are acceptable by the rules of Section XI, paragraph IWB 3600. These evaluations should prove useful for assessment of the results of future inservice inspections.

The results of these evaluations have been developed in the form of handbook charts, presented separately for each of the following regions of the pressurizer:

- o Upper shell to upper middle shell weld (seam PC04)
- o Upper middle shell to lower middle shell weld (PC03)
- o Lower middle shell longitudinal weld (PL02)

The geometry of the Byron Unit 2 Model D-series 84 pressurizer is shown schematically in Figure 1-1. All of the regions for which evaluation charts have been developed are identified in this figure by weld seam number. The weld seam number is also identified in parentheses in the above list.

The flaw evaluation charts have been developed based on direct application of the criteria of IWB 3600. The notation used for surface and embedded flaws is shown in Figure 1-2.

The flaw evaluation charts for the lower middle shell longitudinal weld (POL2) have been provided in two forms. The case labelled "covered" is applicable to the portion of this vertical weld which is covered by water. The charts labelled "uncovered" are applicable to the portion of this weld which is not covered by the water and on which the pressurizer spray can impinge. Use of the charts labelled "covered" (which are more liberal) must be justified by the user, by providing assurance that the water level will remain above the region of interest for all the transients listed in Table 2-1.

There are two alternative sets of flaw acceptance criteria for continued service without repair in paragraph IWB-3600 of ASME Code Section XI [1]. Namely,

1. Acceptance Criteria Based on Flaw Size (IWB-3611)
2. Acceptance Criteria Based on Stress Intensity Factor (IWB-3612)

Both criteria are comparable in accuracy for thick sections, and the acceptance criteria (2) have been assessed by past experience to be generally less restrictive for thin sections, and for outside surface flaws in many cases. In all cases, the most beneficial criteria has been used, generally criteria (2).

CRITERIA BASED ON FLAW SIZE

The code acceptance criteria stated in IWB-3611 of Section XI are:

$a_f \leq .1\, a_c$ For normal conditions (upset & test conditions inclusive)

and $a_f \leq .5\, a_i$ For faulted conditions (emergency condition inclusive)

where

a_f = The maximum size to which the detected flaw is calculated to grow at the end of 40 years design life, or till the next inspection time.

a_c = The minimum critical flaw size under normal operating conditions (upset and test conditions inclusive)

a_i = The minimum critical flaw size for initiation of nonarresting growth under postulated faulted conditions. (emergency conditions inclusive)

To determine whether a flaw is acceptable for continued service without repair, both requirements must be met simultaneously. However, both criteria have been considered in advance before the charts were constructed. Only the most restrictive results were used in the charts.

CRITERIA BASED ON STRESS INTENSITY FACTOR

As mentioned in the preceeding paragraphs, the criteria used for the construction of the charts in this handbook are from the least restrictive of IWB 3611 or IWB 3612 of Section XI.

The term stress intensity factor (K_I) is defined as the driving force on a crack. It is a function of the size of the crack and the applied stresses, as well as the overall geometry of the structure. In contrast, the fracture toughness (K_{Ia}, K_{Ic}) is a measure of the resistance of the material to propagation of a crack. It is a material property, and a function of temperature.

The criteria is stated in IWB 3612:

$K_I \leq \frac{K_{Ia}}{\sqrt{10}}$ For normal conditions (upset & test conditions inclusive)

$K_I \leq \frac{K_{Ic}}{\sqrt{2}}$ For faulted conditions (emergency conditions inclusive)

where

K_I = The maximum applied stress intensity factor for the flaw size a_f to which a detected flaw will grow, during the conditions under consideration, at the end of design life, or to the next inspection.

K_{Ia} = Fracture toughness based on crack arrest for the corresponding crack tip temperature.

K_{Ic} = Fracture toughness based on fracture initiation for the corresponding crack tip temperature.

To determine whether a flaw is acceptable for continued service without repair, both criteria must be met simultaneously. However, both criteria have been considered in advance before the charts were constructed. Only the most restrictive results were used in the charts.

PRIMARY STRESS LIMITS

In addition to satisfying the fracture criteria, it is required that the primary stress limits of Section III, paragraph NB 3000 be satisfied. A local area reduction of the pressure retaining membrane must be used, equal to the area of the indication, and the stresses increased to reflect the smaller cross section. All the flaw acceptance tables provided in this handbook have included this consideration.

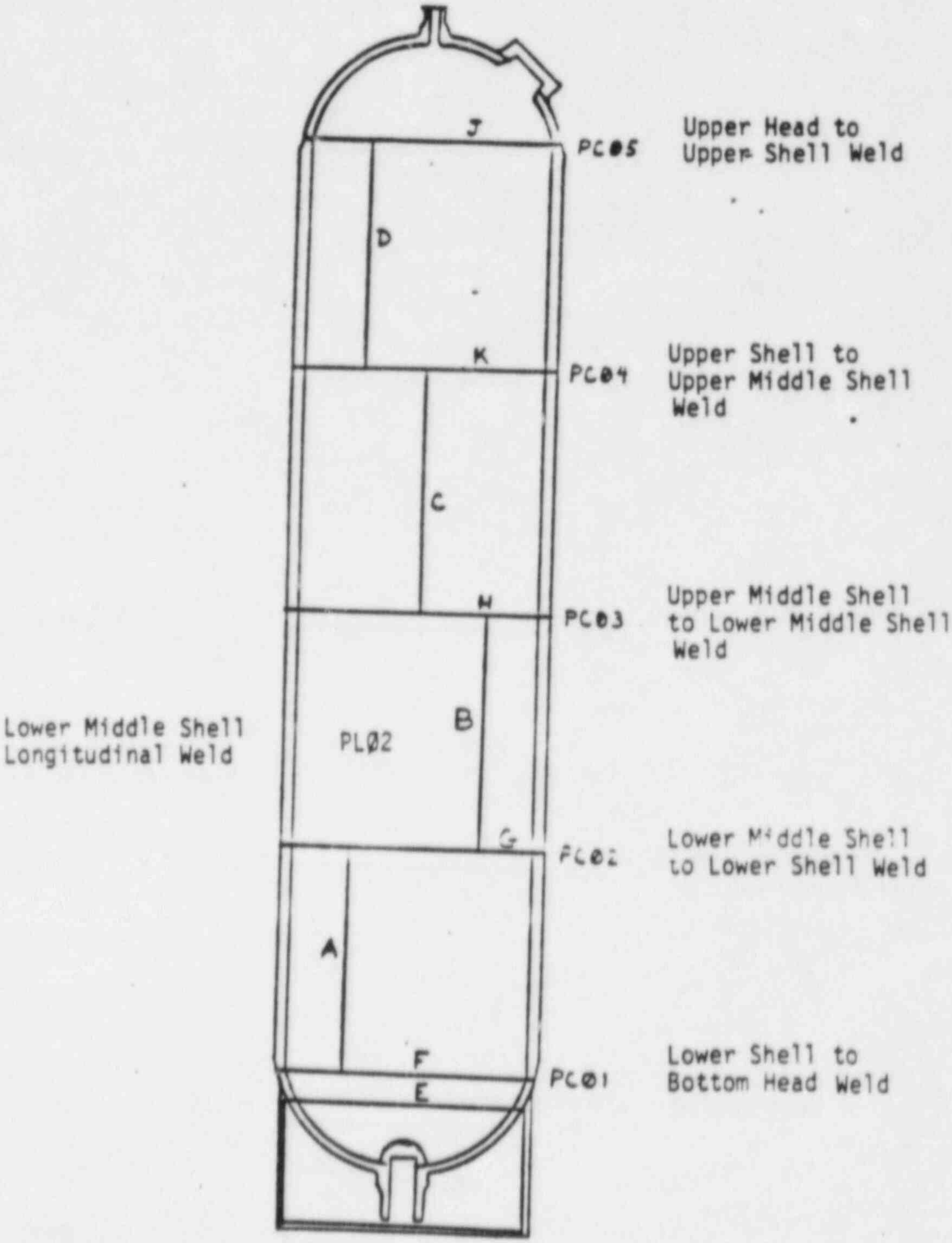
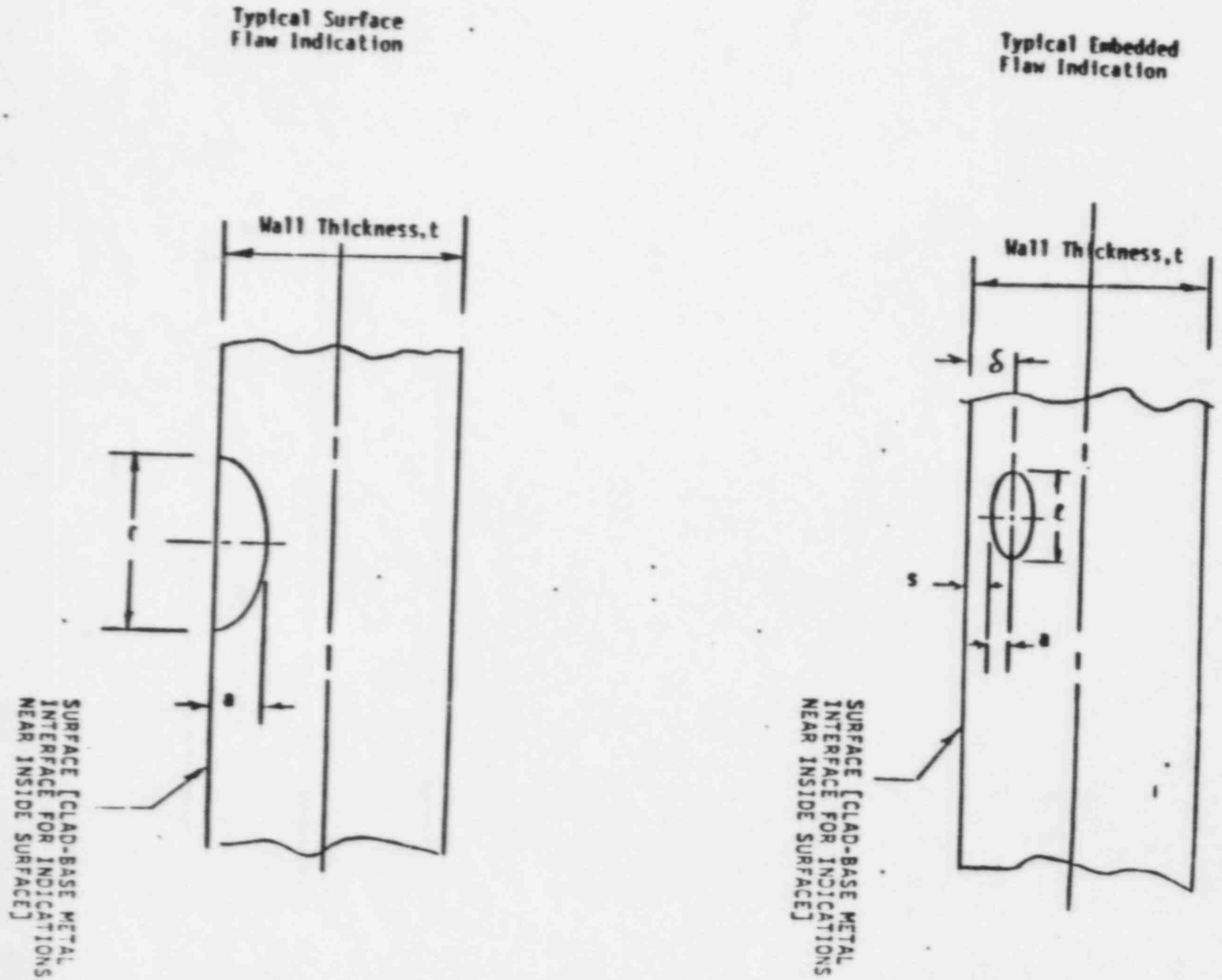


Figure 1-1 Schematic of Byron Unit 2 D-84 Series Pressurizer

FIGURE 1-2 Typical Notation of Surface and Embedded Flaw Indications



2. LOAD CONDITIONS, FRACTURE ANALYSIS METHODS AND MATERIAL PROPERTIES

TRANSIENTS FOR THE PRESSURIZER

The design transients for the Byron Unit 2 pressurizer are listed in Table 2-1. Both the minimum critical flaw sizes, such as a_c under normal operating conditions, or a_i under faulted conditions for criteria (1) of IWB-3611, and the stress intensity factors, K_I, for criteria (2) of IWB-3612, are a function of the stresses at the cross-section where the flaw of interest is located, along with the material properties. Therefore, the first step for the evaluation of a flaw indication is to determine the appropriate limiting load conditions for the location of interest.

The key parameters used in the evaluation of any indications discovered during inservice inspection are the critical depths, first, that for the governing normal, upset and tests conditions and second, that for the governing emergency and faulted conditions.

It should be noted here that the flaw evaluation charts have been constructed based on all the operational transients for the pressurizer. The pressure tests have been purposely omitted from the chart construction, because the severity of these tests can be mitigated by increasing the test temperature.

STRESS INTENSITY FACTOR CALCULATIONS

One of the key elements of the critical flaw size calculations is the determination of the driving force or stress intensity factor (K_I). This was done using expressions available from the literature. In all cases the stress intensity factor for the critical flaw size calculations utilized a representation of the actual stress profile rather than a linearization. This was necessary to provide the most accurate determination possible of the critical flaw size, and is particularly important for consideration of emergency and faulted conditions, where the stress profile is generally nonlinear and often very steep. The stress profile was represented by a cubic polynomial:

$$\sigma(x) = A_0 + A_1 \frac{x}{t} + A_2 \left(\frac{x}{t}\right)^2 + A_3 \left(\frac{x}{t}\right)^3$$

where x is the coordinate distance into the wall

t = wall thickness

σ = stress perpendicular to the plane of the crack

For the surface flaw with length six times its depth, the stress intensity factor expression of McGowan and Raymund [2] was used.

The stress intensity factor K_I (ϕ) can be calculated anywhere along the crack front. The point of maximum crack depth is represented by $\phi = 0$. The following expression is used for calculating K_I (ϕ):

$$K_I(\phi) = \frac{\sqrt{\pi a}}{Q} \left(\cos^2\phi + \frac{a^2}{c^2} \sin^2\phi\right)^{1/4} \left(A_0 H_0 + \frac{2}{\pi} \frac{a}{t} A_1 H_1 + \frac{1}{2} \frac{a^2}{t^2} A_2 H_2 + \frac{4}{3\pi} \frac{a^3}{t^3} A_3 H_3\right)$$

The magnification factors $H_0(\phi)$, $H_1(\phi)$, $H_2(\phi)$ and $H_3(\phi)$ are obtained by the procedure outlined in Reference [2].

The stress intensity factor calculation for a semi-circular surface flaw, (aspect ratio 2:1) was carried out using the expressions developed by Raju and Newman [3]. Their expression utilizes the same cubic representation of the stress profile and gives precisely the same result as the expression of McGowan and Raymund for the 6:1 aspect ratio flaw, and the form of the equation is similar to that of McGowan and Raymund above.

The stress intensity factor expression used for a continuous surface flaw was that developed by Buchalet and Bamford [4]. Again the stress profile is represented as a cubic polynomial, as shown above, and these coefficients as well as the magnification factors are combined in the expression for K_I below:

$$K_I = \sqrt{\pi a}\,[A_0 F_1 + \frac{2a}{\pi} A_1 F_2 + \frac{a^2}{2} A_2 F_3 + \frac{4}{3\pi} a^3 A_3 F_4]$$

where F_1, F_2, F_3, F_4 are magnification factors, available in [4].

The stress intensity factor calculation for an embedded flaw was taken from work by Shah and Kobayashi [5] which is applicable to an embedded flaw in an infinite medium, subjected to an arbitrary stress profile. This expression has been shown to be applicable to embedded flaws in a thick-walled pressure vessel in a recent paper by Lee and Bamford [6].

FRACTURE TOUGHNESS

The other key element in the determination of critical flaw sizes is the fracture toughness of the material. The fracture toughness has been taken directly from the reference curves of Appendix A, Section XI. In the transition temperature region, these curves can be represented by the following equations:

$$K_{Ic} = 33.2 + 2.806 \exp. [0.02 (T-RT_{NDT} + 100°F)]$$

$$K_{Ia} = 26.8 + 1.233 \exp. [0.0145 (T-RT_{NDT} + 160°F)]$$

where K_{IC} and K_{IA} are in ksi$\sqrt{in}$.

The upper shelf temperature regime requires utilization of a shelf toughness which is not specified in the ASME Code. A value of 200 ksi$\sqrt{in}$ has been used here. This value is consistent with general practice in such evaluations, as shown for example in reference [7], which provides the background and technical basis of Appendix A of Section XI.

The other key element in the determination of the fracture toughness is the value of RT_{NDT}, which is a parameter determined from Charpy V-notch and drop-weight tests. For this analysis, it was assumed that the RT_{NDT} is $60^{o}F$ These RT_{NDT} values are considered to be an upper bound for base and weld material in pressurizer based on earlier work and the guarantees which are available from fabricators.

CRITICAL FLAW SIZE DETERMINATION

The applied stress intensity factor (K_I) and the material fracture toughness values (K_{Ia} and K_{Ic}) were used to determine the allowable flaw size values used to construct the handbook charts. For normal, upset and test conditions, the critical flaw size a_c is determined as the depth at which the applied stress intensity factor K_I exceeds the arrest fracture toughness K_{Ia}.

For emergency and faulted conditions the minimum flaw size for crack initiation is obtained from the first intersection of the applied stress intensity factor (K_I) curve with the static fracture toughness (K_{Ic}) curve.

TABLE 2-1 PRESSURIZER TRANSIENTS - BYRON UNIT 2

	Transient	# of Cycles
1	Heatup	200
2	Cooldown	200
3	No Load	200
4	Full Load	13,200
5	Unit Loading	13,200
6	Turbine Roll Test	20
7	Step Load Increase	2000
8	Boron Concentration Equalization	26,400
9	Group #1 Umbrella	520
	Inadvertent Startup of an Inactive Loop	
	Loss of Load	
	Inadvertent S.I. Actuation	
	Large Step Load Decrease with Steam Dump	
	Normal Loop Shutdown	
	Normal Loop Startup	
10	Inadvertent Auxiliary Spray/Inadvertent RCS Depressurization	10
11	Inadvertent RCS Depressurization	540
12	OBE	400
13	Primary Side Hydrotest	10
14	Primary Side Leak Test	200
15	Secondary Side Leak Test	200

3. FATIGUE CRACK GROWTH

In applying code acceptance criteria as introduced in Section 1, the final flaw size a_f used in criteria (1) is defined as the minimum flaw size to which the detected flaw is calculated to grow at the end of the design life, or until the next inspection time. In this handbook, ten-, twenty-, and thirty- inspection periods are assumed.

These crack growth calculations have been carried out for all the regions of the Byron Unit 2 pressurizer for which evaluation charts have been constructed. This section will examine the calculations, and provide the methodology used as well as the assumptions.

The crack growth calculations carried out were rather extensive, because a range of flaw shapes have been considered, to encompass the range of flaw shapes which could be encountered in service.

ANALYSIS METHODOLOGY

The fatigue crack growth analysis procedure involves postulating an initial flaw at specific regions and predicting the growth of that flaw due to an imposed series of loading transients. The input required for a fatigue crack growth analysis is basically the information necessary to calculate the parameter K_I which depends on crack and structure geometry and the range of applied stresses in the area where the crack exists. Once K_I is calculated, the growth due to that particular stress cycle can be calculated by equations given below and in Figure 3-1. This increment of growth is then added to the original crack size, and the analysis proceeds to the next transient. The procedure is continued in this manner until all the transients known to occur in the period of evaluation have been analyzed.

The transients considered in the analysis are all the design transients contained in the pressurizer equipment specification, as shown in Section 2, Table 2-1. These transients are spread equally over the design lifetime of the vessel, with the exception that the preoperational tests are considered first. Faulted conditions are not considered because their frequency of occurrence is too low to affect fatigue crack growth.

Crack growth calculations were carried out for a range of flaw depths, and three basic types. The first type was a surface flaw with length equal to six times its depth, and whose analysis was previously reported. The second was a continuous surface flaw, which represents a worst case for surface flaws, and the third was an embedded flaw, with length equal to five times its width. For all cases the flaw was assumed to maintain a constant shape as it grew.

STRESS INTENSITY FACTOR EXPRESSIONS

Stress intensity factors were calculated from methods available in the literature for each of the flaw types analyzed. The surface flaw with aspect ratio 6:1 was analyzed using an expression developed by McGowan and Raymund [2] where the stress intensity factor K is calculated from the actual stress profile through the wall at the location of interest.

The maximum and minimum stress profiles corresponding to each transient are represented by a third order polynomial, such that:

$$\sigma(X) = A_0 + A_1 \frac{X}{t} + A_2 \frac{X^2}{t^2} + A_3 \frac{X^3}{t^3}$$

The stress intensity factor $K_I(\phi)$ can be calculated anywhere along the crack front. The point of maximum crack depth is represented by $\phi = 0$. The following expression is used for calculating $K_I(\phi)$.

$$K_I(\phi) = \frac{\sqrt{\pi a}}{Q} \left(\cos^2\phi + \frac{a^2}{c^2}\sin^2\phi\right)^{1/4} \left(A_0 H_0 + \frac{2}{\pi}\frac{a}{t} A_1 H_1 + \frac{1}{2}\frac{a^2}{t^2} A_2 H_2 + \frac{4}{3\pi}\frac{a^3}{t^3} A_3 H_3\right)$$

The magnification factors $H_0(\phi)$, $H_1(\phi)$, $H_2(\phi)$ and $H_3(\phi)$ are obtained by the procedure outlined in reference [2].

The stress intensity factor for a continuous surface flaw was calculated using an expression for an edge cracked plate [8]. The stress distribution is linearized through the wall thickness to determine membrane and bending stress and the applied K is calculated from:

$$K_I = \sigma_m Y_m \sqrt{a} + \sigma_B Y_B \sqrt{a}$$

The magnification factors Y_m and Y_B are taken from [8] and a is the crack depth.

For embedded flaws the stress intensity factor is much lower than for a surface flaw of equivalent size. This, combined with the fact that the fatigue crack growth rate for embedded flaws is much lower, leads to the conclusion that fatigue crack growth from embedded flaws is generally very low. The stress intensity factor calculation for an embedded flaw was taken from work by Shah and Kobayashi [5] which is applicable to an embedded flaw in an infinite medium, subjected to an arbitrary stress profile. This expression has been shown to be applicable to embedded flaws in a thick-walled pressure vessel in a recent paper by Lee and Bamford [6].

In regions where crack growth for embedded flaws exceeded one percent in 40 years, the crack growth results were factored directly into the embedded flaw evaluation charts.

CRACK GROWTH RATE REFERENCE CURVES

The crack growth rate curves used in the analyses were taken directly from Appendix A of Section XI of the ASME Code. Water environment curves were used for all inside surface flaws, and the air environment curve was used for embedded flaws and outside surface flaws.

For water environments the reference crack growth curves are shown in Fig. 3-1, and growth rate is a function of both the applied stress intensity factor range, and the R ratio (K_{min}/K_{max}) for the transient.

For $R<0.25$

$$(\Delta K_I < 19 \text{ ksi}\sqrt{\text{in}}) \quad \frac{da}{dN} = (1.02 \times 10^{-6}) \, \Delta K_I^{5.95}$$

$$(\Delta K_I > 19 \text{ ksi}\sqrt{\text{in}}) \quad \frac{da}{dN} = (1.01 \times 10^{-3}) \, \Delta K_I^{1.95}$$

where $\frac{da}{dN}$ = Crack Growth rate, micro-inches/cycle.

For $R>0.65$

$$(\Delta K_I < 12 \text{ ksi}\sqrt{\text{in}}) \quad \frac{da}{dN} = (1.20 \times 10^{-5}) \, \Delta K_I^{5.95}$$

$$(\Delta K_I > 12 \text{ ksi}\sqrt{\text{in}}) \quad \frac{da}{dN} = (2.52 \times 10^{-1}) \, \Delta K_I^{1.95}$$

For R ratio between these two extremes, interpolation is recommended.

The crack growth rate reference curve for air environments is a single curve, with growth rate being only a function of applied ΔK. This reference curve is also shown in Figure 3-1.

$$\frac{da}{dN} = (0.0267 \times 10^{-3}) \, \Delta K_I^{3.726}$$

where, $\frac{da}{dN}$ = Crack growth rate, micro-inches/cycle

ΔK_I = stress intensity factor range, ksi$\sqrt{\text{in}}$

$= (K_{Imax} - K_{Imin})$

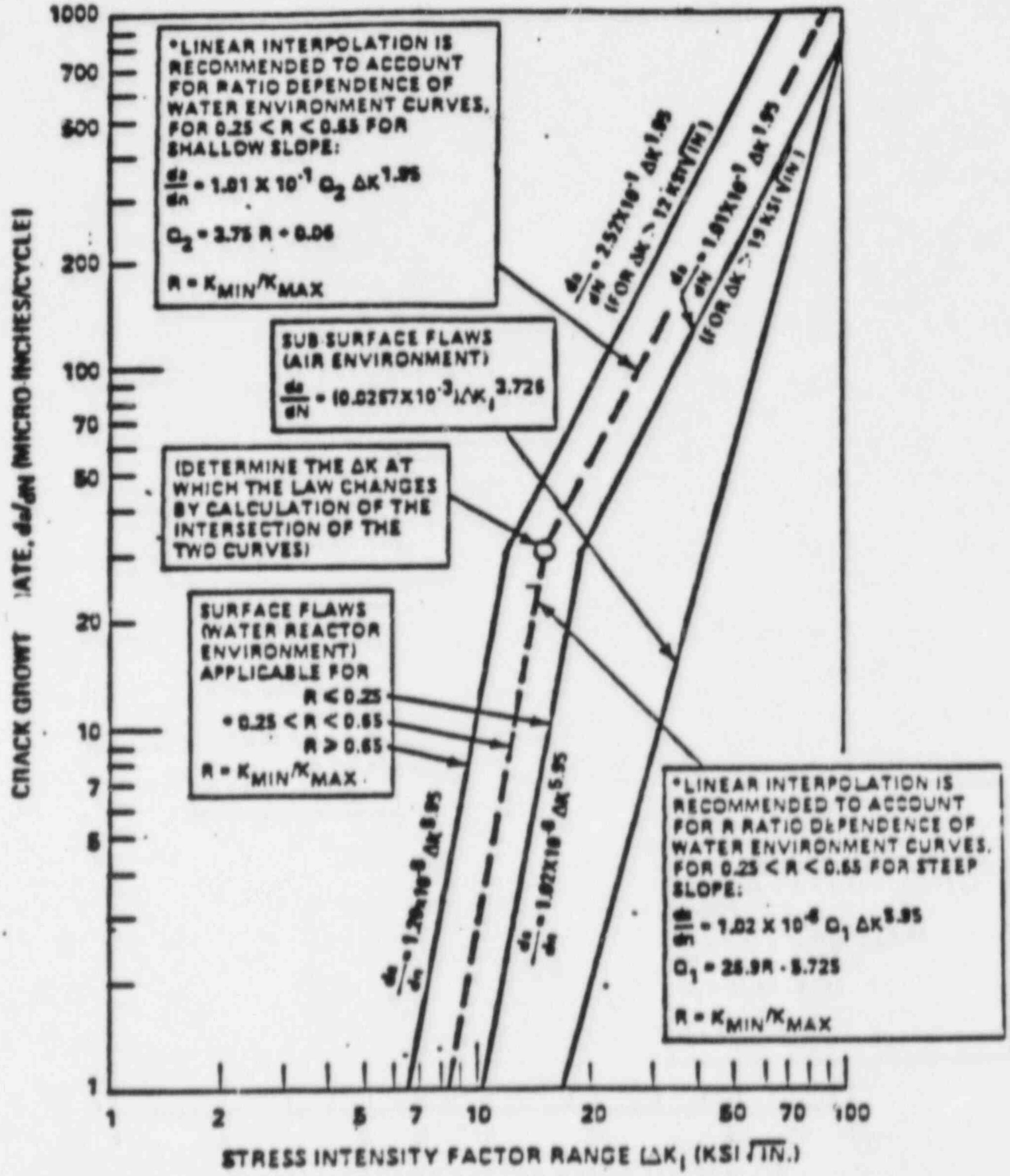


FIG. 3-1 REFERENCE FATIGUE CRACK GROWTH CURVES FOR CARBON AND LOW ALLOY FERRITIC STEELS

4. USE OF THE FLAW EVALUATION CHARTS

EVALUATION PROCEDURE

The evaluation procedures contained in ASME Section XI are clearly specified in paragraph IWB-3600. Use of the evaluation charts herein follows these procedures directly, but the steps are greatly simplified.

Once the indication is discovered, it must be characterized as to its location, length (ℓ) and depth dimension (a for surface flaws, 2a for embedded flaws), including its distance from the inside surface (S) for embedded indications. This characterization is discussed in further detail in paragraph IWA 3000 of Section XI.

The following parameters must be calculated from the above dimensions to use the charts (see Figure 1-2):

- o Flaw Shape parameter, $\frac{a}{\ell}$
- o Flaw depth parameter, $\frac{a}{t}$
- o Surface proximity parameter (for embedded flaws only), $\frac{\delta}{t}$

where

- t = wall thickness of region where indication is located
- ℓ = length of indication
- a = depth of surface flaw; or half depth of embedded flaw in the width direction
- δ = distance from flaw centerline to surface (for embedded flaws only) ($\delta = s + a$)
- S = smallest distance from edge of embedded flaw to surface

Once the above parameters have been determined and the determination made as to whether the indication is embedded or surface, then the two parameters may be plotted directly on the appropriate evaluation chart. Its location on the chart determines its acceptability immediately.

Although the use of the handbook charts is conceptually straight forward, experience in their development and use has led to a number of observations which will be helpful.

Surface Flaws

An example handbook chart for surface flaws is shown in Figure 4-1. The flaw indication parameters (whose calculation is described above) may be plotted directly on the chart to determine acceptability. The lower curve shown (labelled code allowable limit) is simply the acceptance standard from IWB 3500, which is tabulated in Section XI. If the plotted point falls below this line, the indication is acceptable without analytical justification having been required. If the plotted point falls between the code allowable limit line and the lines labelled "upper limits of acceptance by analysis" it is acceptable by virtue of its meeting the requirements of IWB 3600, which allow acceptance by fracture analysis. (Flaws between these lines would, however, require future monitoring per IWB 2420 of Section XI.) The analysis used to develop these lines is documented in this report. There are four of these lines shown in the charts, labelled 10, 20, 30 and 40 years. The years indicate for how long the acceptance limit applies from the date that a flaw indication is discovered, based on fatigue crack growth calculations.

As may be seen in Figure 4-1, the chart gives results for surface flaw shapes up to a semi-circular flaw ($a/\ell = 0.5$). For the unlikely occurrence of flaws which the value of a/ℓ exceeds 0.5, the limits on acceptance for $a/\ell = 0.5$ should be used. The upper limits of acceptance have been set at (a maximum of) twenty percent of the wall thickness in all cases.

Embedded flaws

An example evaluation chart for embedded flaws is shown in Figure 4-2. The heavy diagonal line in the figure can be used directly to determine whether the indication should be characterized as an embedded flaw or whether it is sufficiently close to the surface that it must be considered as a surface flaw (by the rules of Section XI). If the flaw parameters produce a plotted point below the heavy diagonal line, it is acceptable by analysis. If it is above the line, it must be considered a surface flaw and evaluated using the surface flaw chart in Figure 4-1.

The standards for flaw acceptance without analysis cannot be shown in the embedded flaw charts because of their generality. Therefore, they have been plotted separately in Figure 4-3. Note the change in standards with the 1980 code, when the standards became a function of the proximity to the surface, S.

Detailed examples of the use of the charts for both surface and embedded flaws are presented in the following sections.

Surface flaw Example

Suppose an indication has been discovered which is a surface flaw and has the following characterized dimensions:

$a = 0.12"$

$\ell = 1.2"$

$t = 3.13"$

The flaw parameters for the use of the charts are

$\frac{a}{t} = 0.0383\ (3.83\%)$

$\frac{a}{\ell} = 0.10$

Plotting these parameters on Figure 4.1 it is quickly seen that the indication is acceptable by analysis. To justify operation without repair it is necessary to submit this plot along with the Technical Basis document [1] to the regulatory authorities.

Embedded Flaw Example

A circumferential embedded flaw of 0.24 x 5.00", located within 0.2817" from the surface, was detected. Determine whether this flaw should be considered as an embedded flaw.

$$2a = 0.8138"$$
$$S = 0.2817"$$
$$\delta = S + a = 0.2817 + 1/2\ (0.8138) = 0.6886"$$
$$t = 3.13"$$
$$\ell = 5.0"$$

and,

$$a = 1/2 \times 0.8138"$$
$$= 0.4069"$$

Using Figure 4-2:

$$\frac{a}{t} = \frac{0.4069}{3.13} = 0.13$$

$$\frac{\delta}{t} = \frac{0.6886}{3.13} = 0.22$$

Since the plotted point (x) is below diagonal line, the flaw is considered embedded. The flaw is not acceptable, however, since the upper limit for allowable flaws was set at a/t = 12.5%, which corresponds to a total wall penetration ($\frac{2a}{t}$) of 25%.

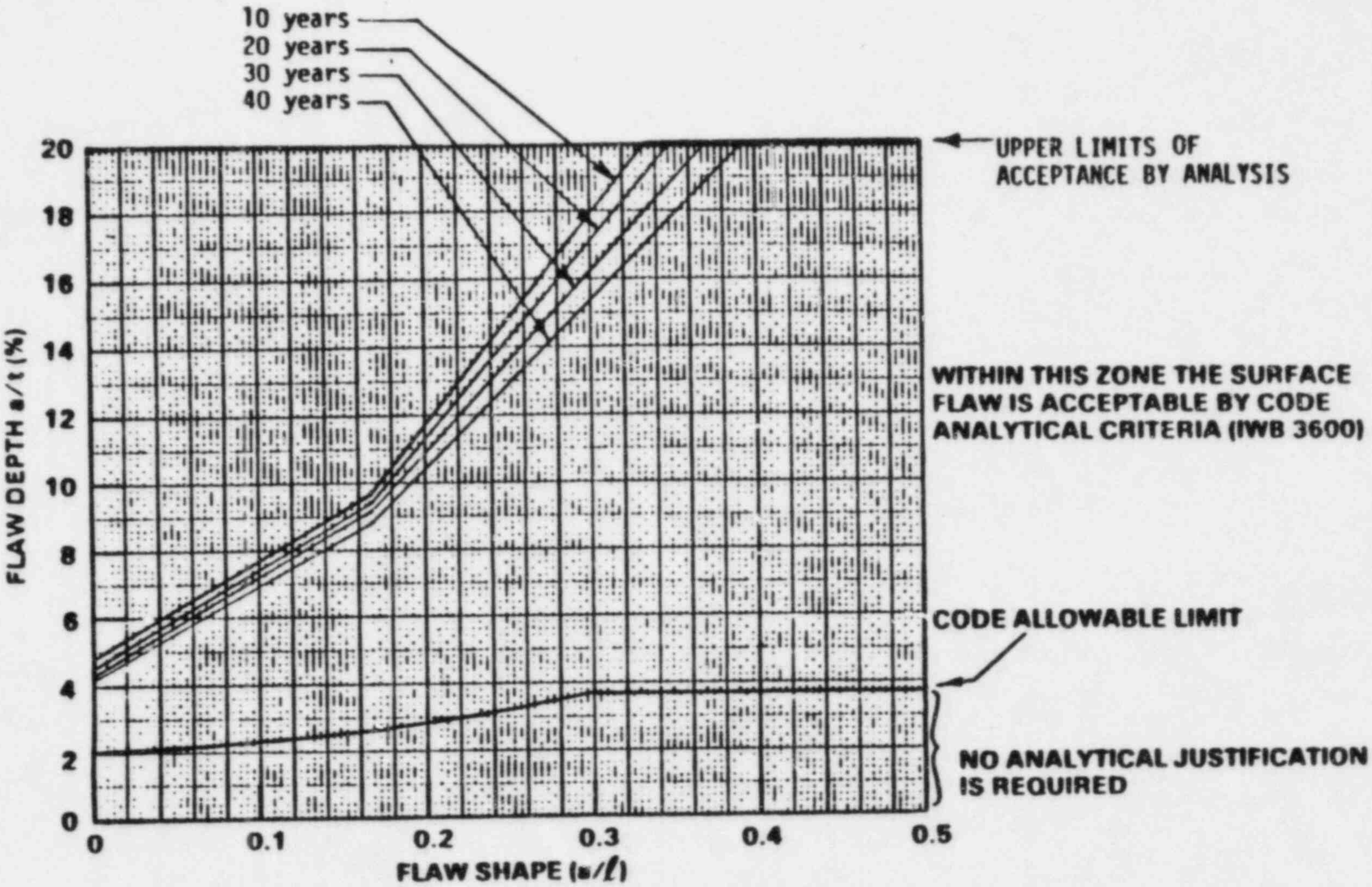


FIGURE 4-1 Example of Surface Flaw Evaluation Chart

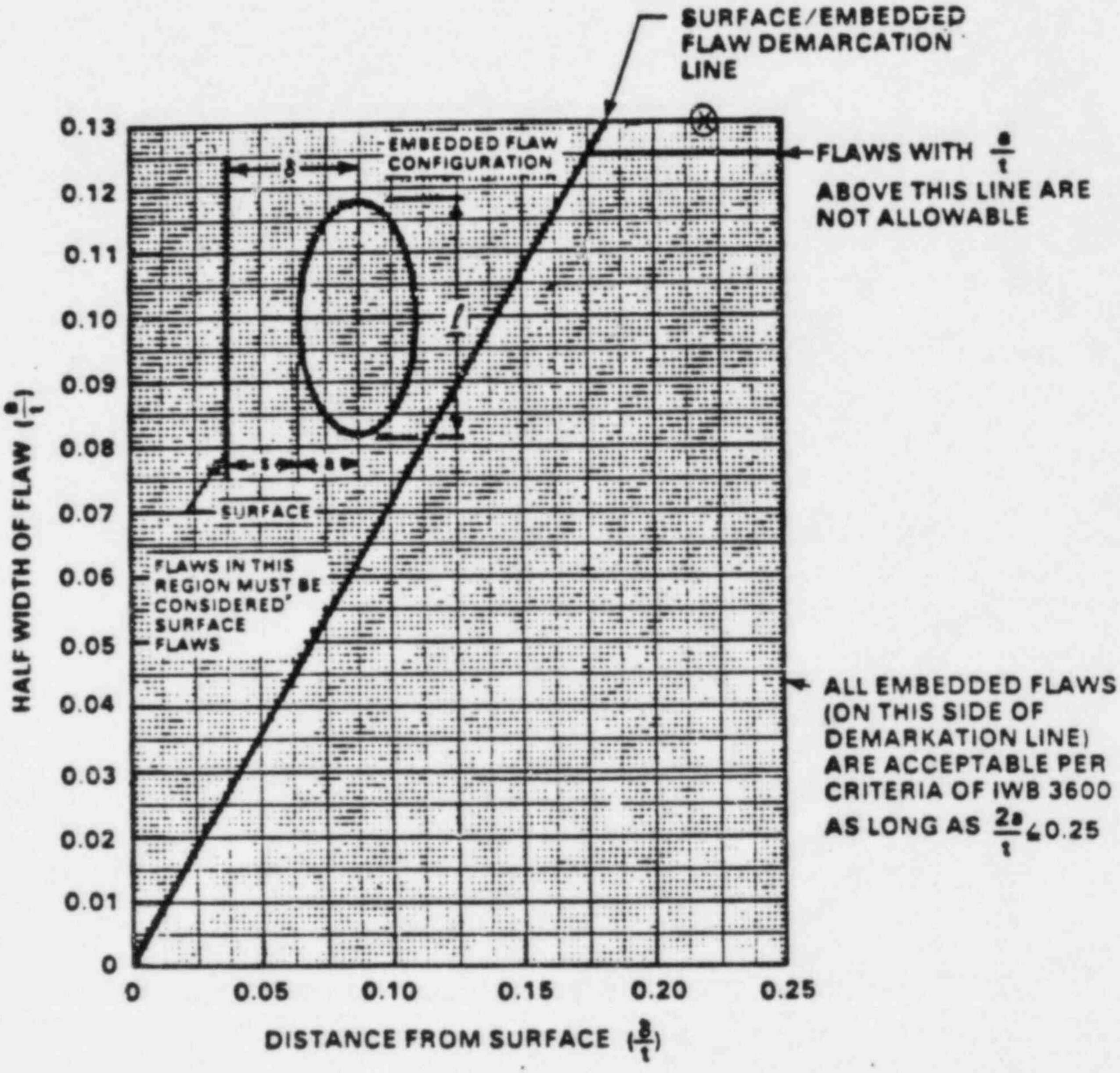


Figure 4-2 Example of Embedded Flaw Evaluation Chart

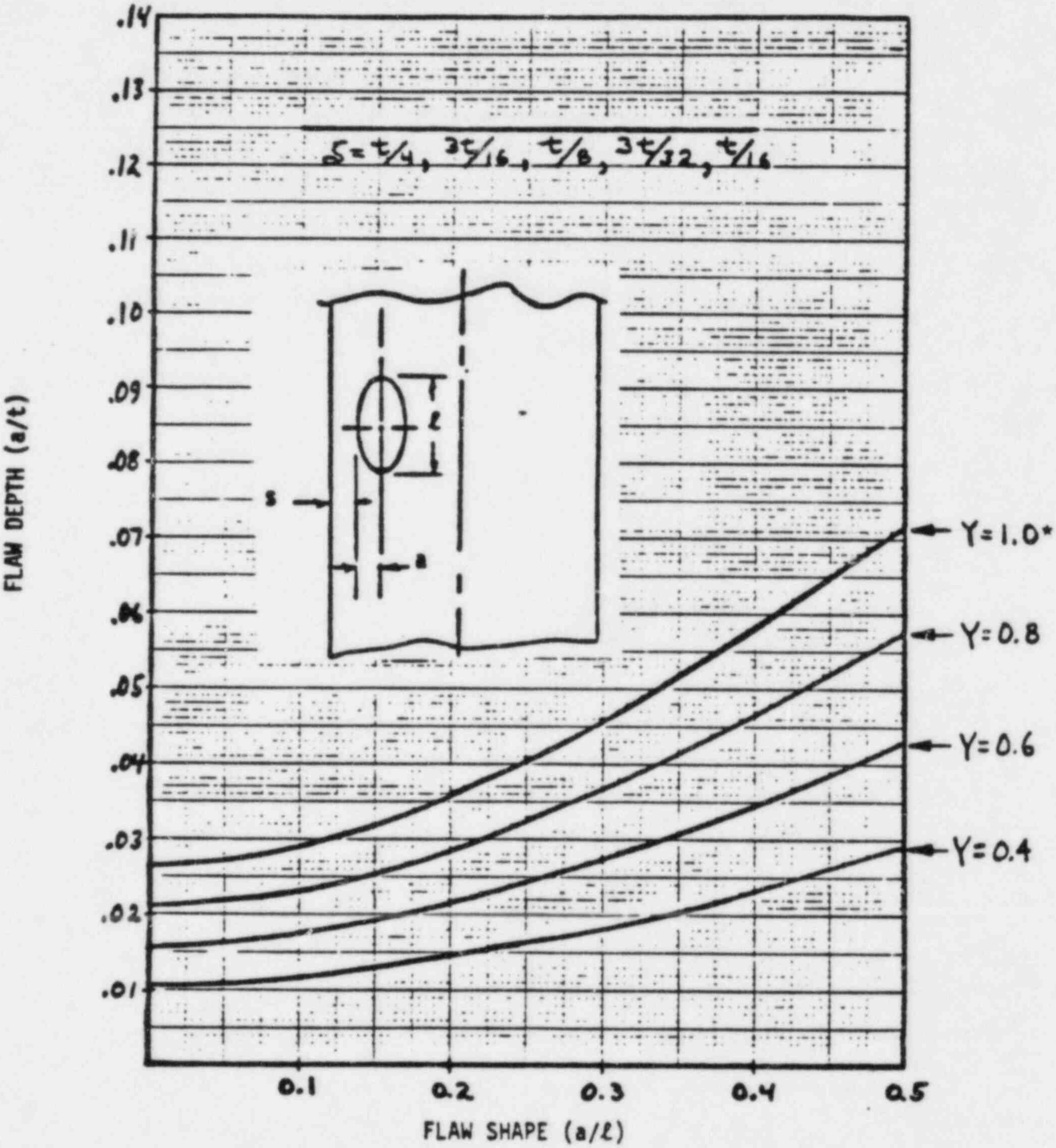


FIGURE 4-3 Acceptance Standards for Embedded Flaws, from Table IWB-3511-1

*Only Y = 1.0 curve applies to ASME Codes prior to 1980 Edition.

5. HANDBOOK CHARTS FOR BRAIDWOOD UNIT 1

In section flaw evaluation charts are provided for each of the regions of interest for the Braidwood Unit 1 model D-84 series pressurizer, as shown in Figure 5-1. The charts are provided in the following order:

° Upper middle shell to lower middle shell weld (PCO3)

Instructions and examples for use of the charts are contained in Section 4.

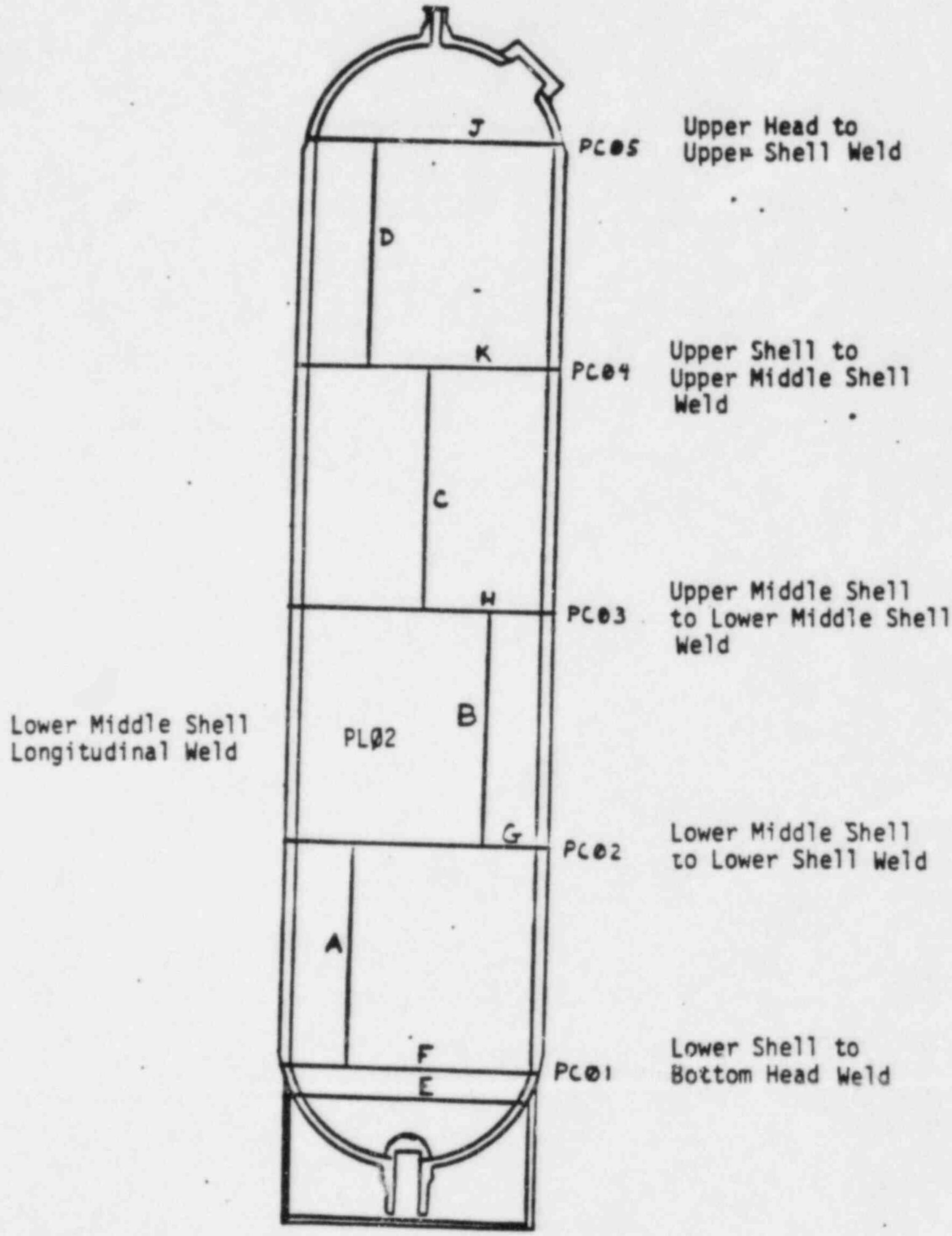
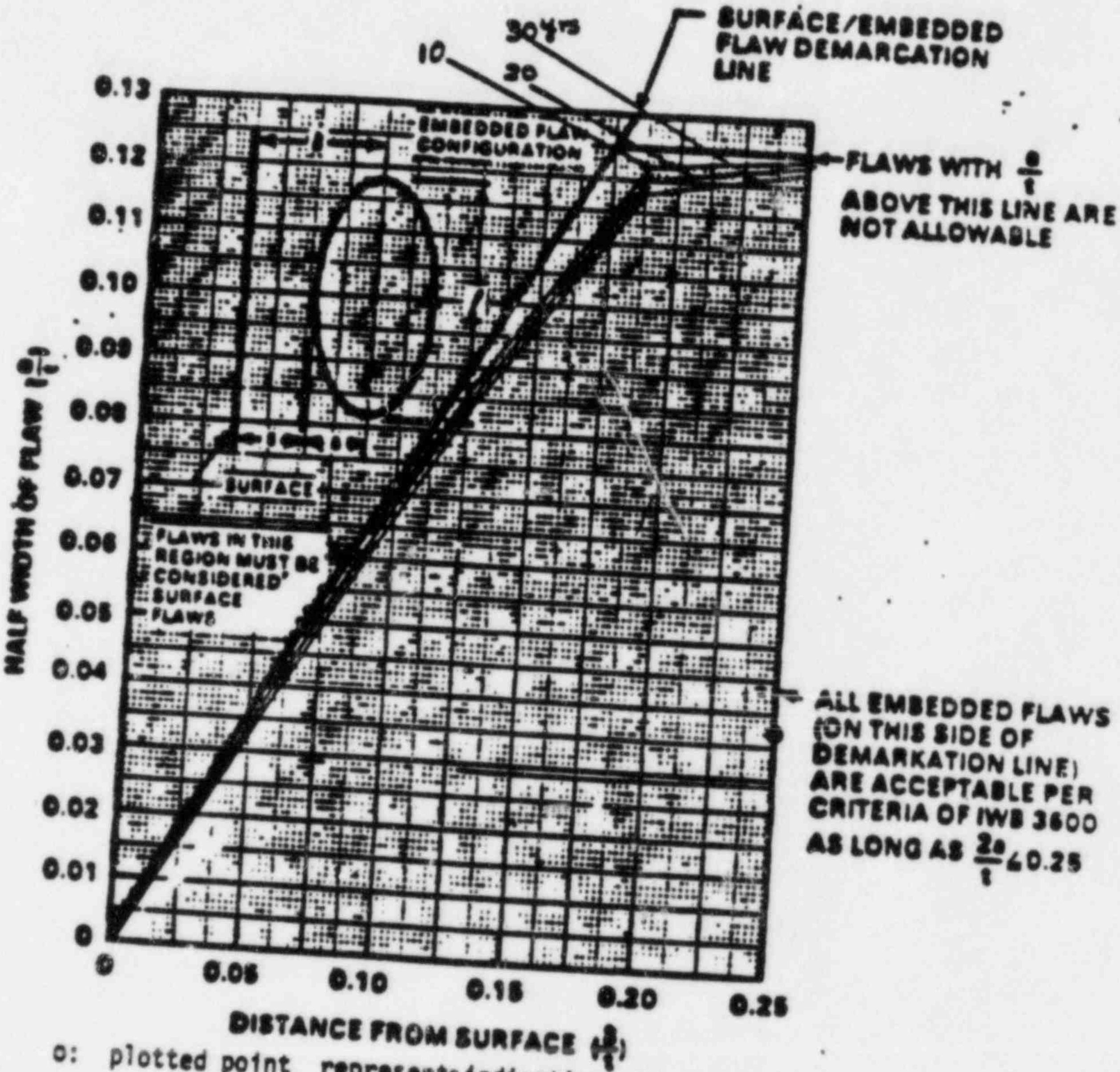


Figure 5-1 Schematic of Byron Unit 2 D-84 Series Pressurizer

BRAIDWOOD UNIT 1



o: plotted point represents indication from 1985 inspection

Figure 5-2 Embedded Flaw Evaluation Charts - Circumferential Flaw in Upper Middle Shell to Lower Middle Shell Weld (PC03/8C)

Note: flaw $\delta/t = 0.562$, $a/\ell = 0.15$, $a/t = 0.036$ is plotted at $\delta/t = 0.25$ conservatively.