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U.S. Nuclear Regulatory Commission
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Washington, DC 20555-0001

Braidwood Station, Units 1 and 2
Facility Operating License Nos. NPF-72 and NPF-77
NRC Docket Nos. 50-456 and 50-457

Byron Station, Units 1 and 2
Facility Operating License Nos. NPF-37 and NPF-66
NRC Docket Nos. 50-454 and 50-455

Subject: Relaxation Request for First Revised Order (EA-03-009) Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors

References:

(1) Letter from S. E. Kuczynski (Exelon Generation Company, LLC) to NRC, "Byron Station, Unit 1, 60-Day Response to First Revised NRC Order EA-03-009, 'Issuance of First Revised NRC Order (EA-03-009) Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors,'" dated June 22, 2005 (ADAMS Accession No. 051730156)

(2) Letter from K. J. Polson (Exelon Generation Company, LLC) to NRC, "Braidwood Station, Unit 2, 60-Day Response to First Revised NRC Order EA-03-009, 'Issuance of First Revised NRC Order (EA-03-009) Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors,'" dated July 5, 2005

On February 11, 2003, the NRC issued Order EA-03-009 for interim inspection requirements for reactor pressure vessel (RPV) heads at pressurized water reactor (PWR) facilities. On February 20, 2004, the NRC issued the First Revised Order EA-03-009 (the Order), which superseded Order EA-03-009. Revision 1 of the Order modified the requirements regarding nondestructive examination of the penetration nozzles.

During the Braidwood Station Unit 2 and Byron Station Unit 1 Spring 2005 refueling outages, Exelon Generation Company (EGC) completed nondestructive examinations (NDE) of the RPV head penetrations in accordance with the Order. As described in Reference 1, for Byron Station Unit 1, and Reference 2, for Braidwood Station Unit 2, these examinations were performed in advance, by one refueling outage, of the due date of February 11, 2008, for those RPV heads

categorized as "low susceptibility" in accordance with Section IV.A and IV.B of the Order. In addition, Braidwood Station Unit 2 and Byron Station Unit 1 have completed the 100% bare metal visual examinations (BMV) required by the Order.

EGC has determined that because of the physical configuration of certain Braidwood Station Unit 2 and Byron Station Unit 1 RPV nozzles, the required coverage specified in Section IV.C.(5)(b)(i) of the Order could not be met for these nozzles and therefore in accordance with Section IV.F.(2) of the Order, relaxation is requested because compliance with the Order would result in a hardship or unusual difficulty without a compensating increase in the level of quality and safety.

Specifically, for twelve Braidwood Station Unit 2 RPV penetration nozzles and six Byron Station Unit 1 RPV penetration nozzles, EGC is requesting relaxation from the Order by proposing to redefine the Section IV.C.(5)(b)(i) inspection area as "the volume of the penetration tube extending from two inches above the J-groove weld down to the lowest elevation that can be practically inspected." The details of the Braidwood Station Unit 2 Relaxation Request are contained in Attachment 1 and Attachment 2 provides the Relaxation Request for Byron Station Unit 1.

The technical justification for the Braidwood Station Unit 2 and Byron Station Unit 1 relaxation requests is provided in Attachment 4, "WCAP-16349-P, Revision 0, 'Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2.'" A non-proprietary version of WCAP-16349 is provided in Attachment 5.

Westinghouse has determined that information contained in Attachment 4 is proprietary, and is thereby supported by an affidavit signed by Westinghouse, the owner of the information. The affidavit sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the considerations listed in paragraph (b)(4) of 10CFR 2.390. Accordingly, it is respectfully requested that the information that is proprietary to Westinghouse be withheld from public disclosure in accordance with 10CFR 2.390, "Public inspections, exemptions, requests for withholding," of the Commission's regulations.

Attachment 3 contains Westinghouse authorization letter CAW-05-2070, its accompanying affidavit, Proprietary Information Notice, and Copyright Notice. Correspondence with respect to the copyright or proprietary aspects of the items listed above or the supporting Westinghouse affidavit, should reference CAW-05-2070 and should be addressed to B. F. Maurer, Acting Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company LLC, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

The attached relaxation requests are specific to Braidwood Station Unit 2 and Byron Station Unit 1; however, this submittal is being placed on the dockets for all four Braidwood Station and Byron Station units since the supporting Westinghouse WCAP-16349 report is applicable to the four units and may be used for the support of future relaxation requests for Braidwood Station Unit 1 and Byron Station Unit 2.

EGC requests that the review and approval of these relaxation requests be completed by September 8, 2006. If you have any questions regarding this letter, please contact David Chrzanowski at (630) 657-2816.

Respectfully,

Joseph A. Bauer
Manager – Licensing

Attachments:

1. Relaxation Request From NRC Order EA-03-009 Section IV, Paragraph C(5)(b)(i) – Braidwood Station, Unit 2

2. Relaxation Request From NRC Order EA-03-009 Section IV, Paragraph C(5)(b)(i) – Byron Station, Unit 1

3. Westinghouse Letter CAW-05-2070, "Application for Withholding Proprietary Information from Public Disclosure"

4. WCAP-16394-P, "Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation; Byron and Braidwood Units 1 and 2," Revision 0 (Proprietary Version)

5. WCAP-16394-NP, Non-Proprietary Version "Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation; Byron and Braidwood Units 1 and 2," Revision 0 (Non-Proprietary Version)

Attachment 1

Relaxation Request From NRC Order EA-03-009
Section IV, Paragraph C(5)(b)(i)

Braidwood Station Unit 2

Attachment 1
Relaxation Request From NRC Order EA-03-009
Section IV, Paragraph C(5)(b)(i)
Braidwood Station Unit 2

Component

Braidwood Station Unit 2 has seventy-nine (79) reactor pressure vessel (RPV) head penetration nozzles comprised of fifty-three (55) penetration tubes with thermal sleeves, twenty-three (23) locations without thermal sleeves, and one (1) vent penetration nozzle.

In accordance with Section IV.A of the First Revised NRC Order EA-03-009 (hereafter referred to as the Order), the Braidwood Station Unit 2 susceptibility category is classified as "low" based on a calculated value of less than eight effective degradation years (EDY) and no previous inspection findings prior to the Spring 2005 refueling outage (A2R11). Results of this examination were previously submitted by letter dated July 5, 2005 (ADAMS Accession No. ML051940300).

NRC Order EA-03-009 Applicable Examination Requirements

The requirements for the nonvisual NDE examinations (ultrasonic and eddy current) performed on the Braidwood Station Unit 2 RPV head during the A2R11 refueling outage are specified in the Order, Section IV, paragraphs C.(3) and C.(5)(b).

Paragraph IV.C.(3) of the Order states in part:

> *"...The requirements of paragraph IV.C.(5)(b) must be completed at least once prior to February 11, 2008, and thereafter, at least every 4 refueling outages or every 7 years, whichever occurs first."*

Paragraph IV.C.(5)(b) of the Order states:

> *"For each penetration, perform a nonvisual NDE in accordance with either (i), (ii) or (iii):*
>
> *(i) Ultrasonic testing of the RPV head penetration nozzle volume (i.e., nozzle base material) from 2 inches above the highest point of the root of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) to 2 inches below the lowest point at the toe of the J-groove weld on a horizontal plane perpendicular to the nozzle axis (or the bottom of the nozzle if less than 2 inches [see Figure IV-1]); OR from 2 inches above the highest point of the root of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) to 1.0-inch below the lowest point at the toe of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) and including all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level (including all residual and normal operation stresses) of 20 ksi tension and greater (see Figure IV-2). In addition, an assessment shall be made to determine if leakage has occurred into the*

annulus between the RPV head penetration nozzle and the RPV head low-alloy steel.

(ii) Eddy current testing or dye penetrant testing of the entire wetted surface of the J-groove weld and the wetted surface of the RPV head penetration nozzle base material from at least 2 inches above the highest point of the root of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) to 2 inches below the lowest point at the toe of the J-groove weld on a horizontal plane perpendicular to the nozzle axis (or the bottom of the nozzle if less than 2 inches [see Figure IV-3]; OR from 2 inches above the highest point of the root of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) to 1.0-inch below the lowest point at the toe of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) and including all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level (including all residual and normal operation stresses) of 20 ksi tension and greater (see Figure IV-4).

(iii) A combination of (i) and (ii) to cover equivalent volumes, surfaces and leak paths of the RPV head penetration nozzle base material and J-groove weld as described in (i) and (ii). Substitution of a portion of a volumetric exam on a nozzle with a surface examination may be performed with the following requirements:

1. On nozzle material below the J-groove weld, both the outside diameter and inside diameter surfaces of the nozzle must be examined.

2. On nozzle material above the J-groove weld, surface examination of the inside diameter surface of the nozzle is permitted provided a surface examination of the J-groove weld is also performed."

Requirement from Which Relaxation is Requested

In accordance with Section IV.F.(2) of the Order, relaxation from the above requirements is requested since compliance with the Order would result in a hardship or unusual difficulty without a compensating increase in the level of quality and safety.

Relaxation is requested from Section IV.C.(5)(b)(i) of the Order to perform ultrasonic testing (UT) of the RPV head penetrations inside the tube from 2 inches above the J-groove weld to:

- 2 inches below the lowest point of the toe of the J-groove weld (or the bottom of the nozzle if less than 2 inches) OR

- 1.0-inch below the lowest point of the toe of the J-groove weld and including all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level of 20 ksi tension and greater.

Based on the physical configuration of the nozzles and the limitations of the test equipment at Braidwood Station Unit 2, it is not possible to achieve the inspection coverage specified in Section IV.C.(5)(b)(i) of the Order for twelve RPV penetration nozzles on Braidwood Station Unit 2.

Relaxation is requested to redefine the inspection area for the affected penetrations as *"the volume of the penetration tube extending from 2" above the J-groove weld down to the lowest elevation that can be practically inspected."*

Reason for Request

The Braidwood Station Unit 2 RPV head penetration non-visual examinations were performed during the Spring 2005 (A2R11) refuel outage. The examinations were performed using Westinghouse/WesDyne equipment and procedures demonstrated through the Electric Power Research Institute (EPRI) Materials Reliability Project. Due to physical limitations and interferences associated with some of the penetrations, the examinations required by Section IV.C.(5)(b)(i) of the Order cannot be performed.

The nozzle inspections of the volume from the J-groove weld root up to two inches above the weld and the leakage assessments required under Section IV, Paragraph C.(5)(b)(i) of the Order were satisfied for all penetrations. The lower nozzle inspection volume (one inch below the lowest point at the toe of the J-groove weld including all RPV head penetration nozzle surfaces of 20 ksi tension and greater) required under Section IV, Paragraph C.(5)(b)(i) of the Order were satisfied for all but 12 penetrations. For the lower portion of the penetration defined in Figure IV-2 of the Order, required coverage one inch below the lowest point of the J-groove weld toe could not be achieved for 12 penetrations (i.e., numbers 40, 46, 66, 67, 68, 70, 71, 73, 74, 76, 77, and 78).

<u>Component Geometry</u>

For Braidwood Station Unit 2, the bottom of each RPV head penetration nozzle includes a threaded region approximately 1.00 inch long on the outside diameter along with a chamfered area at the inside diameter which extends approximately 0.76 inches from the bottom of the penetration tube (see Figure 1). The chamfered surface is machined at a 20° angle. In addition to the presence of the threaded and chamfered regions on all penetration tubes, 5 penetration tubes also have a threaded guide cone attached to the bottom of the penetration tube via the threaded connection along with a welded set screw and two tack welds.

The distance from the top of the thread relief to the bottom of the fillet of the J-groove weld, identified as "A" in Figure 1, varies based on location of the penetration in the RPV head. These distances are generally longer for penetrations at "inboard" locations and become progressively shorter for penetrations located farther away from the center of the RPV head. At the 12 subject penetration nozzles (i.e., numbers 40, 46, 66, 67, 68, 70, 71, 73, 74, 76, 77, and 78) the configuration is such that the distance from the lowest point at the toe of the J-groove weld to the bottom of the scanned region is less than the one inch lower boundary limit specified in section IV.C.5(b)(i) of the Order.

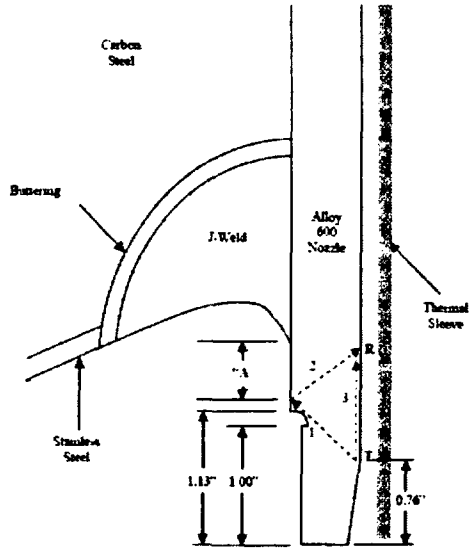

Figure 1
Illustration of Axially Oriented TOFD Examination Coverage on Braidwood Station Unit 2 Penetration Geometry (Including General Dimensions) at 0 Degrees

Examination Details

The inspection system used for Braidwood Station Unit 2 consisted of two probes to perform UT inspection of the penetration nozzles. The first probe type (Trinity Probe) was used to inspect nozzles that contained thermal sleeves (55 total). The second probe type (Open Housing Probe) was used to inspect nozzles without thermal sleeves (23 total). Both probes use axially oriented time-of-flight tip diffraction (TOFD) as the primary crack detection method. The vent line examination (1 total) is not included in the discussion as this examination area has a different geometry that was not limited.

The TOFD technique is a "pitch/catch" ultrasonic method, which uses two transducers (one a transmitter, and one a receiver) oriented along the vertical axis of the probe. The focus point of the TOFD beam is at the midpoint between the

upper and lower transducers. Longitudinal waves are transmitted into the tube at an angle by the transmitter (T) and reflect off the backside of the tube to a receiver (R), as shown in path "1-2" in Figure 1. A lateral wave also travels on the tube inside diameter (ID) surface between the transmitter and receiver as shown in path "3". The transmitting and receiving elements are mounted on a "shoe" with a probe center spacing of 0.925 inches. ID TOFD coverage is provided by the lateral wave to the elevation of the chamfer of the tube on the ID surface. With an axially oriented TOFD transducer pair in the Trinity probe, outside diameter (OD) coverage becomes completely effective at an elevation just above the top of the thread relief. The presence of the thread relief results in a slight masking of the ultrasound to the OD surface to an elevation conservatively estimated at 0.20 inches above the thread relief. In this area however, OD initiated degradation would be detected once the depth of the degradation exceeded the depth of the masked area. With a circumferentially oriented TOFD transducer pair, included in the Open Housing Scanner, OD coverage is extended to the elevation of the top of the chamfer, approximately 0.76 inches above the bottom of the tube. In the threaded region, cracks extending deeper than the threads will be detected.

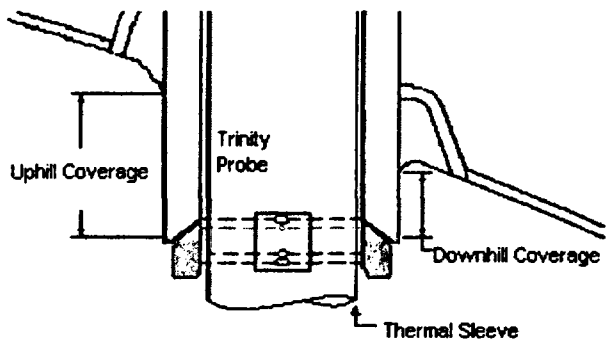

Figure 2
Trinity Probe Inspection Circumferential UT Coverage

The Open Housing Probe has a transducer pair with a 55-degree angle of refraction. The Trinity Probe (Figure 2) has a transducer pair with a 44-degree angle of refraction. Since the Trinity Probe transducers are a smaller size and spacing is less than that of the Open Housing Probe, the focus point of the Trinity Probe transducers are at a lower elevation (closer to the bottom of the tube) than the Open Housing Probe focus point when the probes reach the top of the ID chamfer. However, due to the difference in the refracted angles, the thread relief on the outside diameter (OD) of the tube interferes with the TOFD beam for the Trinity Probe. Due to this interference, there is a small area above the thread relief where the Trinity Probe cannot inspect. Figure 3 shows the lower transducer at the top of the ID chamfer and the OD thread relief interference with the TOFD beam. Figure 4 shows the probe at the minimum (higher) elevation where the TOFD beam is not interrupted by the thread relief.

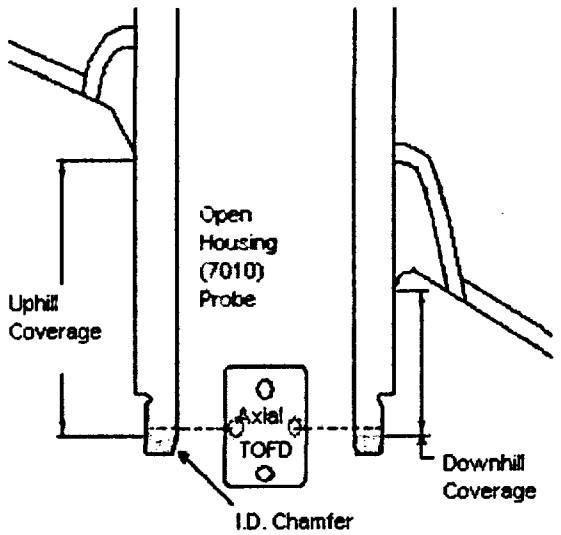

Figure 3
Open Housing Probe Circumferential UT Coverage

The shaded areas from both Figures 3 and 4 make up the total portion of the tube that cannot be inspected. The dimensions listed in Table 1 are based on the maximum coverage limitation of 1.13 inches shown in Figures 1 and 4.

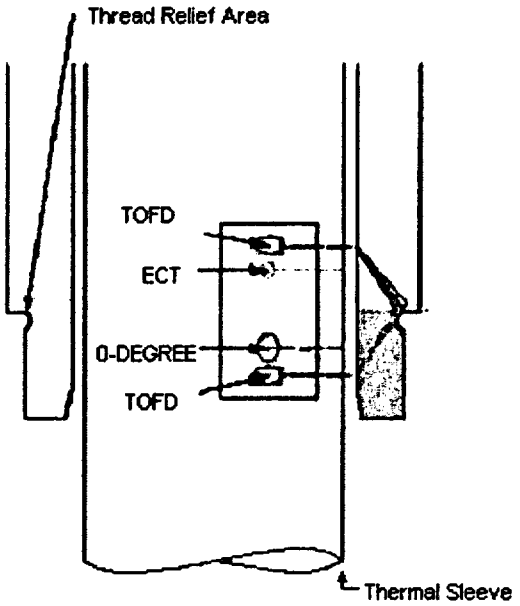

Figure 4
Trinity Probe – Lower TOFD Transducer to Top of Chamfer

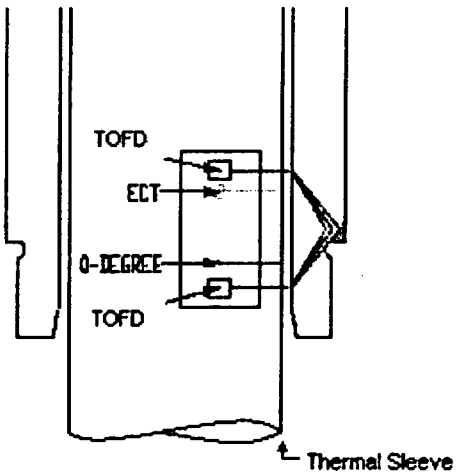

Figure 5
Trinity Probe – TOFD Beam Uninterrupted by Thread Relief

In addition to the axially oriented TOFD transducers (Figure 5), the Open Housing Probe has circumferentially oriented TOFD transducers that the Trinity Probe does not have. This circumferentially oriented TOFD signal allows the Open Housing Probe to inspect the tube down to the top of the ID chamfer. Also, with the Open

Housing Probe's circumferentially oriented transducers, the TOFD beam is not interrupted by the OD thread relief. The dimensions listed in Table 1 reflect the circumferential TOFD transducer coverage limitation of 0.76 inches due to the chamfered region. This is why the Open Housing Probe coverage is consistently greater than the Trinity Probe coverage. Figure 6 shows both the axial and circumferential Open Housing Probe TOFD coverage limitations. The shaded areas indicate the portions of the tube that cannot be inspected.

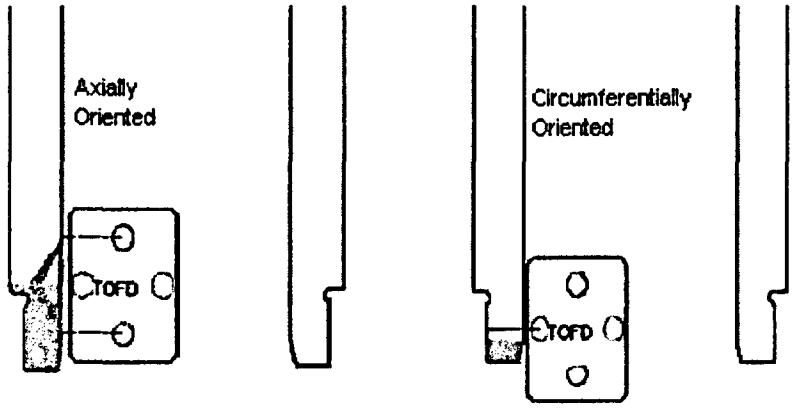

Figure 6
Open Housing Probe Coverage Limitations

The Order allows provisions for dye penetrant inspection. However, dye penetrant inspection would require extensive work under and around the RPV head. Based on electronic dosimetry readings from the examiner performing the vent nozzle manual inspection, the general area radiation level under the Unit 2 head during A2R11 was approximately 4.8 R/hr. General contact readings at the nozzles for Braidwood Station Unit 2 are historically 8 to 10 R/hr. Section IV.C.5(B)(iii)1. of the Order requires penetrant inspection on both the inside and outside diameter surfaces in order to be considered an acceptable substitution for ultrasonic examination. The threaded region on the outside diameter of the penetration tubes along with the presence of the welded guide funnels on penetration tube ends makes a dye penetrant examination on the lower section of the tube impractical. Therefore, performing dye penetrant inspections on the bottom nozzle area would result in significant radiation exposure to personnel without a compensating increase in the level of quality or safety.

Attachment 1
Relaxation Request From NRC Order EA-03-009
Section IV, Paragraph C(5)(b)(i)
Braidwood Station Unit 2

Table 1 contains information specific to the twelve penetrations for which relaxation is being requested. The values for Control Rod Drive Housing (CRDM) penetration hoop stress distributions at a point where the operating stress levels are less than 20 ksi tension (i.e., 20 Ksi Line) were extrapolated from the associated graphs contained in Figures 10 through 15, which are also contained in Appendix A of Topical Report, WCAP-16394-P, Revision 0, *"Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2,"* dated February 2005 (Attachment 4).

Table 1
Penetrations with Limited Examination Volume
(Shaded Areas Do Not Meet Order Requirements)

Penetration Number	Angle (Degrees)	A2R11 Inspection Coverage (Inches Below Weld)		20 Ksi line (Inches below J-Groove Weld)				Inspection Method
		ID	OD	Uphill Side		Downhill Side		
				ID	OD	ID	OD	
40	32.9	1.41	0.96	1.85	.61	.93	.43	Trinity
46	34.1	1.33	0.88	1.85	.61	.93	.43	Trinity
66	43.8	1.37	0.92	3.02	.62	.60	.47	Trinity
67	43.8	1.13	0.68	3.02	.62	.60	.47	Trinity
68	43.8	1.37	0.92	3.02	.62	.60	.47	Trinity
70	43.8	1.09	0.64	3.02	.62	.60	.47	Trinity
71	43.8	1.01	0.56	3.02	.62	.60	.47	Trinity
73	43.8	1.29	0.84	3.02	.62	.60	.47	Trinity
74	47.0	0.80	0.80	3.29	.54	.48	.44	Open Housing
76	47.0	0.92	0.92	3.29	.54	.48	.44	Open Housing
77	47.0	0.96	0.96	3.29	.54	.48	.44	Open Housing
78	47.0	0.68	0.68	3.29	.54	.48	.44	Open Housing

Proposed Alternative and Basis for Use

EGC proposes to define the lower boundary of the inspection volume for the affected RPV head penetration nozzles as: *"the volume of the penetration tube extending from 2" above the J-groove weld down to the lowest elevation that can be practically inspected."*

EGC performed UT examinations to the maximum extent possible and, for Braidwood Station Unit 2, meets all requirements of the Order with the exception of the twelve penetration tubes previously noted.

EGC was unable to completely comply with the requirements for UT inspection for twelve RPV penetration nozzles below the J-groove weld, due to the physical configuration of the nozzles and the limitations of the test equipment. The bottom ends of these nozzles are externally threaded and internally tapered. Loss of UT probe coupling due to the internal taper and/or disruption of the UT signal due to the external thread prevented UT data acquisition in a zone extending to approximately one-inch above the bottom of each nozzle.

Testing of portions of the nozzle significantly below the J-groove weld is not significant to the phenomena of concern. The phenomena that are of concern are leakage through the J-groove weld and circumferential cracking in the nozzle above the J-groove weld. This is appropriately reflected in the requirements of the Order (as stated in Section II above) that the testing extend to two inches above the J-groove weld. However, the Order also requires that testing be extended to:

- 2 inches below the lowest point of the toe of the J-groove weld (or the bottom of the nozzle if less than 2 inches) OR

- 1.0-inch below the lowest point at the toe of the J-groove weld and including all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level of 20 ksi tension or greater.

The nozzle is essentially an open-ended tube, and the nozzle wall below the J-groove weld is not part of the reactor coolant system pressure boundary.

The proposed inspection coverage is adequate because the cited inspection limitation for the RPV head penetration nozzles does not preclude full UT examination coverage of the portions of these nozzles that are of primary interest.

This can be assumed because:

- UT of the most highly stressed portion of the nozzle (the weld heat affected zone) is unaffected by this limitation.

- UT of the interference fit zone above the weld (for leakage assessment) is unaffected by this limitation, and cracks initiating in the unexamined bottom portion (non-pressure boundary) of the nozzle would be of minimal safety significance with respect to pressure boundary leakage or nozzle ejection.

- Since this portion of the nozzle is below the pressure boundary, any cracks would have to grow through a significant examined portion of the tube to reach the pressure boundary.

This proposed alternative is consistent with the analysis submitted in the industry topical report MRP-95, "Materials Reliability Program: Generic Evaluation of Examination Coverage Requirements for Reactor Pressure Vessel Head Penetration Nozzles," and the site-specific analysis in WCAP-16394-P. The zones of inspection selected are such that the stresses in the remaining uninspected zones are at levels for which Primary Water Stress Corrosion Cracking (PWSCC) is considered highly unlikely.

The major inherent conservatisms in WCAP-16394-P are summarized below:

Conservatism in Assumed Crack Geometry

It is understood that high stresses, on the order of the material yield strength, are necessary to initiate PWSCC. There is no known case of stress corrosion cracking of Alloy 600 below the yield stress. The yield strengths for wrought Alloy 600 head penetration nozzles are in the range of 37 ksi to 65 ksi. Weld metal yield strengths are generally higher. The yield strength of the head penetration nozzles for Braidwood Station Unit 2 varies from 36.5 ksi to 60.5 ksi. The stress level of 20 ksi is a conservative value below which PWSCC initiation is extremely unlikely.

Therefore, the assumption of any PWSCC crack initiation in the region of the penetration nozzle with a stress level of 20 ksi or less is conservative. The assumption of a through-wall flaw in these unlikely PWSCC crack initiation regions of the head penetration is an important additional conservatism, since the penetration tubes were inspected with maximum achievable coverage on the tube ID.

Flaw Propagation Calculations and Examination Coverage

A structural integrity evaluation was performed for the Byron and Braidwood Stations Unit 1 and Unit 2 reactor vessel head penetrations under WCAP-16394-P. The basis of this analysis is a detailed three-dimensional elastic-plastic finite element stress analysis of several penetration locations, which considers all the pertinent loadings on the penetration, and a fracture analysis using the crack growth rates recommended by the EPRI Topical Report "Materials Reliability Program (MRP) Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick Wall Alloy 600 Material (MRP-55) Revision 1." A series of crack growth calculations were performed presuming a flaw where the lower extremity of this initial through wall flaw is conservatively postulated to be located on the penetration nozzle where either the inside or outside surface hoop stress drops below 0 ksi. The results of these calculations provided the estimated remaining operating cycles that would elapse before a postulated flaw in the unexamined area of the penetration nozzle would propagate into the pressure boundary formed by the J-groove weld.

The postulated flaw at the lower extent of coverage was located on the flaw growth curve associated with the penetration angle. For those penetrations that do not have a flaw growth curve specific to the tube penetration angle, a conservative curve (nearest the lower penetration angle) was used. The time it would take for the postulated flaws to intersect the weld metal for the minimum coverage achieved was then determined.

Braidwood Station Unit 2 past operating cycles have been approximately 18 months (1.5 calendar years or 1.29 Effective Full Power Years (EFPY) per cycle based on historical data). Braidwood Station Unit 2 will remain on 18-month cycles based on the current long-term schedule. Conservatively using 1.45 EFPY for the remaining four operating cycles until the next required examination, there are 5.8 EFPY between the A2R11 examinations until the next scheduled examination required by the Order. In accordance with the current Order requirements (perform examination within every four refueling outages or seven years, whichever occurs first), the next inspection for the Braidwood Station Unit 2 RPV penetrations must be completed by the A2R15 outage, which is currently scheduled in April of 2011.

Based on A2R11 examination results (see Table 1), the worst-case minimum distance below the J-groove weld to the top of the zone that could not be inspected was determined to be 0.56 inches on the downhill side of the penetration nozzle #71. To account for the inspection tolerance of the inspection equipment (0.04 inches), an axial through-wall flaw was conservatively postulated to be located at 0.50 inches below the J-groove weld in the crack propagation calculation for the downhill side of the penetration nozzle. Using the applicable crack growth rate for the penetration (Figure 8), it would take 5.9 EFPY for the postulated flaw to propagate from that location to the bottom of the J-groove weld, which would occur after the next scheduled inspection.

For the subject penetrations that EGC is seeking relaxation, Figures 7 through 9 (WCAP-16394-P, Figures 6-12, 6-14, and 6-15) provide results of the calculation. The calculation demonstrates that the minimum time for a flaw to propagate from that location to the bottom of the J-groove weld would be greater than four operating cycles. The results of the flaw propagation calculation indicate that, even if a flaw were to occur in the region of the penetration nozzle not being inspected, there would be adequate opportunity for detection prior to the crack reaching the reactor coolant system pressure boundary. The results demonstrate that the extent of the proposed inspection coverage would provide reasonable assurance of the structural integrity of the Unit 2 RPV head penetration nozzles and the J-groove welds.

Conclusion

In all cases, the measured coverage is adequate to allow Braidwood Station Unit 2 to continue to operate prior to the hypothetical flaws reaching the J-groove weld. In accordance with the current Order requirements, the next examination required for the Braidwood Station Unit 2 RPV penetrations would be completed prior to flaw propagation into J-groove welds.

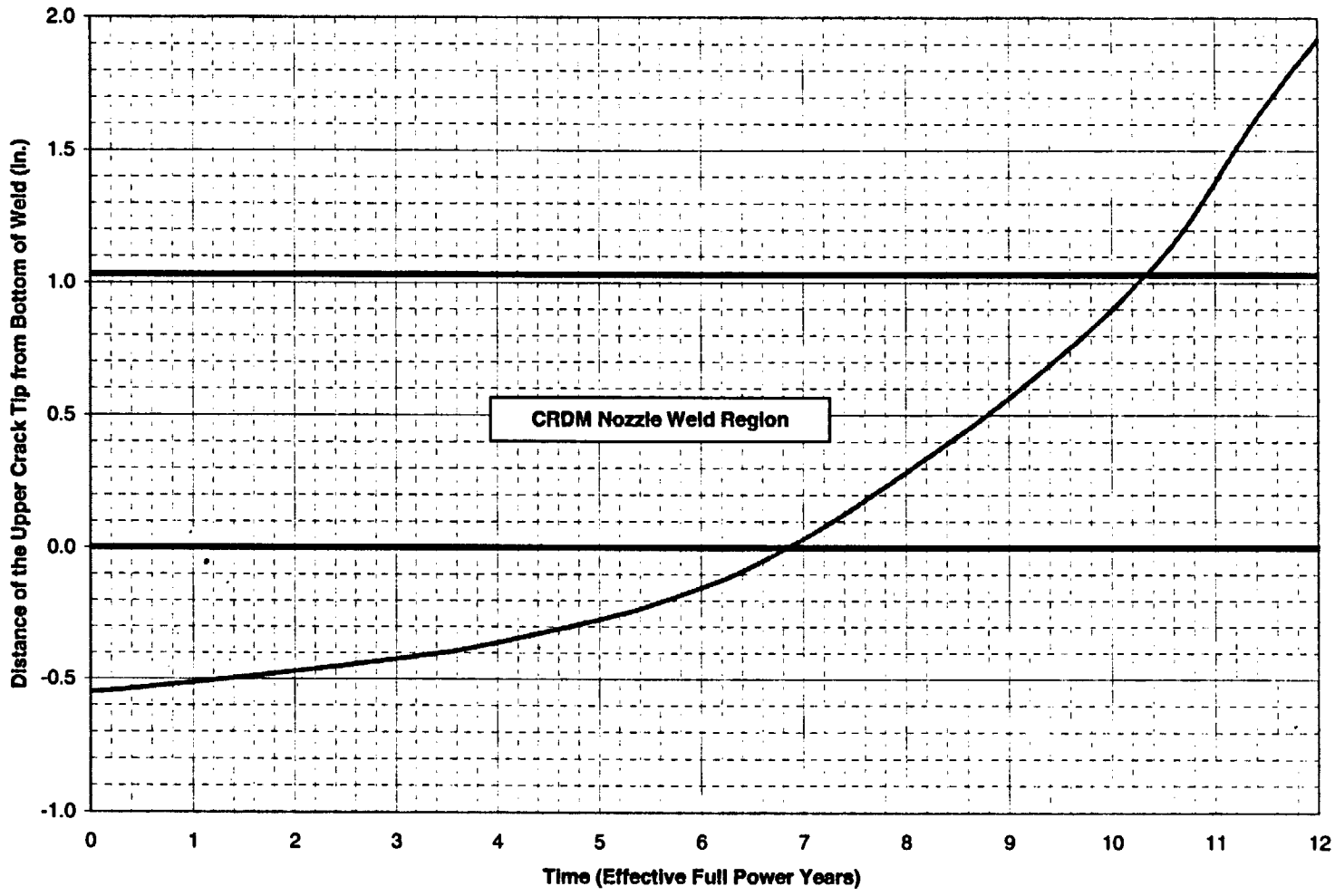

Figure 7
Through -Wall Longitudinal Flaw in the 25.4 Degree CRDM Row Downhill Side - Crack Growth Prediction
(Applies to Penetrations 40 and 46)

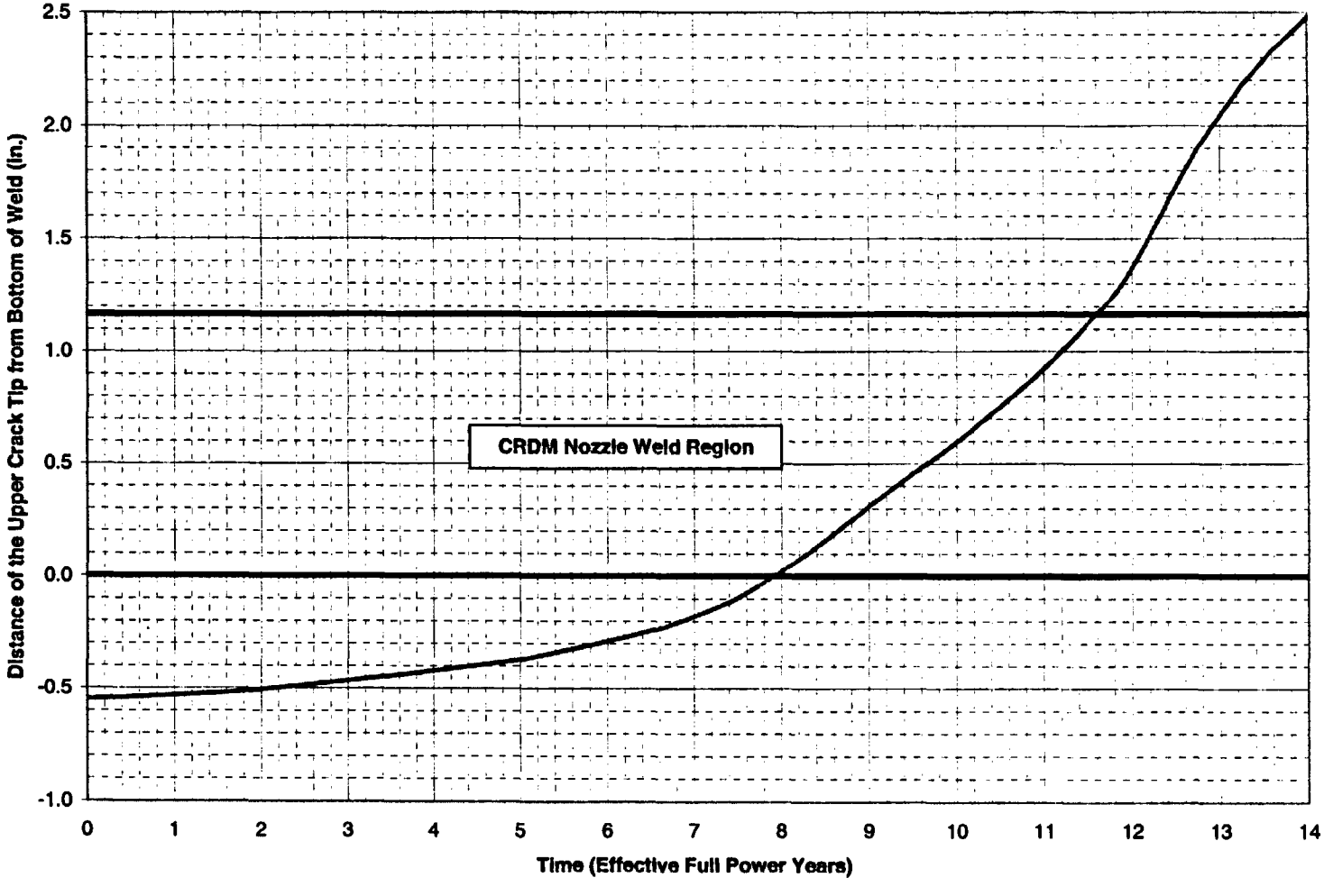

Figure 8
Through -Wall Longitudinal Flaw in the 43.8 Degree CRDM Row Downhill Side - Crack Growth Prediction
(Applies to Penetrations 66, 67, 68, 70, 71, and 73)

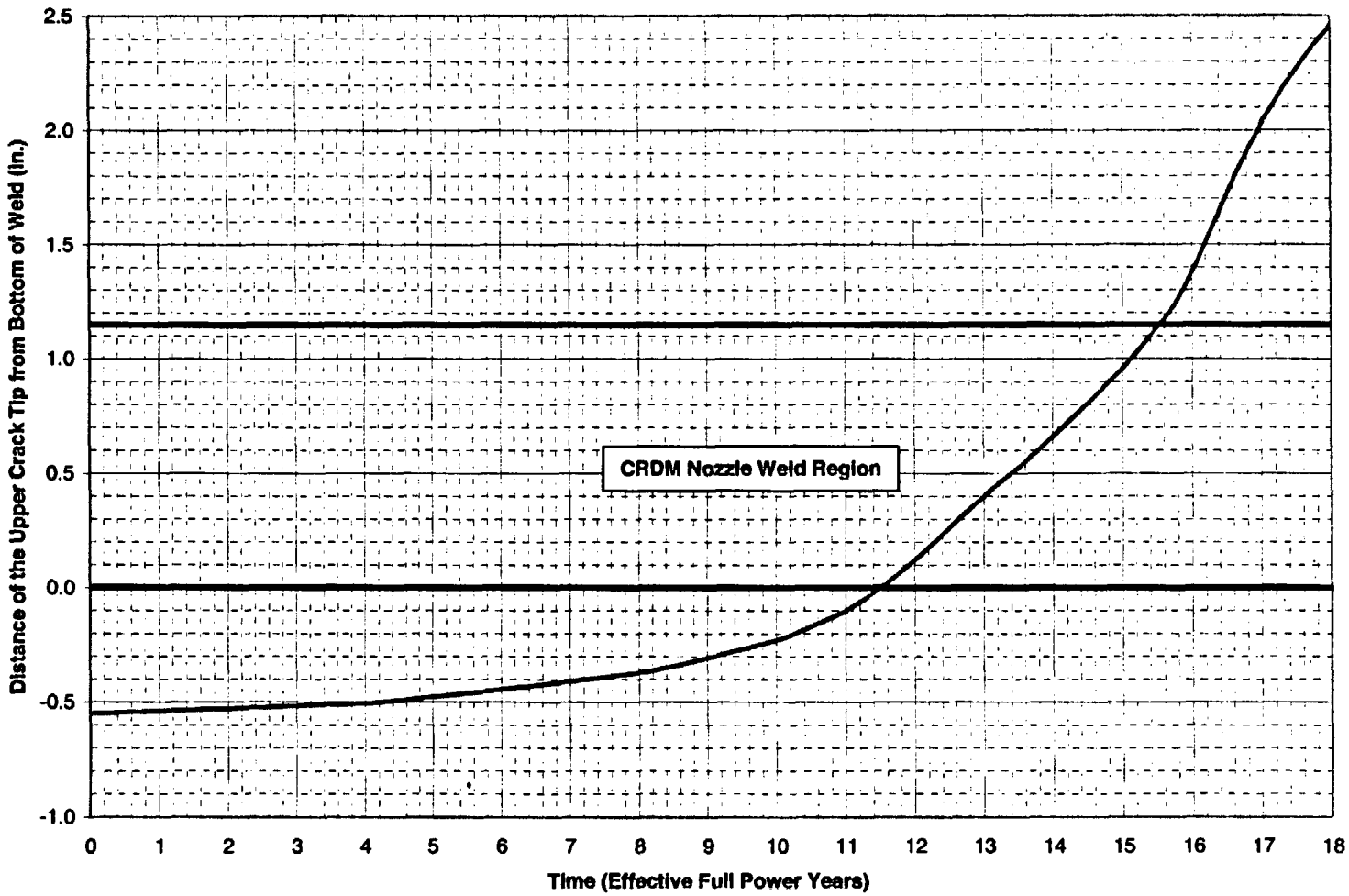

Figure 9
Through -Wall Longitudinal Flaw in the 47.0 Degree CRDM Row Downhill Side - Crack Growth Prediction
(Applies to Penetrations 74, 76, 77, and 78)

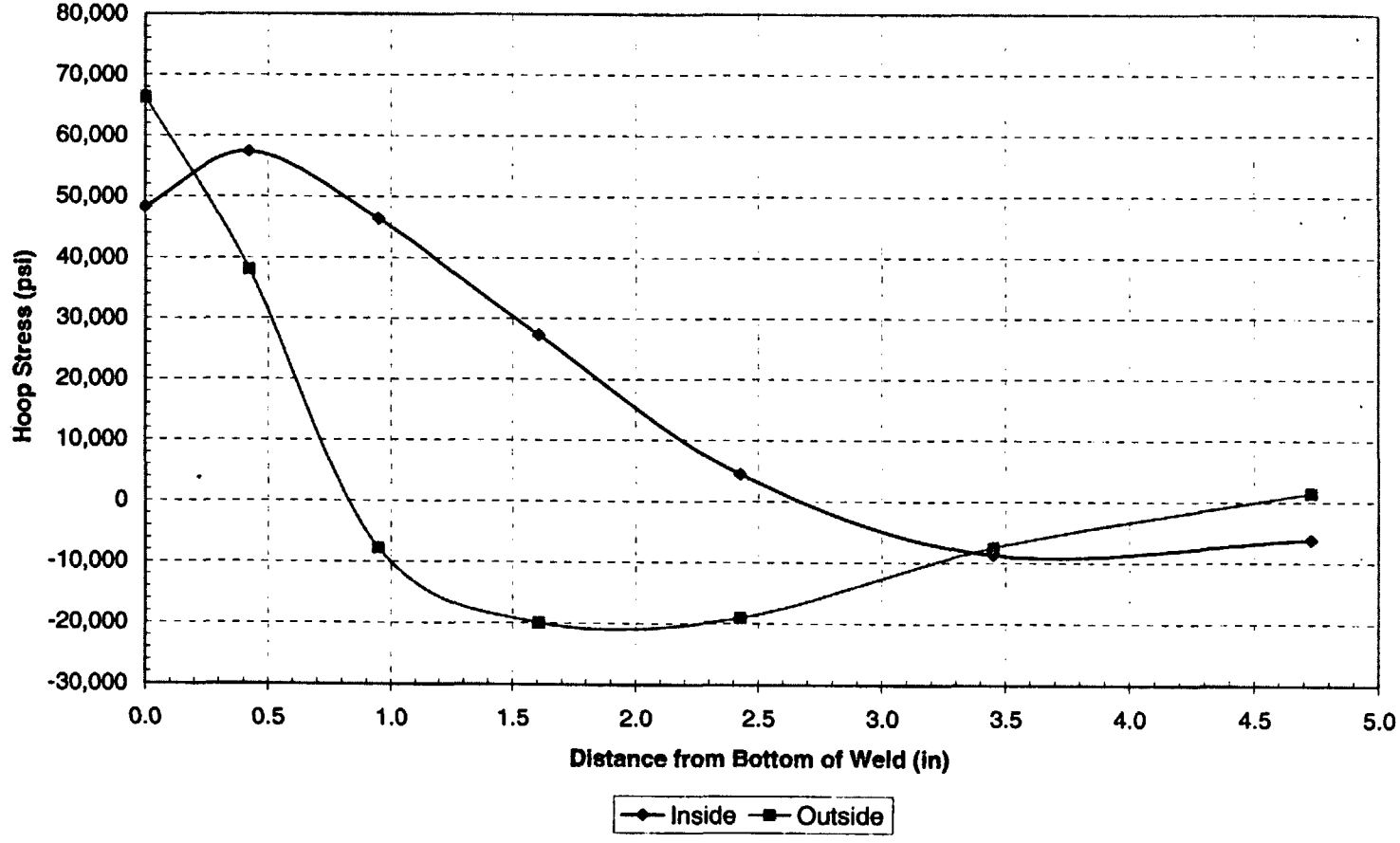

Figure 10
Hoop Stress Distribution Uphill Side
(25.4 Degree CRDM Penetration Nozzle)

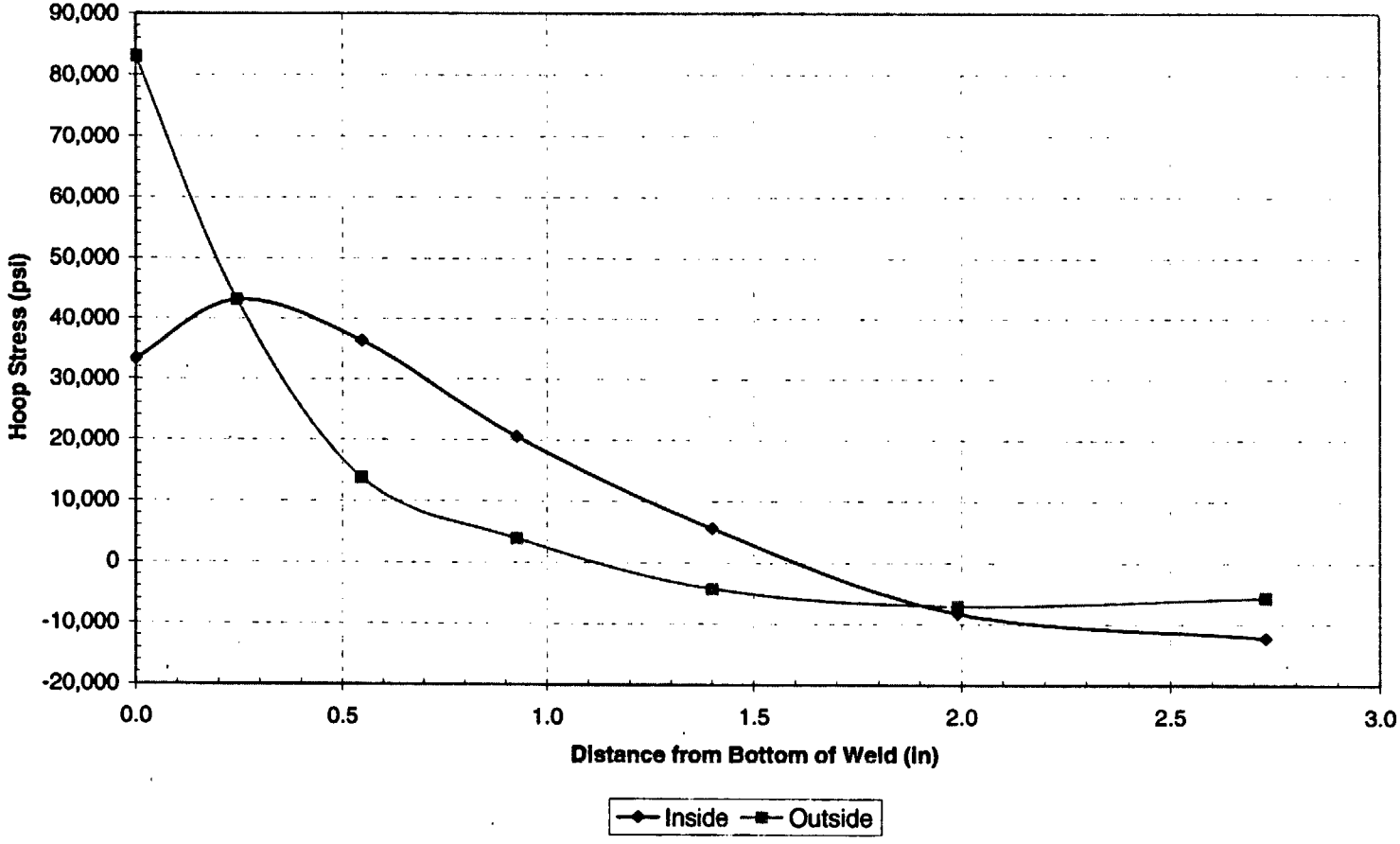

Figure 11
Hoop Stress Distribution Downhill Side
(25.4 Degree CRDM Penetration Nozzle)

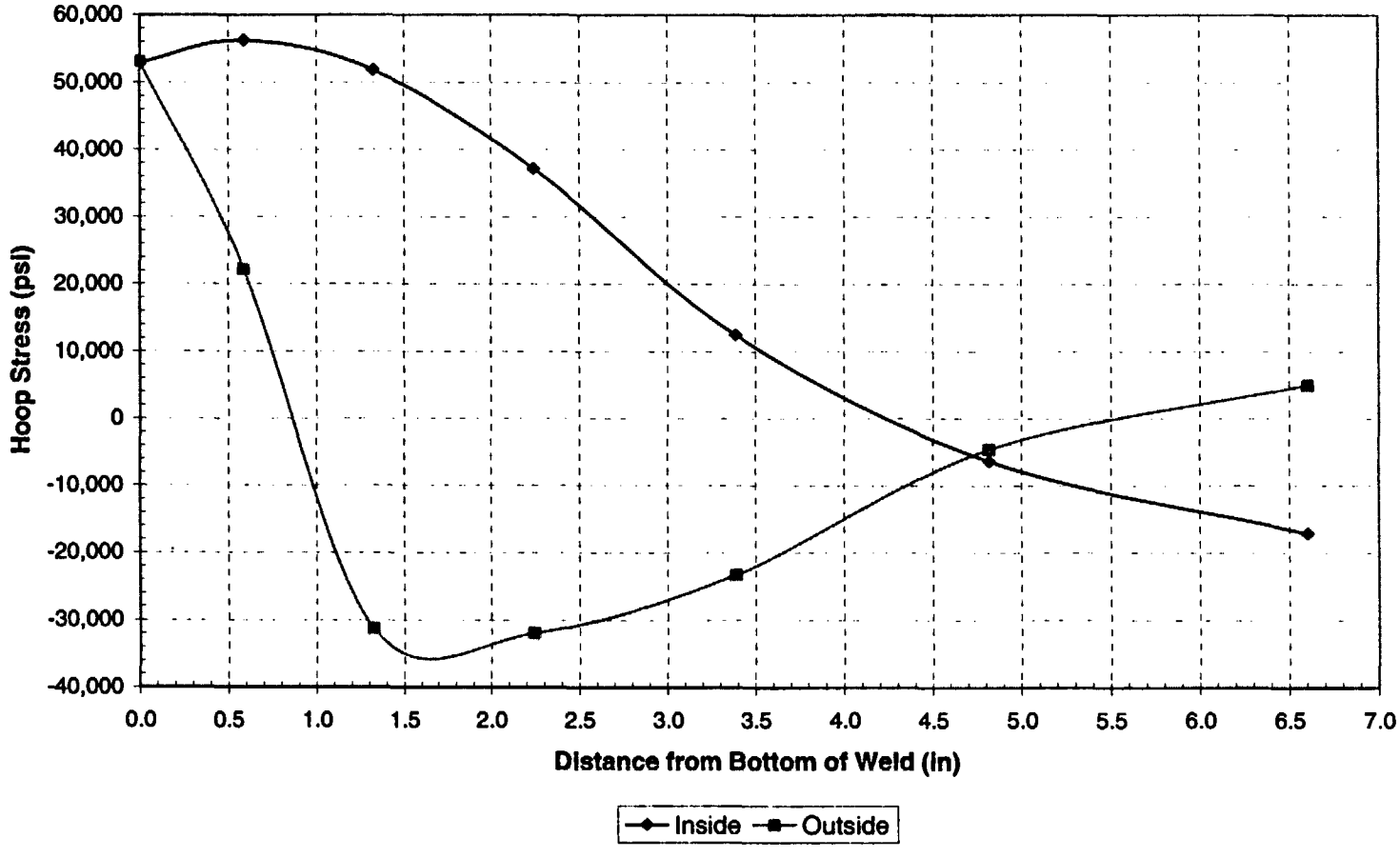

Figure 12
Hoop Stress Distribution Uphill Side
(43.8 Degree CRDM Penetration Nozzle)

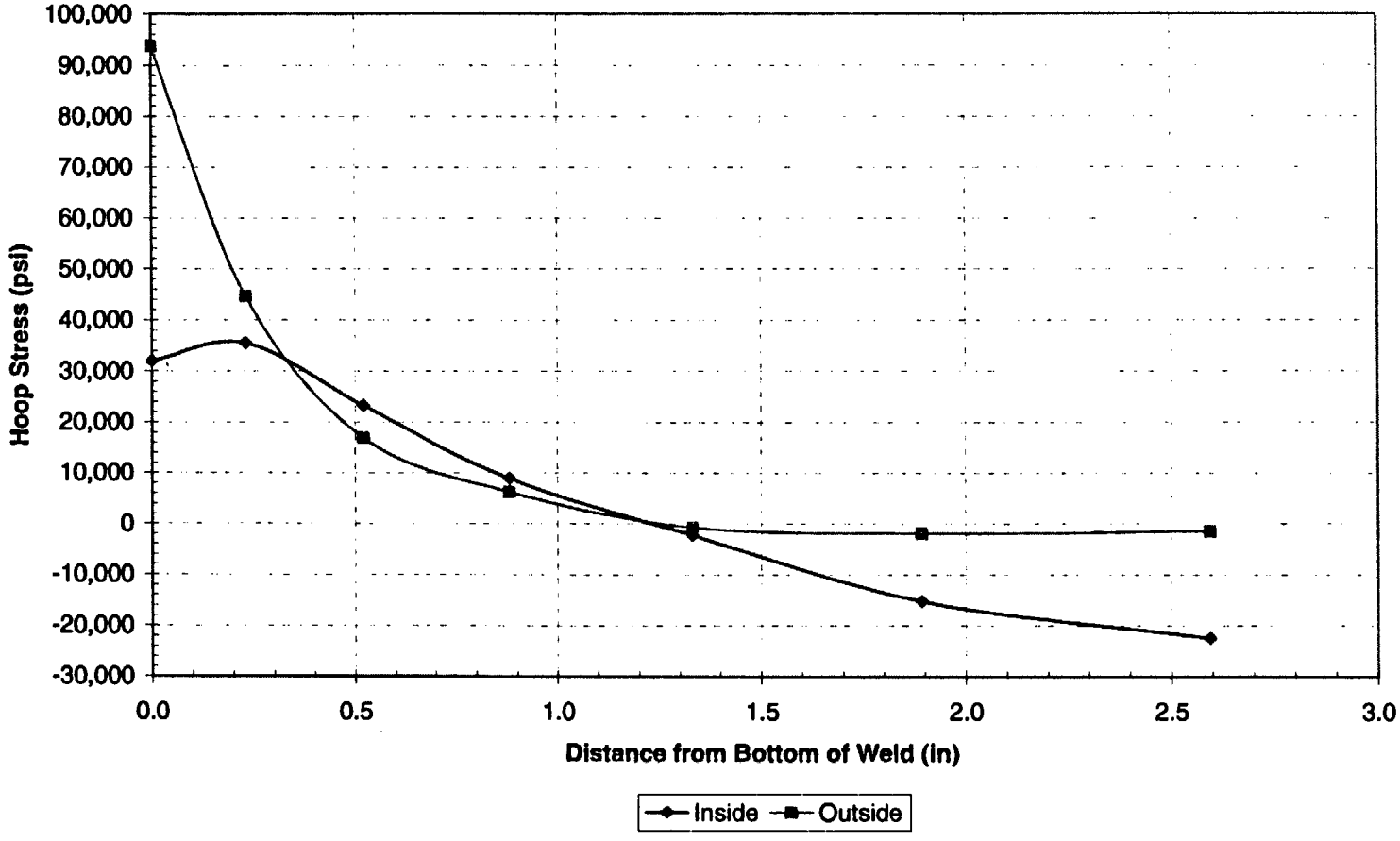

Figure 13
Hoop Stress Distribution Downhill Side
(43.8 Degree CRDM Penetration Nozzle)

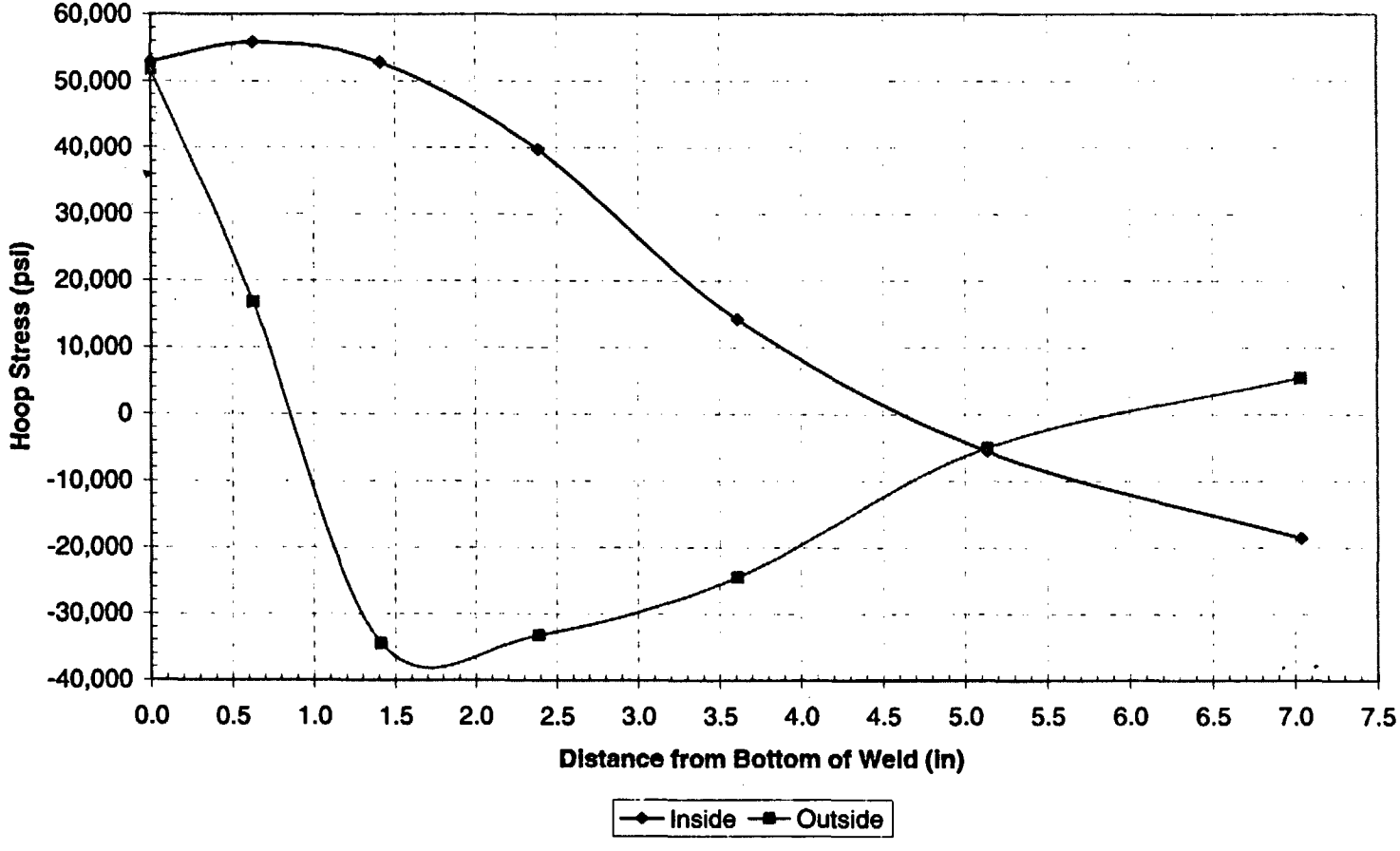

Figure 14
Hoop Stress Distribution Uphill Side
(47 Degree CRDM Penetration Nozzle)

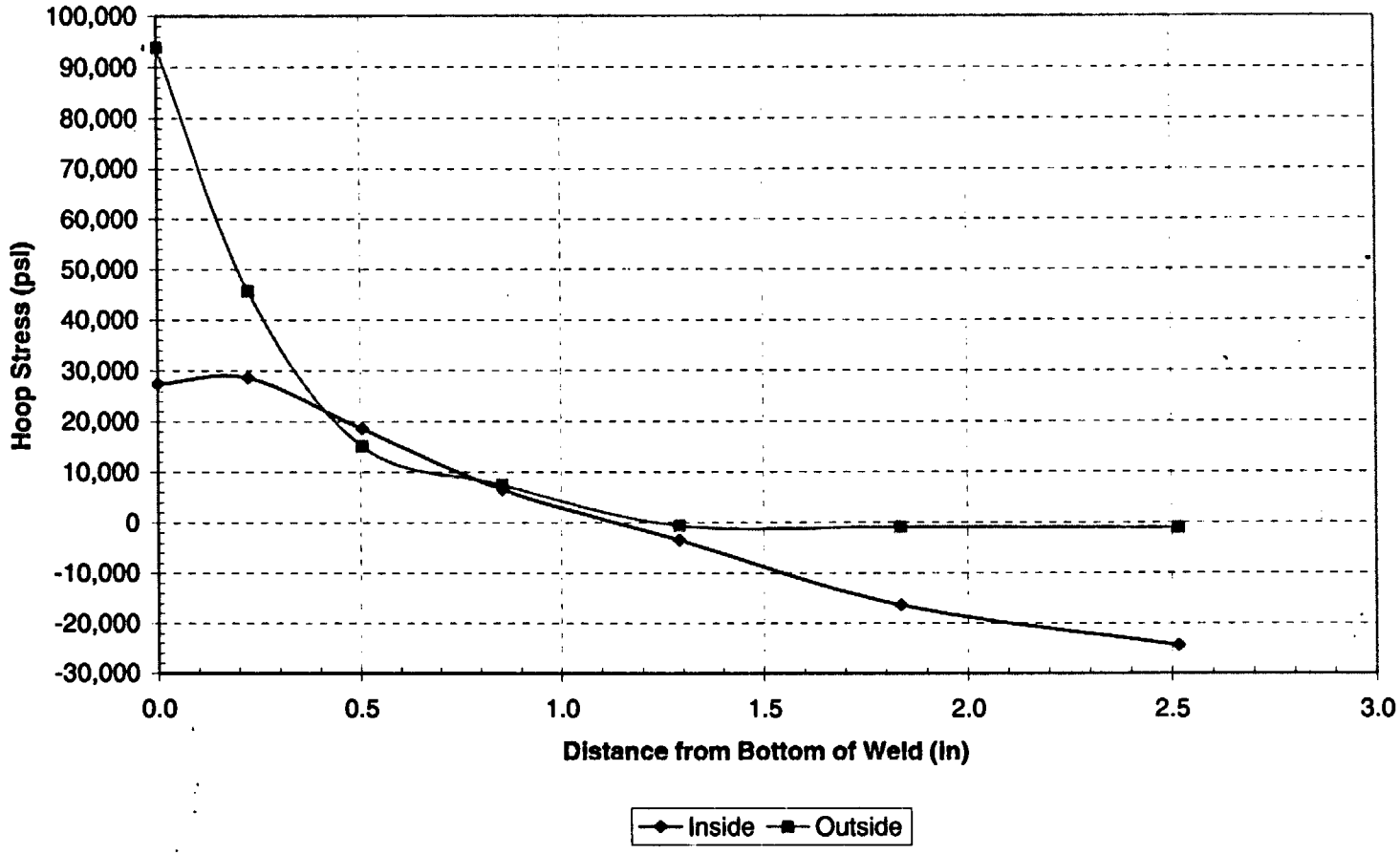

Figure 15
Hoop Stress Distribution Downhill Side
(47 Degree CRDM Penetration Nozzle)

Attachment 2

Relaxation Request From NRC Order EA-03-009
Section IV, Paragraph C(5)(b)(i)

Byron Station, Unit 1

Attachment 2
Relaxation Request From NRC Order EA-03-009
Section IV, Paragraph C(5)(b)(i)
Byron Station, Unit 1

Component

Byron Station Unit 1 has seventy-nine (79) reactor pressure vessel (RPV) head penetration nozzles comprised of fifty-five (55) penetration tubes with thermal sleeves, twenty-three (23) locations without thermal sleeves, and one (1) vent penetration nozzle.

In accordance with Section IV.A of the First Revised NRC Order EA-03-009 (hereafter referred to as the Order), the Byron Station Unit 1 susceptibility category is classified as "low" based on a calculated value of less than eight effective degradation years (EDY) and no previous inspection findings prior to the Spring 2005 refueling outage (B1R13). Results of this examination were previously submitted by letter dated June 22, 2005 (ADAMS Accession No. ML051730156).

NRC Order EA-03-009 Applicable Examination Requirements

The nonvisual NDE examinations (ultrasonic and eddy current) performed on the Byron Station Unit 1 RPV head during the Spring 2005 refueling outage are specified in the Order, Section IV, paragraphs C.(3) and C.(5)(b).

Paragraph IV.C.(3) of the Order states in part:

> *"... The requirements of paragraph IV.C.(5)(b) must be completed at least once prior to February 11, 2008, and thereafter, at least every four refueling outages or every 7 years, whichever occurs first."*

Paragraph IV.C.(5)(b) of the Order states:

> *"For each penetration, perform a nonvisual NDE in accordance with either (i), (ii) or (iii):*
>
> *(i) Ultrasonic testing of the RPV head penetration nozzle volume (i.e., nozzle base material) from 2 inches above the highest point of the root of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) to 2 inches below the lowest point at the toe of the J-groove weld on a horizontal plane perpendicular to the nozzle axis (or the bottom of the nozzle if less than 2 inches [see Figure IV-1]); OR from 2 inches above the highest point of the root of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) to 1.0-inch below the lowest point at the toe of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) and including all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level (including all residual and normal operation stresses) of 20 ksi tension and greater (see Figure IV-2). In addition, an assessment shall be made to determine if leakage has occurred into the*

annulus between the RPV head penetration nozzle and the RPV head low-alloy steel.

(ii) Eddy current testing or dye penetrant testing of the entire wetted surface of the J-groove weld and the wetted surface of the RPV head penetration nozzle base material from at least 2 inches above the highest point of the root of the J-groove. weld (on a horizontal plane perpendicular to the nozzle axis) to 2 inches below the lowest point at the toe of the J-groove weld on a horizontal plane perpendicular to the nozzle axis (or the bottom of the nozzle if less than 2 inches [see Figure IV-3]; OR from 2 inches above the highest point of the root of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) to 1.0-inch below the lowest point at the toe of the J-groove weld (on a horizontal plane perpendicular to the nozzle axis) and including all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level (including all residual and normal operation stresses) of 20 ksi tension and greater (see Figure IV-4).

(iii) A combination of (i) and (ii) to cover equivalent volumes, surfaces and leak paths of the RPV head penetration nozzle base material and J-groove weld as described in (i) and (ii). Substitution of a portion of a volumetric exam on a nozzle with a surface examination may be performed with the following requirements:

2. On nozzle material below the J-groove weld, both the outside diameter and inside diameter surfaces of the nozzle must be examined.

2. On nozzle material above the J-groove weld, surface examination of the inside diameter surface of the nozzle is permitted provided a surface examination of the J-groove weld is also performed."

Requirement from Which Relaxation Is Requested

In accordance with Section IV.F.(2) of the Order, relaxation from the above requirements is requested since compliance with the Order would result in a hardship or unusual difficulty without a compensating increase in the level of quality and safety.

Relaxation is requested from Section IV.C.(5)(b)(i) of the Order to perform ultrasonic testing (UT) of the RPV head penetrations inside the tube from 2 inches above the J-groove weld to:

- two inches below the lowest point of the toe of the J-groove weld (or the bottom of the nozzle if less than two inches) OR

- one inch below the lowest point of the toe of the J-groove weld and including all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level of 20 ksi tension and greater.

Based on the physical configuration of the nozzles and the limitations of the test equipment at Byron Station Unit 1, it is not possible to achieve the inspection coverage specified in Section IV.C.(5)(b)(i) of the Order for six RPV penetration nozzles on Byron Station Unit 1.

Relaxation is requested to redefine the inspection area for the affected penetrations as *"the volume of the penetration tube extending from 2" above the J-groove weld down to the lowest elevation that can be practically inspected."*

Reason for Request

The Byron Station Unit 1 RPV head penetration non-visual examinations were performed during the Spring 2005 (B1R13) refuel outage. The examinations were performed using Westinghouse/WesDyne equipment and procedures demonstrated through the Electric Power Research Institute (EPRI) Materials Reliability Project. Due to physical limitations and interferences associated with some of the penetrations, the full examination volume required by Section IV.C.(5)(b)(i) of the Order cannot be achieved for six RPV penetration nozzles.

The nozzle inspections of the volume from the J-groove weld root up to 2 inches above the weld and the leakage assessments required under Section IV, Paragraph C.(5)(b)(i) of the Order were satisfied for all penetrations. The lower nozzle inspection volume (1.0-inch below the lowest point at the toe of the J-groove weld including all RPV head penetration nozzle surfaces of 20 ksi tension and greater) required under Section IV, Paragraph C.(5)(b)(i) of the Order were satisfied for all but six penetrations. For the lower portion of the penetration defined in Figure IV-2 of the Order, required coverage one inch below the lowest point of the J-groove weld toe could not be achieved for six penetrations (numbers 62, 66, 68, 69, 74, and 75).

<u>Component Geometry</u>

For Byron Station Unit 1, the bottom of each RPV head penetration nozzle includes a threaded region approximately 1.00 inch long on the outside diameter along with a chamfered area at the inside diameter which extends approximately 0.76 inches from the bottom of the penetration tube (see Figure 1). The chamfered surface is machined at a 20° angle. In addition to the presence of the threaded and chamfered regions on all penetration tubes, five penetration tubes also have a threaded guide cone attached to the bottom of the penetration tube via the threaded connection along with a welded set screw and two tack welds.

The distance from the top of the thread relief to the bottom of the fillet of the J-groove weld, identified as "A" in Figure 1, varies based on location of the penetration in the RPV head. These distances are generally longer for penetrations at "inboard" locations and become progressively shorter for penetrations located farther away from the center of the RPV head. At the six subject penetration nozzles (i.e., numbers 62, 66, 68, 69, 74, and 75) the configuration is such that the distance from the lowest point at the toe of the J-groove weld to the bottom of the scanned region is less than the one inch lower boundary limit specified in Section IV, Paragraph C.5(b)(i) of the Order.

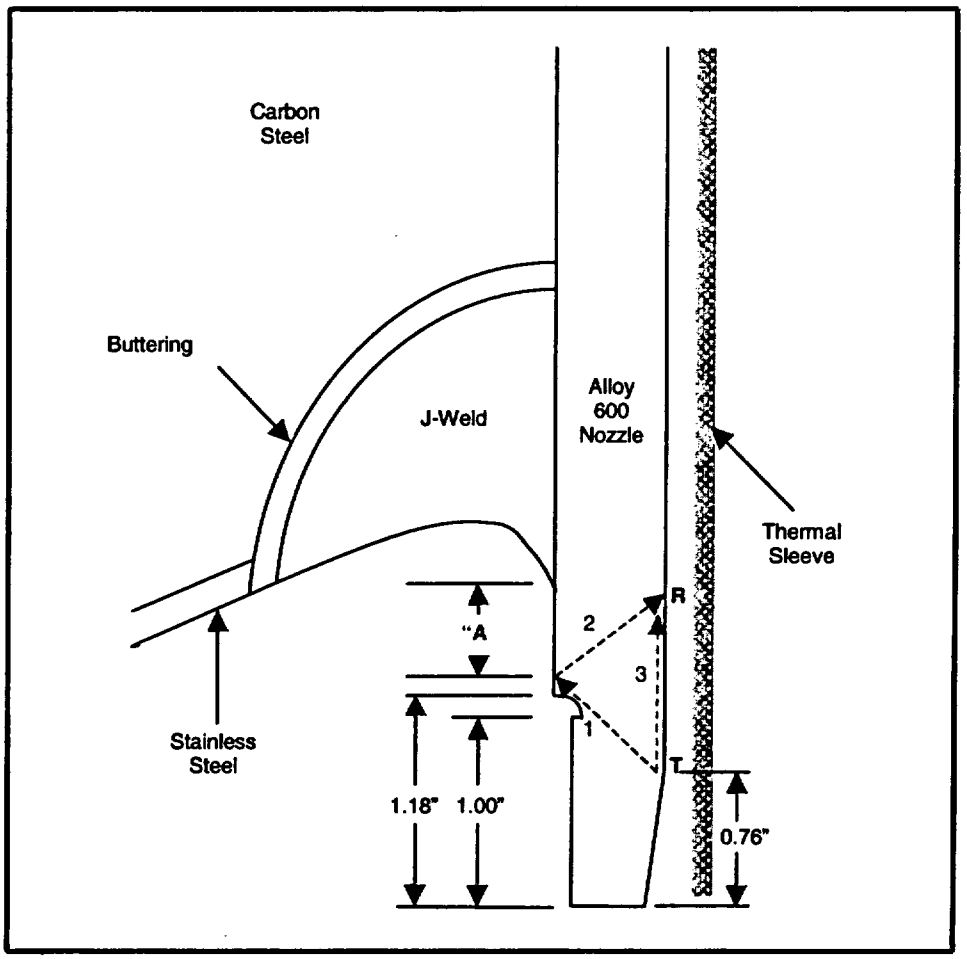

Figure 1
Illustration of Axially Oriented TOFD Examination Coverage on Byron Station Unit 1
Penetration Geometry (Including General Dimensions) at 0 Degrees

Examination Details

The inspection system used for Byron Station Unit 1 consisted of two probes to perform UT inspection of the penetration nozzles. The first probe type (Trinity Probe) was used to inspect nozzles that contained thermal sleeves (55 total). The second probe type (Open Housing Probe) was used to inspect nozzles without thermal sleeves (23 total). Both probes use axially oriented time-of-flight tip diffraction (TOFD) as the primary crack detection method. The vent line examination (one total) is not included in the discussion as this examination area has a different geometry that was not limited.

The TOFD technique is a "pitch/catch" ultrasonic method, which uses two transducers (one a transmitter, and one a receiver) oriented along the vertical axis of the probe. The focus point of the TOFD beam is at the midpoint between the upper and lower transducers. Longitudinal waves are transmitted into the tube at an angle by the transmitter (T) and reflect off the backside of the tube to a receiver (R), as shown in path "1-2" in Figure 1. A lateral wave also travels on the tube inside diameter (ID) surface between the transmitter and receiver as shown in path "3". The transmitting and receiving elements are mounted on a "shoe" with a probe center spacing of 0.925 inches. ID TOFD coverage is provided by the lateral wave to the elevation of the chamfer of the tube on the ID surface. With an axially oriented TOFD transducer pair in the Trinity probe, outside diameter (OD) coverage becomes completely effective at an elevation just above the top of the thread relief. The presence of the thread relief results in a slight masking of the ultrasound to the OD surface to an elevation conservatively estimated at 0.20 inches above the thread relief. In this area however, OD initiated degradation would be detected once the depth of the degradation exceeded the depth of the masked area. With a circumferentially oriented TOFD transducer pair, included in the Open Housing Scanner, OD coverage is extended to the elevation of the top of the chamfer, approximately 0.76 inches above the bottom of the tube. In the threaded region, cracks extending deeper than the threads will be detected.

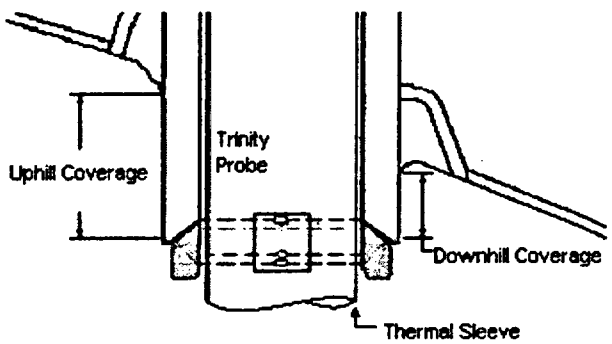

Figure 2
Trinity Probe Inspection Circumferential UT Coverage

The Open Housing Probe has a transducer pair with a 55-degree angle of refraction. The Trinity Probe (Figure 2) has a transducer pair with a 44-degree angle of refraction. Since the Trinity Probe transducers are a smaller size and spacing is less than that of the Open Housing Probe, the focus point of the Trinity Probe transducers are at a lower elevation (closer to the bottom of the tube) than the Open Housing Probe focus point when the probes reach the top of the ID chamfer. However, due to the difference in the refracted angles, the thread relief on the outside diameter (OD) of the tube interferes with the TOFD beam for the Trinity Probe. Due to this interference, there is a small area above the thread relief where the Trinity Probe cannot inspect. Figure 3 shows the lower transducer at the top of the ID chamfer and the OD thread relief interference with the TOFD beam. Figure 4 shows the probe at the minimum (higher) elevation where the TOFD beam is not interrupted by the thread relief.

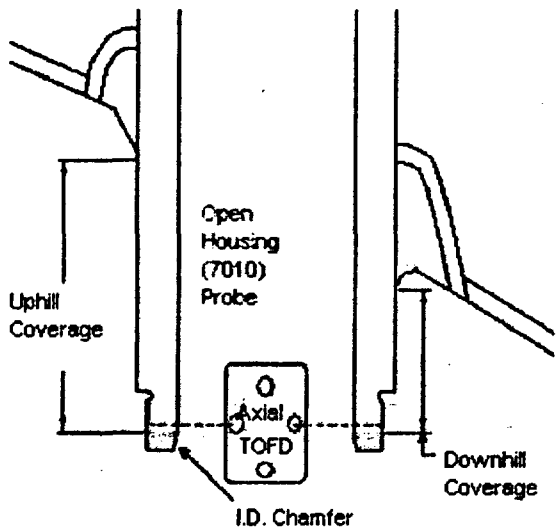

Figure 3
Open Housing Probe Circumferential UT Coverage

The shaded areas from both Figures 3 and 4 make up the total portion of the tube that cannot be inspected. The dimensions listed in Table 1 are based on the maximum coverage limitation of 1.18 inches shown in Figures 1 and 4.

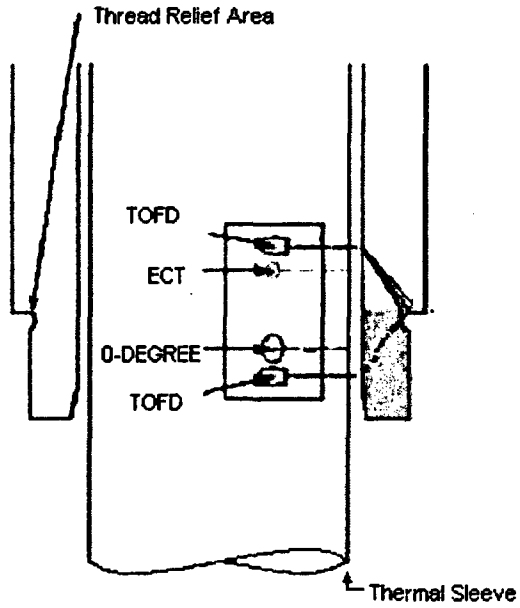

Figure 4
Trinity Probe – Lower TOFD Transducer to Top of Chamfer

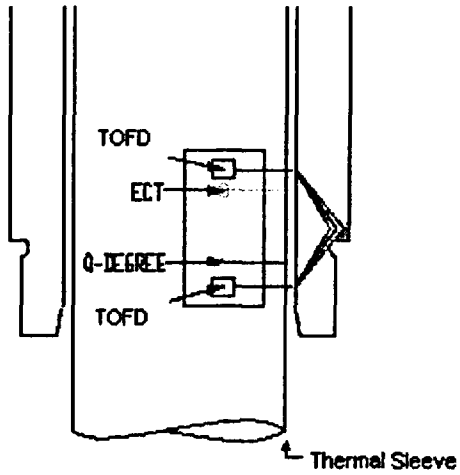

Figure 5
Trinity Probe – TOFD Beam Uninterrupted by Thread Relief

In addition to the axially oriented TOFD transducers (Figures 5), the Open Housing Probe has circumferentially oriented TOFD transducers that the Trinity Probe does not have. This circumferentially oriented TOFD signal allows the Open Housing Probe to inspect the tube down to the top of the ID chamfer. Also, with the Open Housing Probe's circumferentially oriented transducers, the TOFD beam is not

interrupted by the OD thread relief. The dimensions listed in Table 1 reflect the circumferential TOFD transducer coverage limitation of 0.76 inches due to the chamfered region. This is why the Open Housing Probe coverage is consistently greater than the Trinity Probe coverage. Figure 6 shows both the axial and circumferential Open Housing Probe TOFD coverage limitations. The shaded areas indicate the portions of the tube that cannot be inspected.

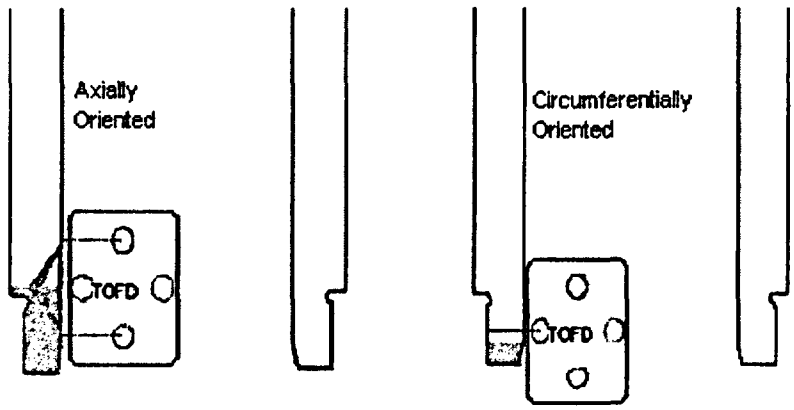

Figure 6
Open Housing Probe Coverage Limitations

The Order allows provisions for dye penetrant inspection. However, dye penetrant inspection would require extensive work under and around the RPV head. Based on electronic dosimetry readings from the examiner performing the vent nozzle manual inspection, the general area radiation levels under the Unit 1 head during B1R13 ranged from 1.7 R/hr at one foot off the floor to 5.6 R/hr near the funnels. General contact readings at the nozzles for Byron Station Unit 1 are historically 8 to 10 R/hr. Section IV.C.5(B)(iii) 1 of the Order requires penetrant inspection on both the inside and outside diameter surfaces in order to be considered an acceptable substitution for ultrasonic examination. The threaded region on the outside diameter of the penetration tubes along with the presence of the welded guide funnels on penetration tube ends makes a dye penetrant examination on the lower section of the tube impractical. Therefore, performing manual dye penetrant inspections on the bottom nozzle area would result in significant radiation exposure to personnel without a compensating increase in the level of quality or safety.

Table 1 contains information specific to the six penetrations for which relaxation is being requested. The values for Control Rod Drive Housing (CRDM) penetration hoop stress distributions at a point where the operating stress levels are less than 20 ksi tension (i.e., 20 ksi Line) were extrapolated from the associated graphs contained in Figures 10 through 15, which are also contained in Appendix A of Topical Report WCAP-16394-P, Revision 0, "Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2," dated February 2005 (Attachment 4).

Table 1
Penetrations with Limited Examination Volume
(Shaded Areas Do Not Meet Order Requirements)

Penetration Number	Angle (Degrees)	B1R13 Inspection Coverage (Inches Below Weld)	20 Ksi line (Inches below J-Groove Weld)				Inspection Method
			Uphill Side		Downhill Side		
			ID	OD	ID	OD	
62	42.8	0.84	2.9	.62	.62	.46	Open Housing
66	43.8	0.96	3.02	.62	.60	.47	Trinity
68	43.8	0.50	3.02	.62	.60	.47	Trinity
69	43.8	0.68	3.02	.62	.60	.47	Trinity
74	47	0.72	3.3	.60	.43	.47	Open Housing
75	47	0.56	3.3	.60	.43	.47	Open Housing

Proposed Alternative and Basis for Use

EGC proposes to define the lower boundary of the inspection volume for the affected RPV head penetration nozzles as: *"the volume of the penetration tube extending from 2" above the J-groove weld down to the lowest elevation that can be practically inspected."*

EGC performed UT examinations to the maximum extent possible and, for Byron Station Unit 1, meets all requirements of the Order with the exception of the six penetration tubes previously noted.

EGC was unable to completely comply with the requirements for UT inspection for six RPV penetration nozzles below the J-groove weld, due to the physical configuration of the nozzles and the limitations of the test equipment. The bottom ends of these nozzles are externally threaded and internally tapered. Loss of UT probe coupling due to the internal taper and/or disruption of the UT signal due to the external thread prevented UT data acquisition in a zone extending to approximately one-inch above the bottom of each nozzle.

Testing of portions of the nozzle significantly below the J-groove weld is not significant to the phenomena of concern. The phenomena that are of concern are leakage through the J-groove weld and circumferential cracking in the nozzle above the J-groove weld. This is appropriately reflected in the requirements of the Order (as stated in Section II above) that the testing extend to two inches above the J-groove weld. However, the Order also requires that testing be extended to:

- two inches below the lowest point of the toe of the J-groove weld (or the bottom of the nozzle if less than two inches) OR

- one inch below the lowest point at the toe of the J-groove weld and including all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level of 20 ksi tension or greater.

The nozzle is essentially an open-ended tube, and the nozzle wall below the J-groove weld is not part of the reactor coolant system pressure boundary.

The proposed inspection coverage is adequate because the cited inspection limitation for the RPV head penetration nozzles does not preclude full UT examination coverage of the portions of these nozzles that are of primary interest.

This can be assumed because:

- UT of the most highly stressed portion of the nozzle (the weld heat affected zone) is unaffected by this limitation.

- UT of the interference fit zone above the weld (for leakage assessment) is unaffected by this limitation, and cracks initiating in the unexamined bottom portion (non-pressure boundary) of the nozzle would be of minimal safety significance with respect to pressure boundary leakage or nozzle ejection.

- Since this portion of the nozzle is below the pressure boundary, any cracks would have to grow through a significant examined portion of the tube to reach the pressure boundary.

This proposed alternative is consistent with the analysis submitted in the industry topical report MRP-95, "Materials Reliability Program: Generic Evaluation of Examination Coverage Requirements for Reactor Pressure Vessel Head Penetration Nozzles," and the site-specific analysis in WCAP-16394-P. The zones of inspection selected are such that the stresses in the remaining uninspected zones are at levels for which Primary Water Stress Corrosion Cracking (PWSCC) is considered highly unlikely.

The major inherent conservatisms in WCAP-16394-P are summarized below:

Conservatism in Assumed Crack Geometry

It is understood that high stresses, on the order of the material yield strength, are necessary to initiate PWSCC. There is no known case of stress corrosion cracking of Alloy 600 below the yield stress. The yield strengths for wrought Alloy 600 head penetration nozzles are in the range of 37 ksi to 65 ksi. Weld metal yield strengths are generally higher. The yield strength of the head penetration nozzles for Byron Station Unit 1 varies from 36.5 ksi to 60.5 ksi. The stress level of 20 ksi is a conservative value below which PWSCC initiation is extremely unlikely.

Therefore, the assumption of any PWSCC crack initiation in the region of the penetration nozzle with a stress level of 20 ksi or less is conservative. The assumption of a through-wall flaw in these unlikely PWSCC crack initiation regions of the head penetration is an important additional conservatism, since the penetration tubes were inspected with maximum achievable coverage on the tube ID.

Flaw Propagation Calculations and Examination Coverage

A structural integrity evaluation was performed for the Byron and Braidwood Stations Unit 1 and Unit 2 reactor vessel head penetrations under WCAP-16394-P. The basis of this analysis is a detailed three-dimensional elastic-plastic finite element stress analysis of several penetration locations, which considers all the pertinent loadings on the penetration, and a fracture analysis using the crack growth rates recommended by the EPRI Topical Report "Materials Reliability Program (MRP) Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick Wall Alloy 600 Material (MRP-55) Revision 1." A series of crack growth calculations were performed presuming a flaw where the lower extremity of this initial through wall flaw is conservatively postulated to be located on the penetration nozzle where either the inside or outside surface hoop stress drops below 0 ksi. The results of these calculations provided the estimated remaining operating cycles that would elapse before a postulated flaw in the unexamined area of the penetration nozzle would propagate into the pressure boundary formed by the J-groove weld.

The postulated flaw at the lower extent of coverage was located on the flaw growth curve associated with the penetration angle. For those penetrations that do not have a flaw growth curve specific to the tube penetration angle, a conservative curve (nearest the lower penetration angle) was used. The time it would take for the postulated flaws to intersect the weld metal for the minimum coverage achieved was then determined.

Byron Station Unit 1 past operating cycles has been approximately 18 months (1.5 calendar years or 1.42 Effective Full Power Years (EFPY) per cycle based on historical data). Byron Unit 1 will remain on 18-month cycles based on the current

long-term schedule. Conservatively using 1.45 EFPY for the remaining four operating cycles until the next required examination, there are 5.8 EFPY between the B1R13 examinations and the next scheduled examination required by the Order. In accordance with the current Order requirements (perform examination within every four refueling outages or seven years, whichever occurs first), the next inspection for the Byron Station Unit 1 RPV penetrations must be completed by the B1R17 outage, which is currently scheduled in March of 2011.

Based on B1R13 examination results (see Table 1), the worst-case minimum distance below the J-groove weld to the top of the zone that could not be inspected was determined to be 0.50 inches on the downhill side of the penetration nozzle #68. To account for the inspection tolerance of the inspection equipment (0.01 inches), an axial through-wall flaw was conservatively postulated to be located at 0.49 inches below the J-groove weld in the crack propagation calculation for the downhill side of the penetration nozzle. Using the applicable crack growth rate for the penetration (Figure 10), it would take 6.0 EFPY for the postulated flaw to propagate from that location to the bottom of the J-groove weld, which would occur after the next scheduled inspection. Note that the normal instrument data acquisition resolution (tolerance) used during the CRDM Volumetric examinations is 0.04 inches. This is the standard examination tolerance and has been used by Braidwood Station and Byron Station to determine the final examination coverage values; however, for penetration nozzle #68, the examination resolution was increased to 0.01 inches to minimize the uncertainty.

For the subject penetrations that EGC is seeking relaxation, Figures 7 through 9 (WCAP-16394-P, Figures 6-13 through 6-15) provide results of the calculation. Two additional Crack Growth predictions were completed by Westinghouse for Penetrations 68 and 75 and are included as Figures 10 and 11. The calculation demonstrates that the minimum time for a flaw to propagate from that location to the bottom of the J-groove weld would be greater than four operating cycles. The results of the flaw propagation calculation indicate that, even if a flaw were to occur in the region of the penetration nozzle not being inspected, there would be adequate opportunity for detection prior to the crack reaching the reactor coolant system pressure boundary. The results demonstrate that the extent of the proposed inspection coverage would provide reasonable assurance of the structural integrity of the Unit 1 RPV head penetration nozzles and the J-groove welds.

Conclusion

In all cases, the measured coverage is adequate to allow Byron Station Unit 1 to continue to operate prior to the hypothetical flaws reaching the J-groove weld. In accordance with the current Order requirements, the next examination required for the Byron Station Unit 1 RPV penetrations would be completed prior to flaw propagation into J-groove welds.

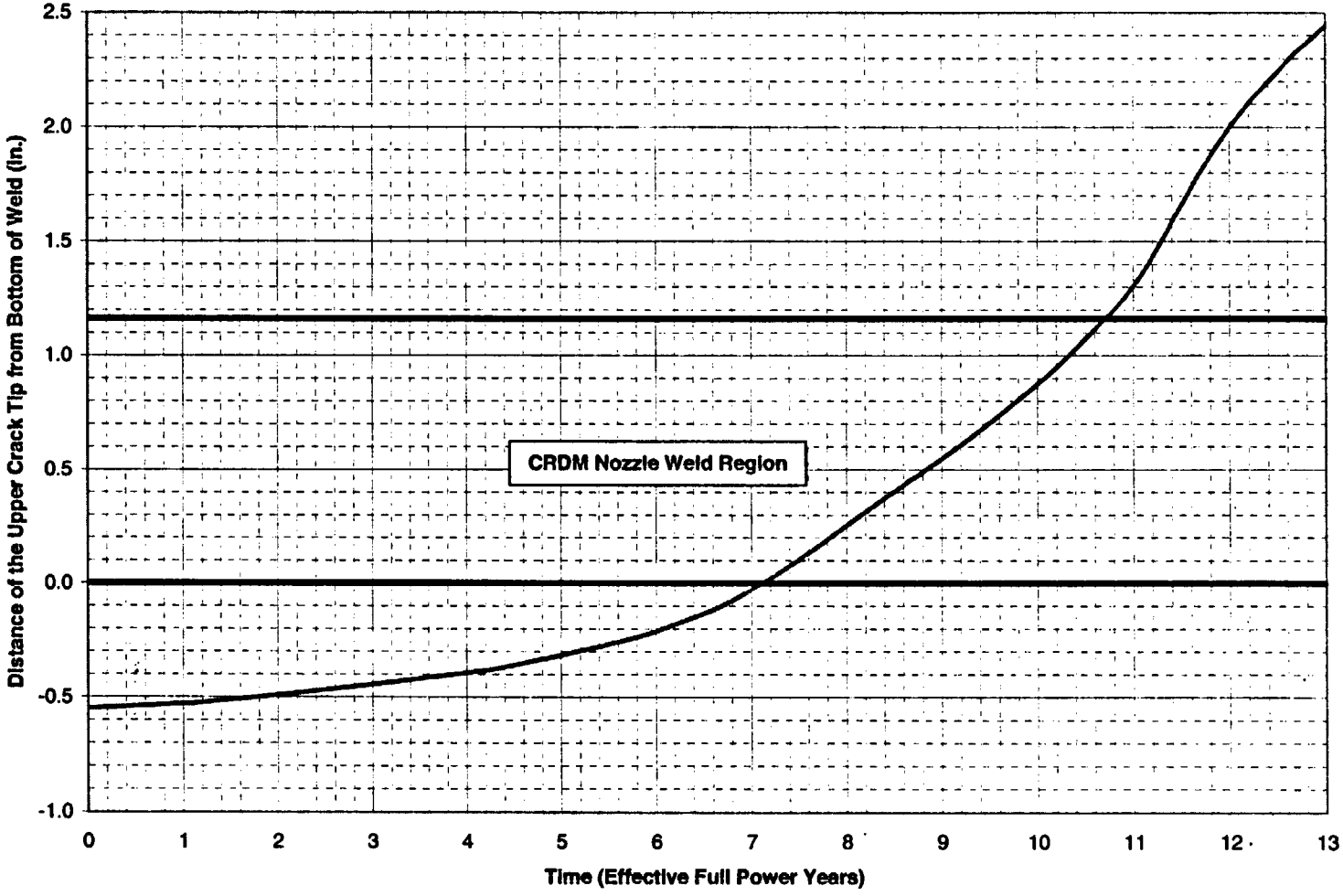

Figure 7
Through -Wall Longitudinal Flaw in the 42.8 Degree CRDM Row Downhill Side - Crack Growth Prediction
(Applies to Penetration 62)

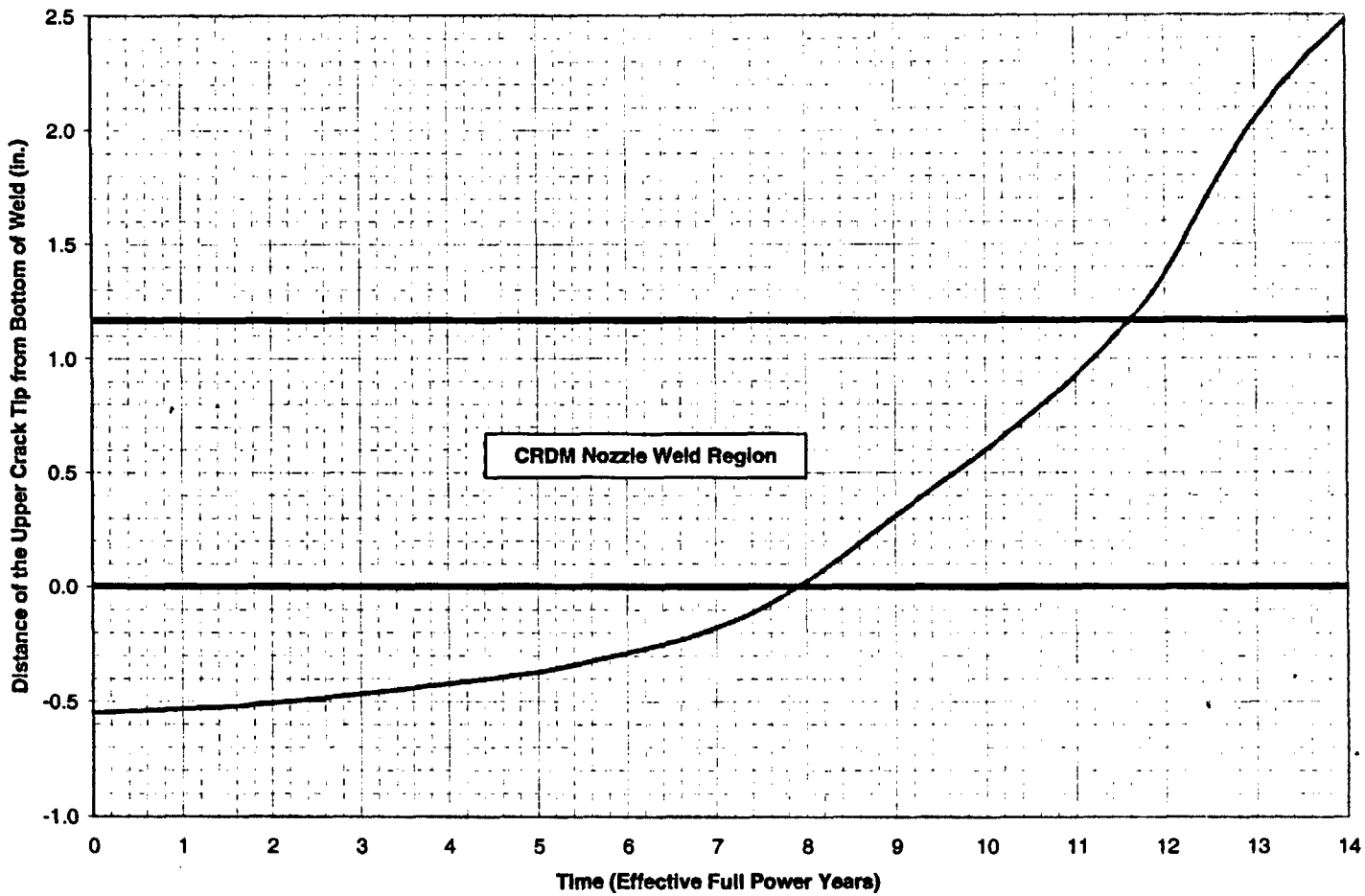

Figure 8
Through -Wall Longitudinal Flaw in the 43.8 Degree CRDM Row Downhill Side - Crack Growth Prediction
(Applies to Penetrations 66, and 69)

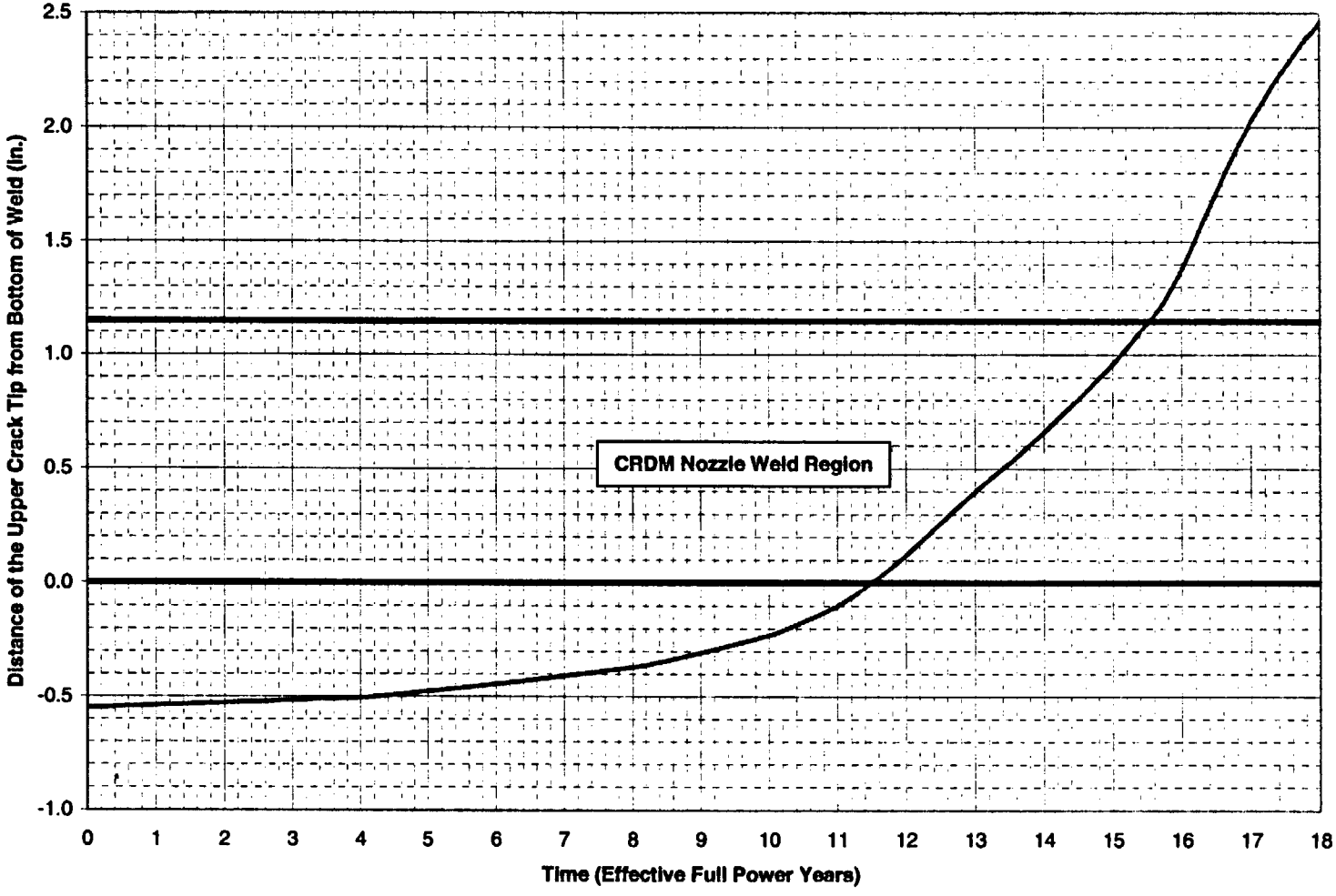

Figure 9
Through -Wall Longitudinal Flaw in the 47.0 Degree CRDM Row Downhill Side - Crack Growth Prediction
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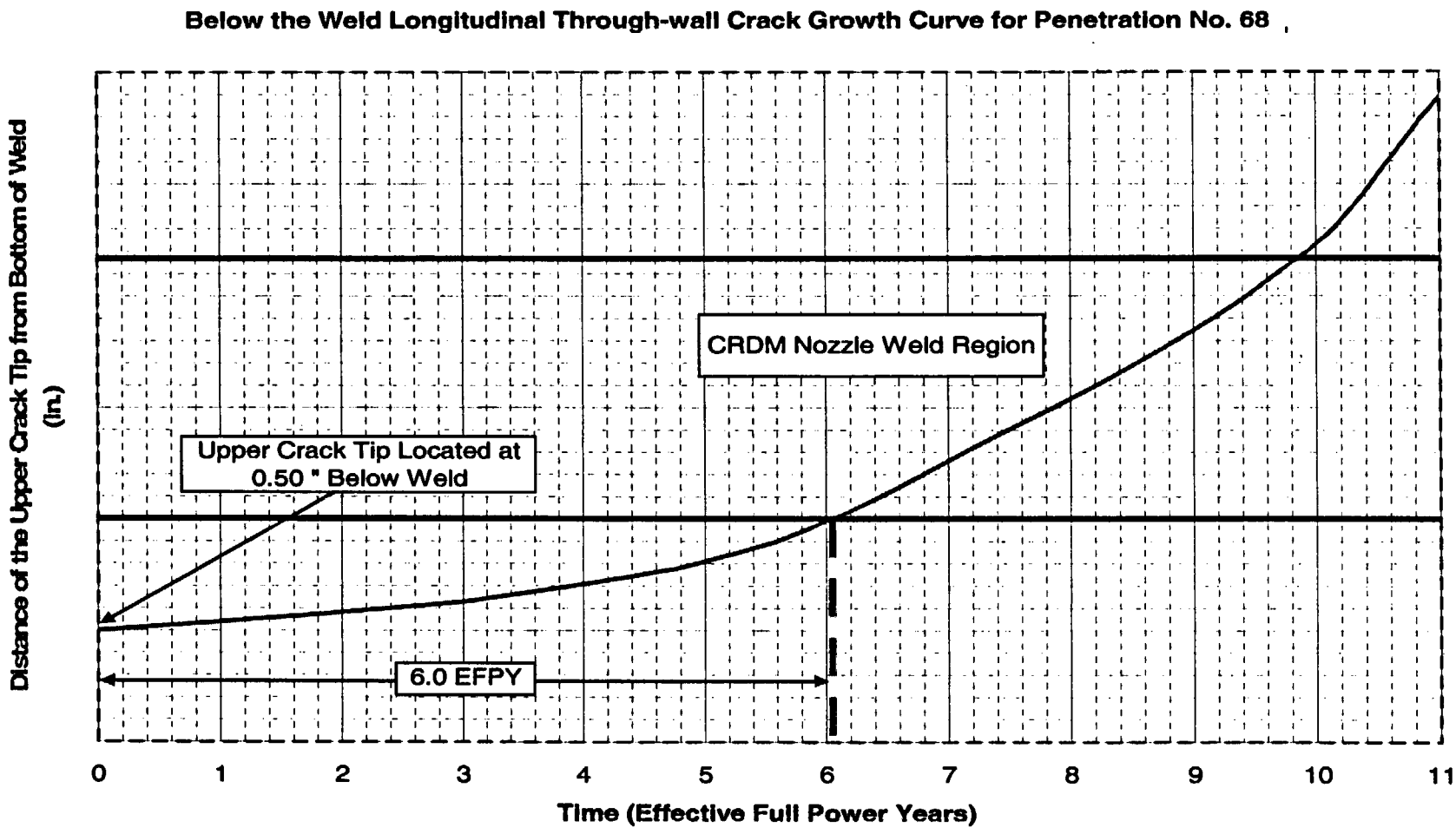

Figure 10
Below the Weld Longitudinal Through-wall Crack Growth Curve for Penetration 68

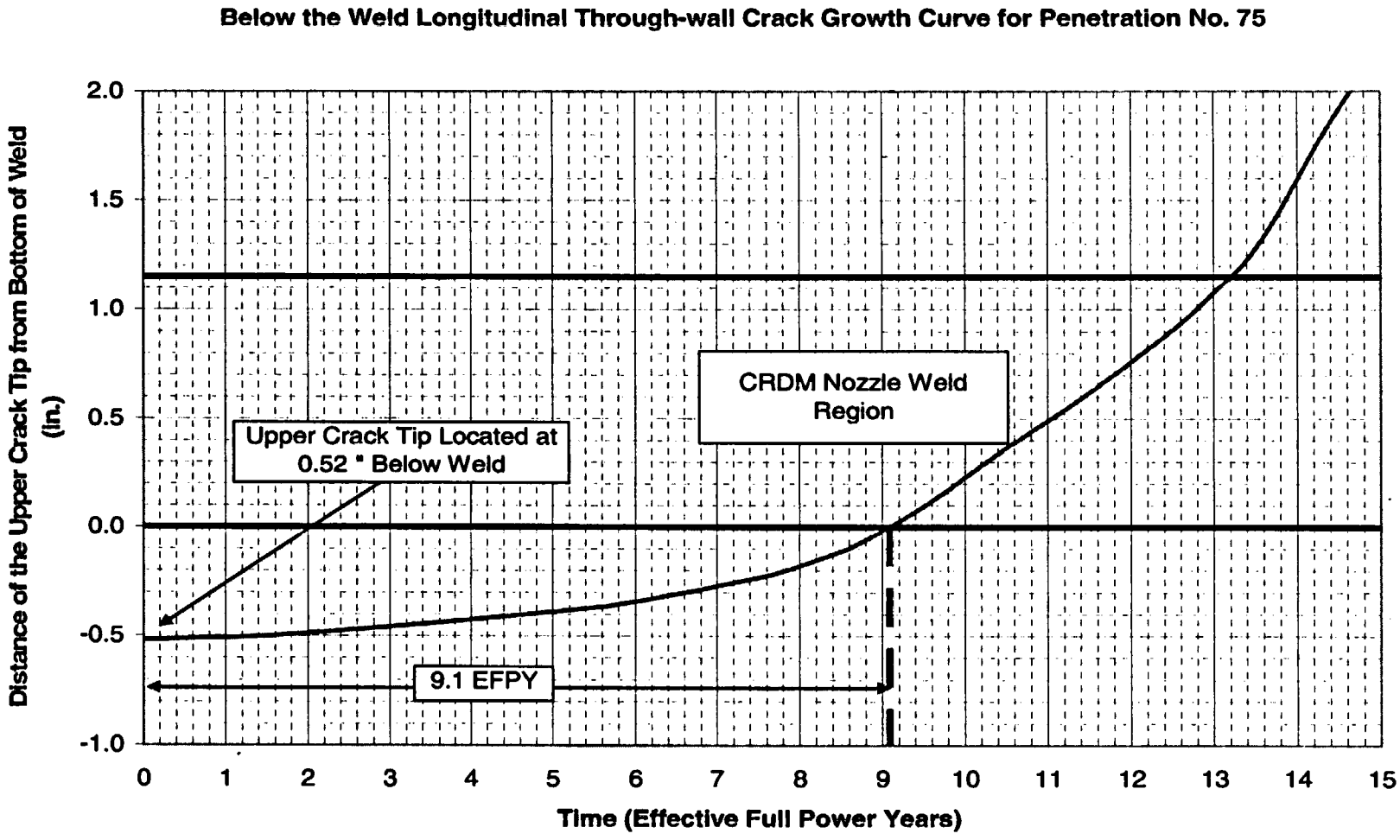

Figure 11
Below the Weld Longitudinal Through-wall Crack Growth Curve for Penetration 75

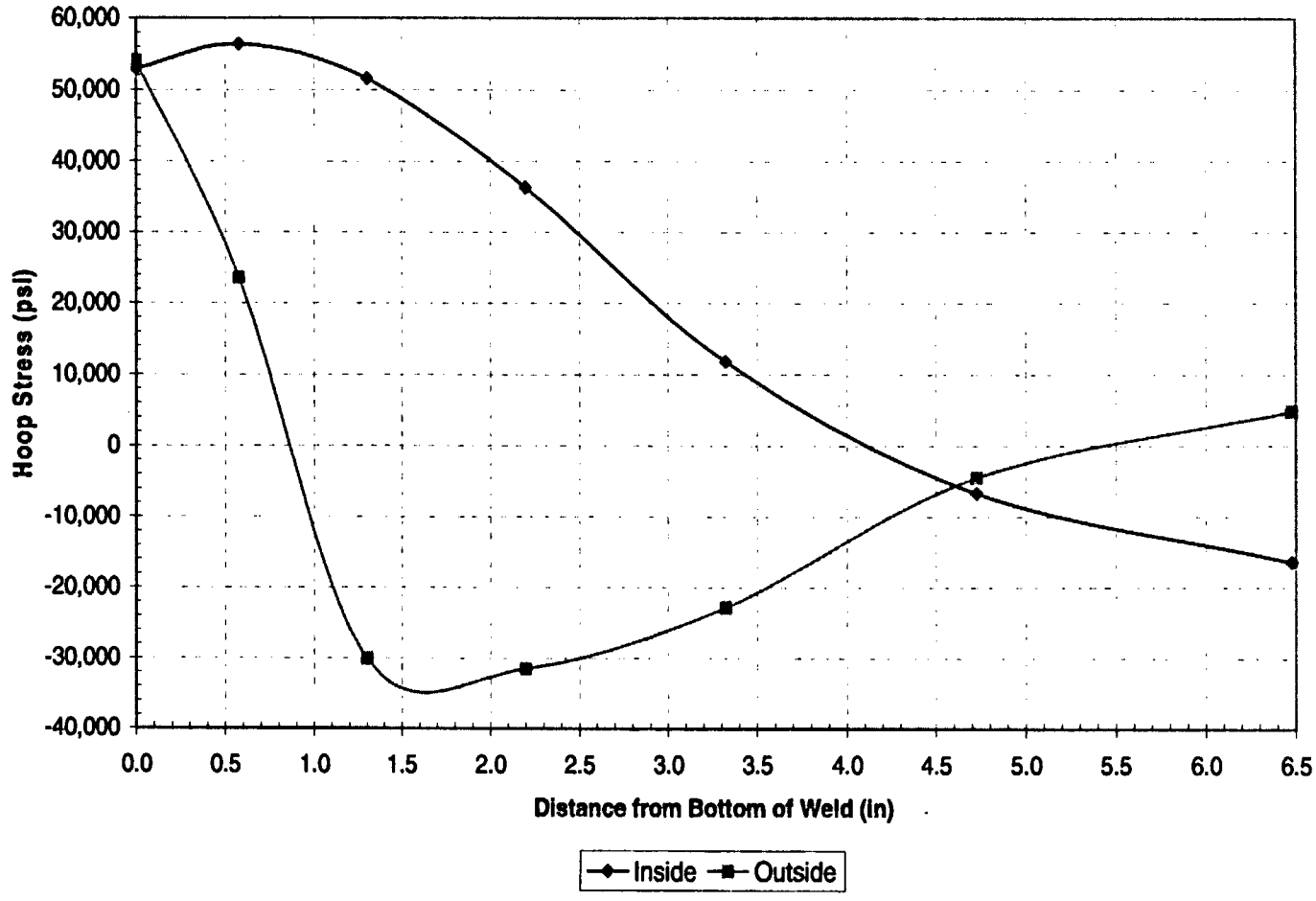

Figure 12
Hoop Stress Distribution Uphill Side
(42.8 Degree CRDM Penetration Nozzle)

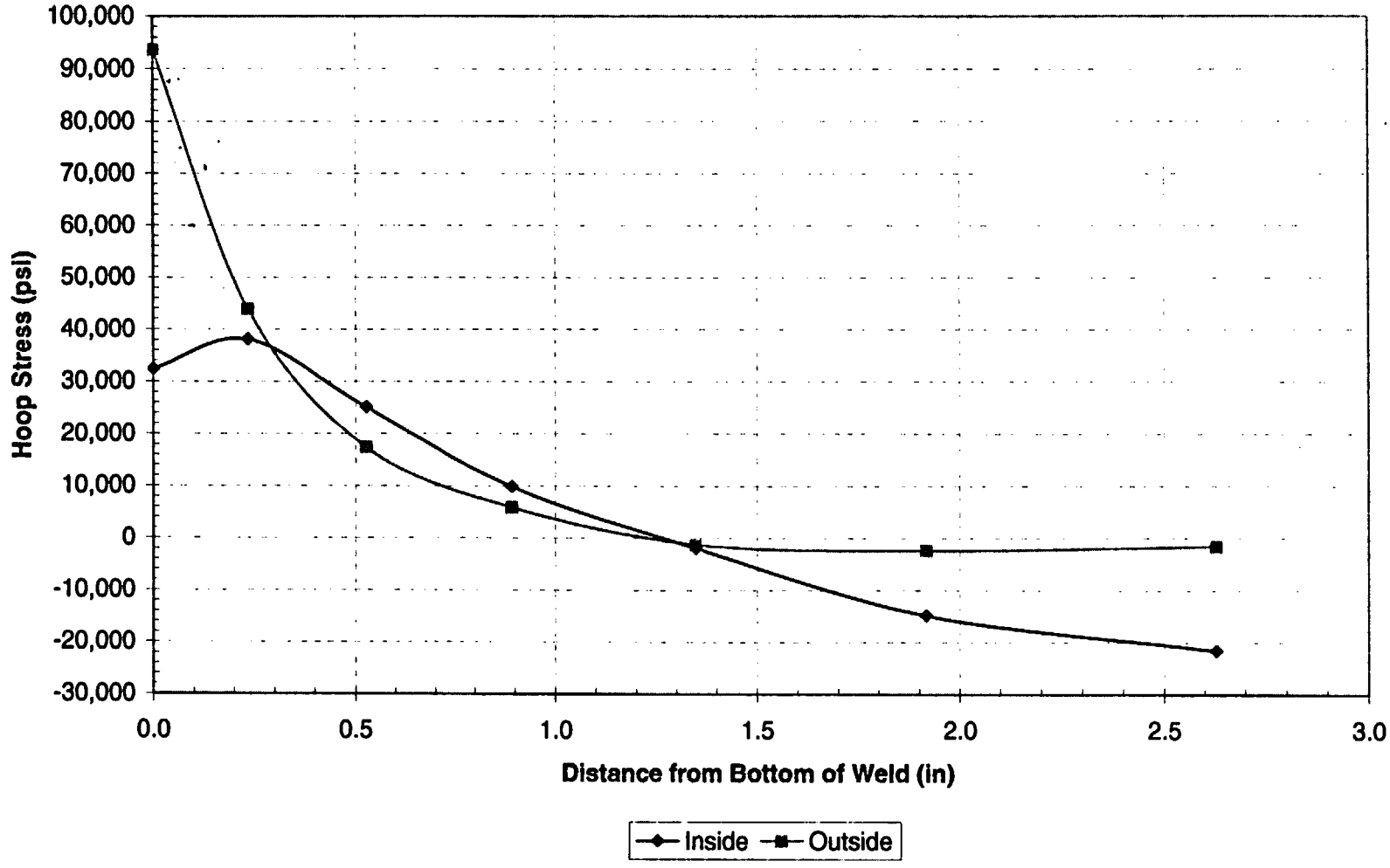

Figure 13
Hoop Stress Distribution Downhill Side
(42.8 Degree CRDM Penetration Nozzle)

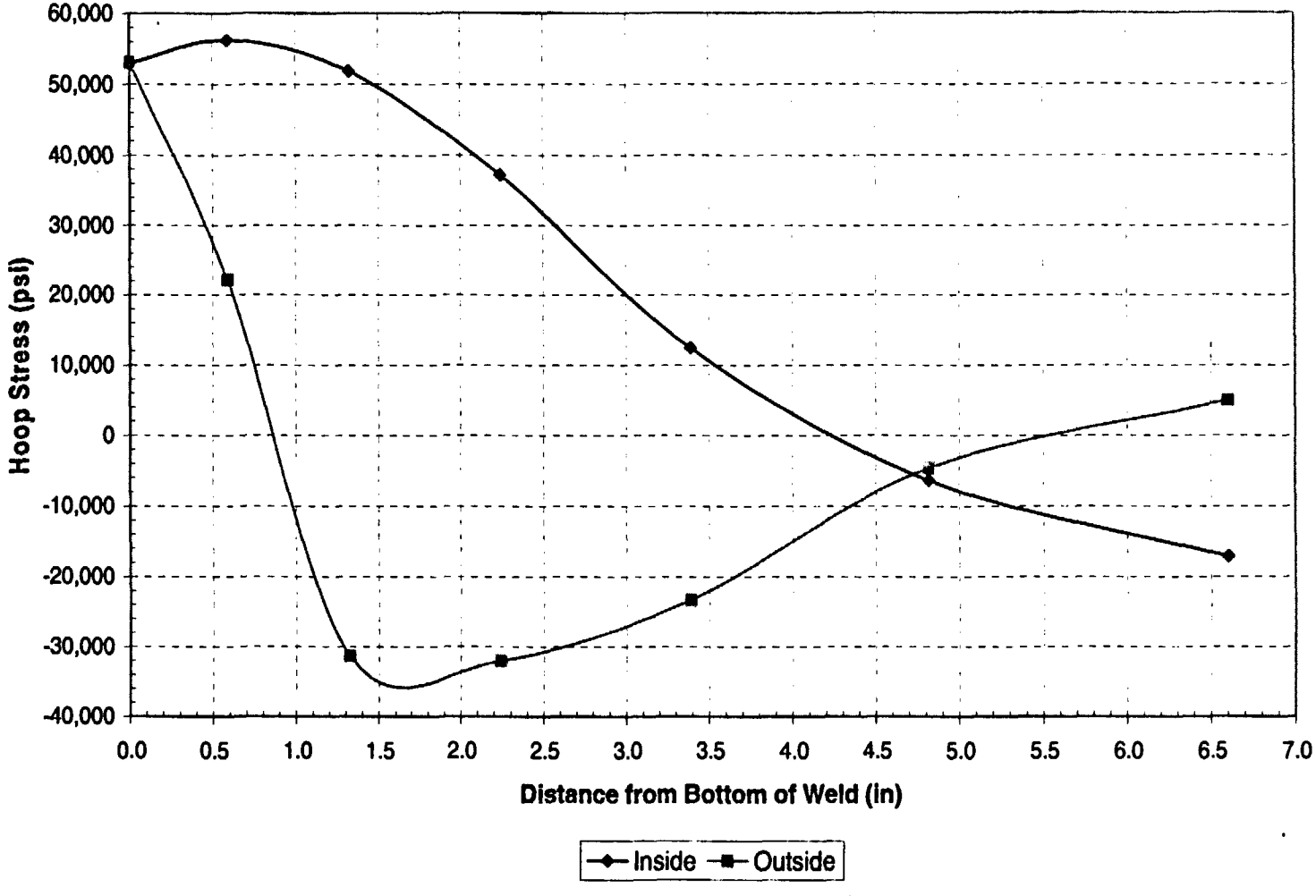

Figure 14
Hoop Stress Distribution Uphill Side
(43.8 Degree CRDM Penetration Nozzle)

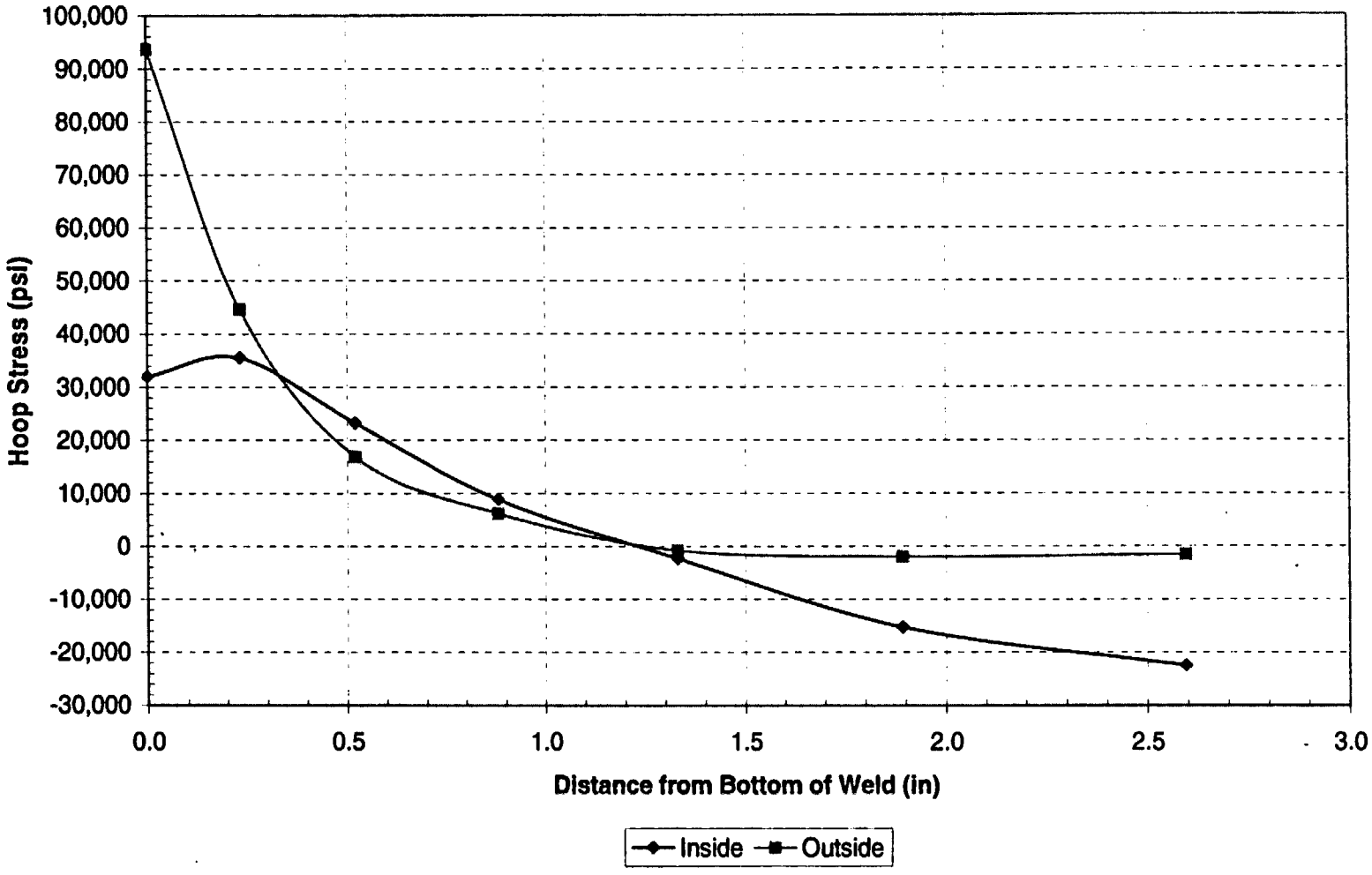

Figure 15
Hoop Stress Distribution Downhill Side
(43.8 Degree CRDM Penetration Nozzle)

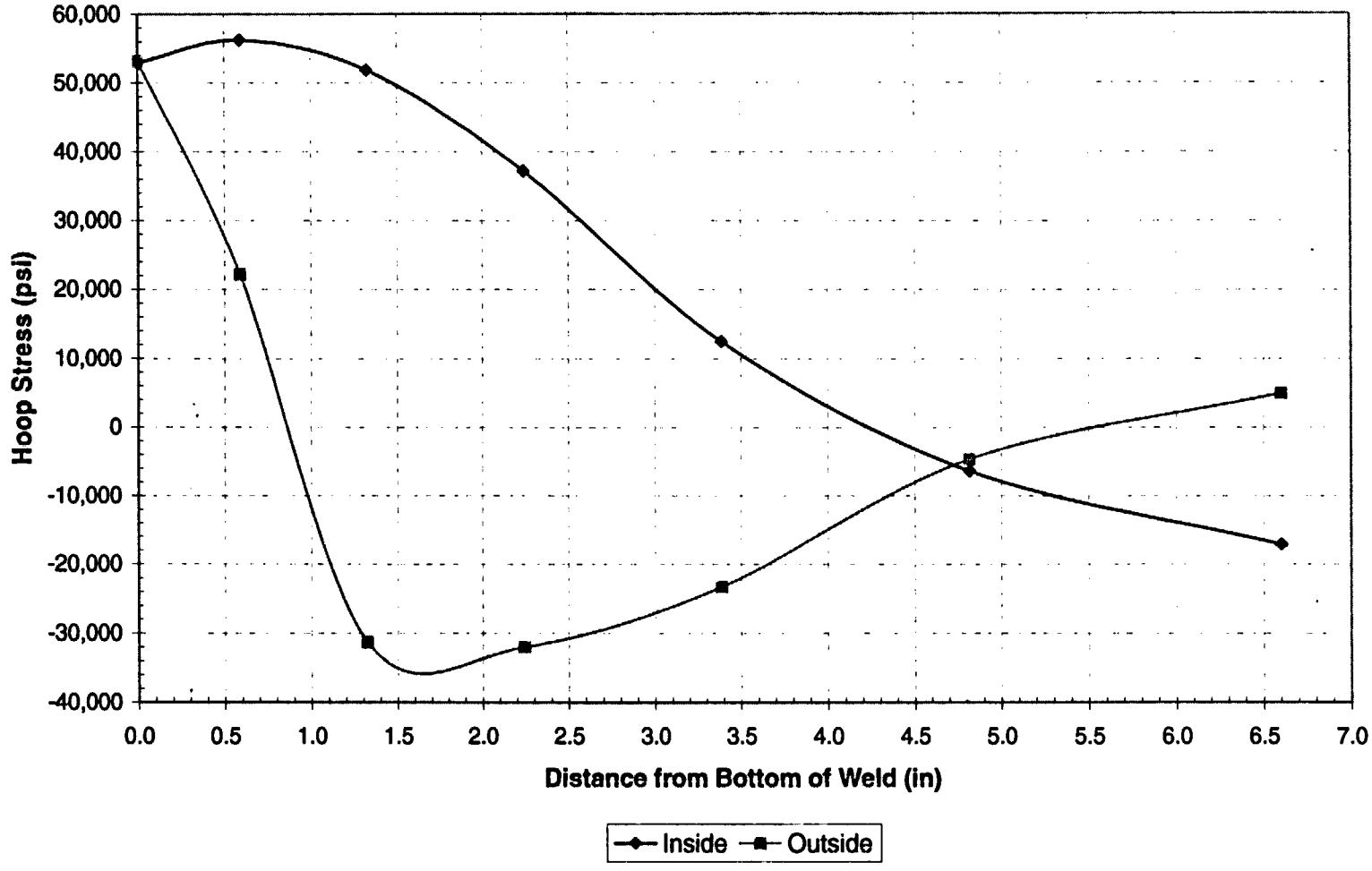

Figure 16
Hoop Stress Distribution Uphill Side
(47 Degree CRDM Penetration Nozzle)

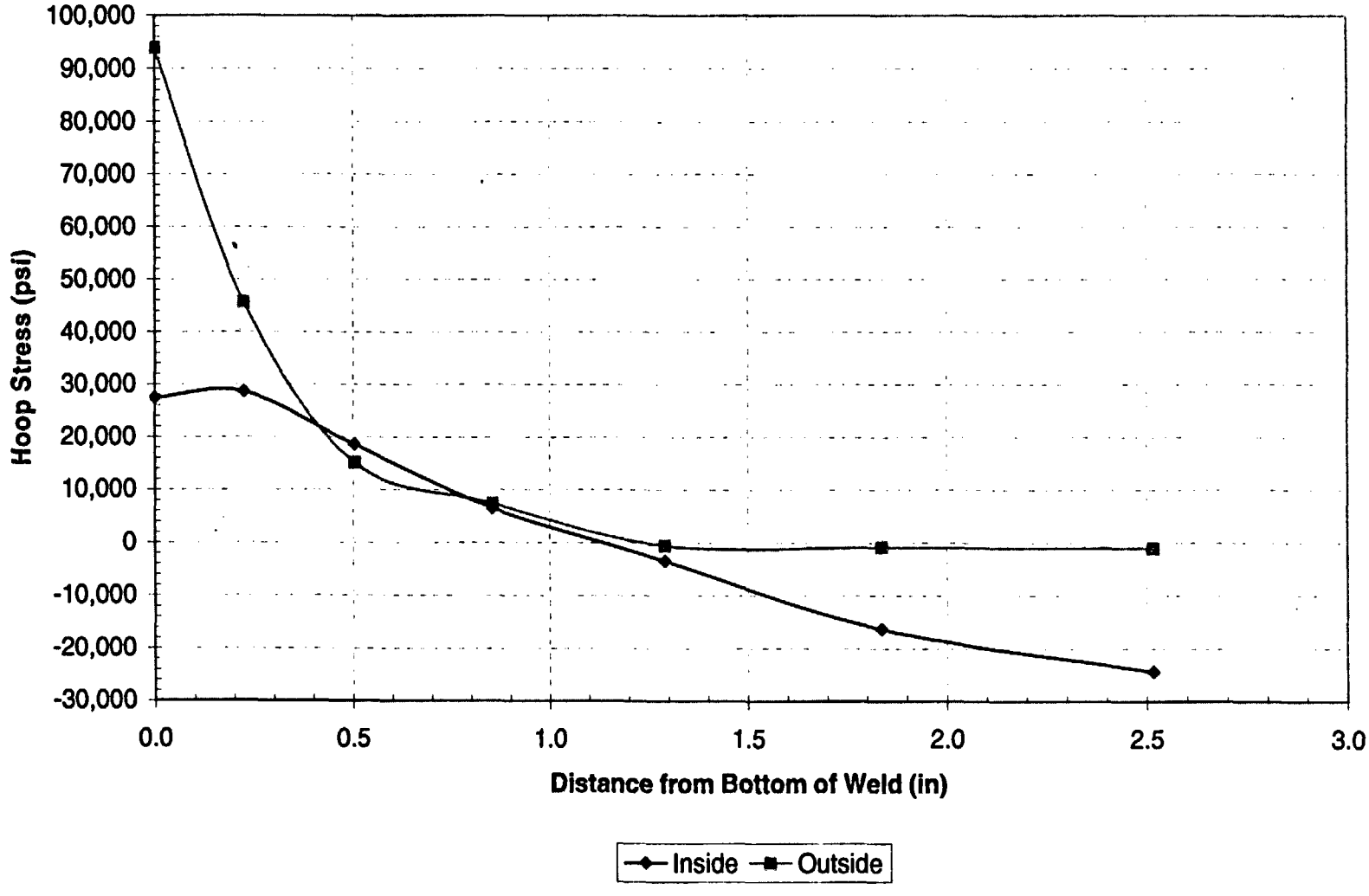

Figure 17
Hoop Stress Distribution Downhill Side
(47 Degree CRDM Penetration Nozzle)

Attachment 3

Westinghouse Letter CAW-05-2070

Application for Withholding Proprietary Information from Public Disclosure

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Direct tel: (412) 374-4419
Direct fax: (412) 374-4011
e-mail: maurerbf@westinghouse.com

Our ref: CAW-05-2070

November 18, 2005

APPLICATION FOR WITHHOLDING PROPRIETARY
INFORMATION FROM PUBLIC DISCLOSURE

Subject: WCAP-16394-P, Revision 0, "Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2," February 2005 (Proprietary)

The proprietary information for which withholding is being requested in the above-referenced report is further identified in Affidavit CAW-05-2070 signed by the owner of the proprietary information, Westinghouse Electric Company LLC. The affidavit, which accompanies this letter, sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the considerations listed in paragraph (b)(4) of 10 CFR Section 2.390 of the Commission's regulations.

Accordingly, this letter authorizes the utilization of the accompanying affidavit by Exelon Nuclear.

Correspondence with respect to the proprietary aspects of the application for withholding or the Westinghouse affidavit should reference this letter, CAW-05-2070, and should be addressed to B. F. Maurer, Acting Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company LLC, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

B. F. Maurer, Acting Manager
Regulatory Compliance and Plant Licensing

Enclosures

cc: B. Benney
L. Feizollahi

bcc: B. F. Maurer (ECE 4-7A) 1L
R. Bastien, 1L (Nivelles, Belgium)
C. Brinkman, 1L (Westinghouse Electric Co., 12300 Twinbrook Parkway, Suite 330, Rockville, MD 20852)
RCPL Administrative Aide (ECE 4-7A) 1L, 1A (letter and affidavit only)
Christopher Ng, 1L (Waltz Mill)

CAW-05-2070

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared B. F. Maurer, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company LLC (Westinghouse), and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

B. F. Maurer, Acting Manager
Regulatory Compliance and Plant Licensing

Sworn to and subscribed
before me this 18th day
of November, 2005

Notary Public

Notarial Seal
Sharon L. Fiori, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires January 29, 2007
Member, Pennsylvania Association Of Notaries

(1) I am Acting Manager, Regulatory Compliance and Plant Licensing, in Nuclear Services, Westinghouse Electric Company LLC (Westinghouse), and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rule making proceedings, and am authorized to apply for its withholding on behalf of Westinghouse.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.390 of the Commission's regulations and in conjunction with the Westinghouse "Application for Withholding" accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by Westinghouse in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.390 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information that is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.390, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked in WCAP-16394-P, Revision 0, "Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2," February 2005 (Proprietary), being transmitted by the Exelon Nuclear letter and Application for Withholding Proprietary Information from Public Disclosure, to the Document Control Desk. The proprietary information as submitted by Westinghouse for Byron and Braidwood Units 1 and 2 is expected to be applicable for other licensee submittals in response to certain NRC requirements for justification of the use of fracture mechanics analyses to support continued safe operation of Byron and Braidwood Units 1 and 2 with the presence of a crack in a control rod drive head penetration.

This information is part of that which will enable Westinghouse to:

(a) Determine the allowable time of safe operation if cracks are found.

(b) Assist the customer to obtain NRC approval.

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of similar information to its customers for purposes of meeting NRC requirements for licensing documentation.

(b) Westinghouse can sell support and defense of continued safe operation with the presence of cracks in a control rod drive head penetration.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar support documentation and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended.

Further the deponent sayeth not.

PROPRIETARY INFORMATION NOTICE

Transmitted herewith are proprietary and/or non-proprietary versions of documents furnished to the NRC in connection with requests for generic and/or plant-specific review and approval.

In order to conform to the requirements of 10 CFR 2.390 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.390(b)(1).

COPYRIGHT NOTICE

The reports transmitted herewith each bear a Westinghouse copyright notice. The NRC is permitted to make the number of copies of the information contained in these reports which are necessary for its internal use in connection with generic and plant-specific reviews and approvals as well as the issuance, denial, amendment, transfer, renewal, modification, suspension, revocation, or violation of a license, permit, order, or regulation subject to the requirements of 10 CFR 2.390 regarding restrictions on public disclosure to the extent such information has been identified as proprietary by Westinghouse, copyright protection notwithstanding. With respect to the non-proprietary versions of these reports, the NRC is permitted to make the number of copies beyond those necessary for its internal use which are necessary in order to have one copy available for public viewing in the appropriate docket files in the public document room in Washington, DC and in local public document rooms as may be required by NRC regulations if the number of copies submitted is insufficient for this purpose. Copies made by the NRC must include the copyright notice in all instances and the proprietary notice if the original was identified as proprietary.

Exelon Nuclear

Letter for Transmittal to the NRC

The following paragraphs should be included in your letter to the NRC:

Enclosed are:

1. 6 copies of WCAP-16394-P, Revision 0, Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2," February 2005 (Proprietary)

2. 6 copies of WCAP-16394-P, Revision 0, Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2," February 2005 (Non-proprietary)

Also enclosed is Westinghouse authorization letter CAW-05-2070 with accompanying affidavit, Proprietary Information Notice, and Copyright Notice.

As Item 1 contains information proprietary to Westinghouse Electric Company LLC, it is supported by an affidavit signed by Westinghouse, the owner of the information. The affidavit sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the considerations listed in paragraph (b) (4) of Section 2.390 of the Commission's' regulations.

Accordingly, it is respectfully requested that the information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.390 of the Commission's regulations.

Correspondence with respect to the copyright or proprietary aspects of the items listed above or the supporting Westinghouse affidavit should reference CAW-05-2070 and should be addressed to B. F. Maurer, Acting Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company LLC, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Attachment 5

WCAP-16394-NP, Non-Proprietary Version
Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations
To Support Continued Operation; Byron and Braidwood Units 1 and 2

(Non-Proprietary Version)

Westinghouse Non-Proprietary Class 3

WCAP-16394-NP
Revision 0

February 2005

Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2

Westinghouse

WCAP-16394-NP
Revision 0

Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: Byron and Braidwood Units 1 and 2

V. Q. Vo

February 2005

Verifier: _____
S. Jirawongkraisorn
Piping Analysis & Fracture Mechanics

Approved: _____
S. A. Swamy
Piping Analysis & Fracture Mechanics

Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

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1 INTRODUCTION

In September of 1991, a leak was discovered in the Reactor Vessel Control Rod Drive Mechanism (CRDM) head penetration region of an operating plant. This has led to the question of whether such a leak could occur at the CRDM penetrations of Byron and Braidwood Units 1 and 2. It shall be noted that the term "CRDM" is used generically in this report for any of the reactor vessel upper head penetrations, which includes the control rod mechanism, instrumentation penetrations, Part Length CRDM and spare penetrations. The typical geometry of interest for a CRDM penetration nozzle is shown in Figure 1-1. Throughout this report, the penetration rows have been identified by their angle of intersection with the head. The locations of the head penetrations for Byron and Braidwood Units 1 and 2 are shown in Figure 1-2 [1A, 2A, 3A, 4A] and the angles for each penetration are identified in Table 1-1 [1B, 1C, 2B, 2C, 3B, 3C, 4B, 4C]. Note that Byron Units 1 and 2 and Braidwood Units 1 and 2 have the same upper head penetration configurations.

The CRDM leak resulted from cracking in Alloy 600 base metal, which occurred in the outermost penetrations of a number of operating plants. The outermost CRDM locations, as well as a number of intermediate CRDM locations, were chosen for fracture mechanics analyses to support continued safe operation of Byron and Braidwood Units 1 and 2 if such cracks were to be found. The outermost penetrations were chosen due to the high stress level and the likelihood of cracking, while the intermediate penetrations were chosen to provide additional results so that a trend on crack growth may be established as a function of the radial locations of the penetration nozzles. The dimensions of all the CRDM penetrations are identical, with a 4.00 inch Outside Diameter (OD) and a wall thickness of 0.625 inches [1C, 2C, 3C, 4C]. All of these dimensions are summarized in Table 6-2.

The basis of the analysis was a detailed three-dimensional elastic-plastic finite element stress analysis of several penetration locations, as described in detail in Section 5 and a fracture analysis as described in Section 6. The fracture analysis was carried out using crack growth rates recommended by the EPRI Materials Reliability Program (MRP-55) [11A]. These rates are consistent with service experience. The results are presented in the form of flaw tolerance charts. If indications are found, the charts will determine the allowable service life of safe operation. The service life calculated in the flaw tolerance charts are all in Effective Full Power Years (EFPY).

Note that there are several locations in this report where proprietary information has been bracketed and deleted. For each of the bracketed locations, reasons for proprietary classifications are given using a standardized system. The proprietary brackets are labeled with three different letters to provide this information. The explanation for each letter is given below:

a. The information reveals the distinguishing aspects of a process or component, structure, tool, method, etc., and the prevention of its use by Westinghouse's competitors, without license from Westinghouse, gives Westinghouse a competitive economic advantage.

c. The information, if used by a competitor, would reduce the competitor's expenditure of resources or improve the competitor's advantage in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product.

e. The information reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

Table 1-1 Byron and Braidwood Units 1 and 2 Head Penetration Nozzles with Intersection Angles Identified [1B, 1C, 2B, 2C, 3B, 3C, 4B, 4C]

Nozzle No.	Angle (Degrees)	Nozzle No.	Angle (Degrees)	Nozzle No.	Angle (Degrees)
1	0.0	27	25.4	53	35.2
2	11.1	28	25.4	54	37.4
3	11.1	29	25.4	55	37.4
4	11.1	30	29.3	56	37.4
5	11.1	31	29.3	57	37.4
6	15.8	32	29.3	58	37.4
7	15.8	33	29.3	59	37.4
8	15.8	34	29.3	60	37.4
9	15.8	35	29.3	61	37.4
10	17.7	36	29.3	62	42.8
11	17.7	37	29.3	63	42.8
12	17.7	38	32.9	64	42.8
13	17.7	39	32.9	65	42.8
14	22.6	40	32.9	66	43.8
15	22.6	41	32.9	67	43.8
16	22.6	42	34.1	68	43.8
17	22.6	43	34.1	69	43.8
18	24.0	44	34.1	70	43.8
19	24.0	45	34.1	71	43.8
20	24.0	46	34.1	72	43.8
21	24.0	47	34.1	73	43.8
22	25.4	48	34.1	74	47.0
23	25.4	49	34.1	75	47.0
24	25.4	50	35.2	76	47.0
25	25.4	51	35.2	77	47.0
26	25.4	52	35.2	78	47.0

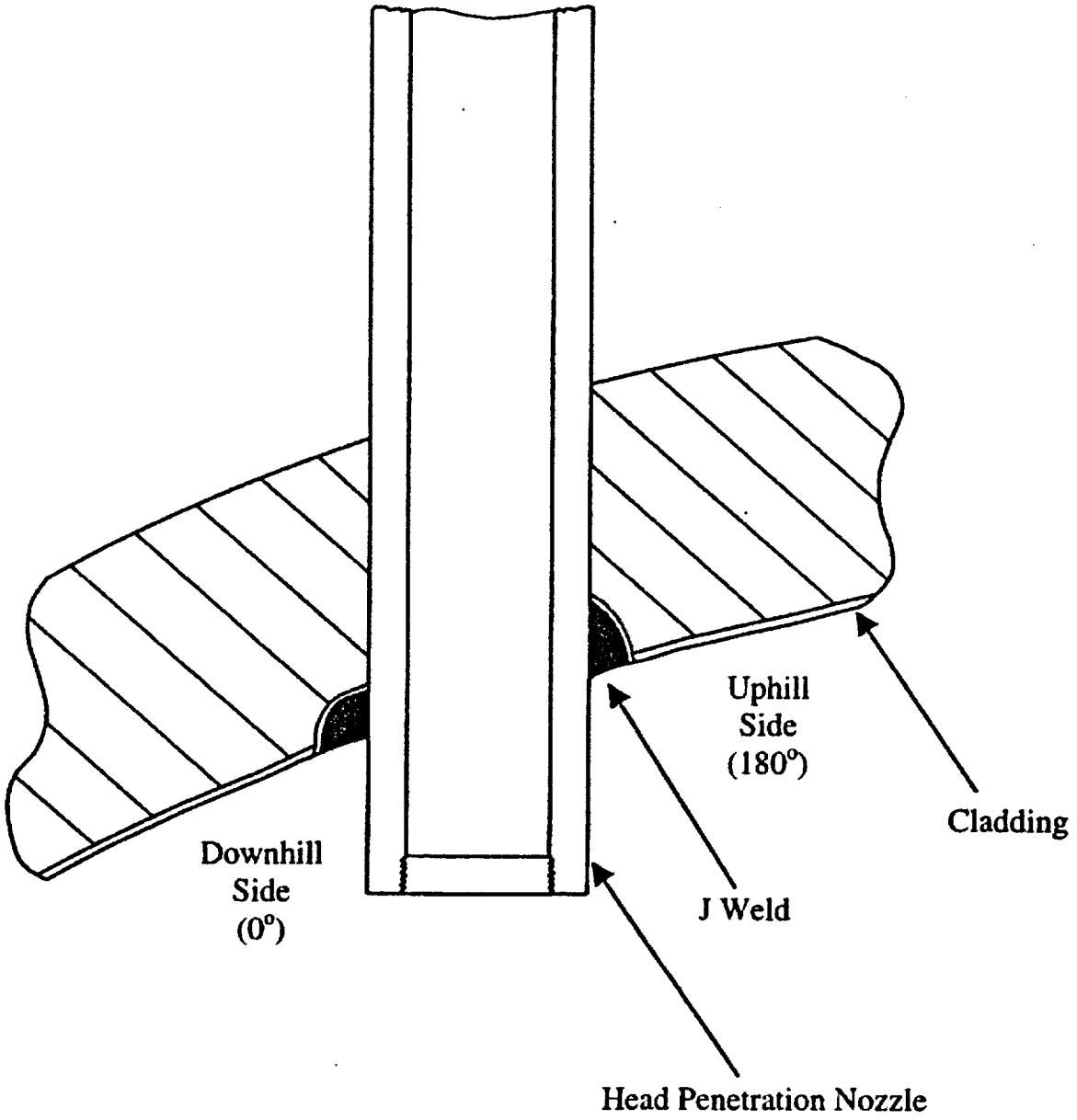


Figure 1-1 Typical Reactor Vessel Control Rod Drive Mechanism (CRDM) Penetration

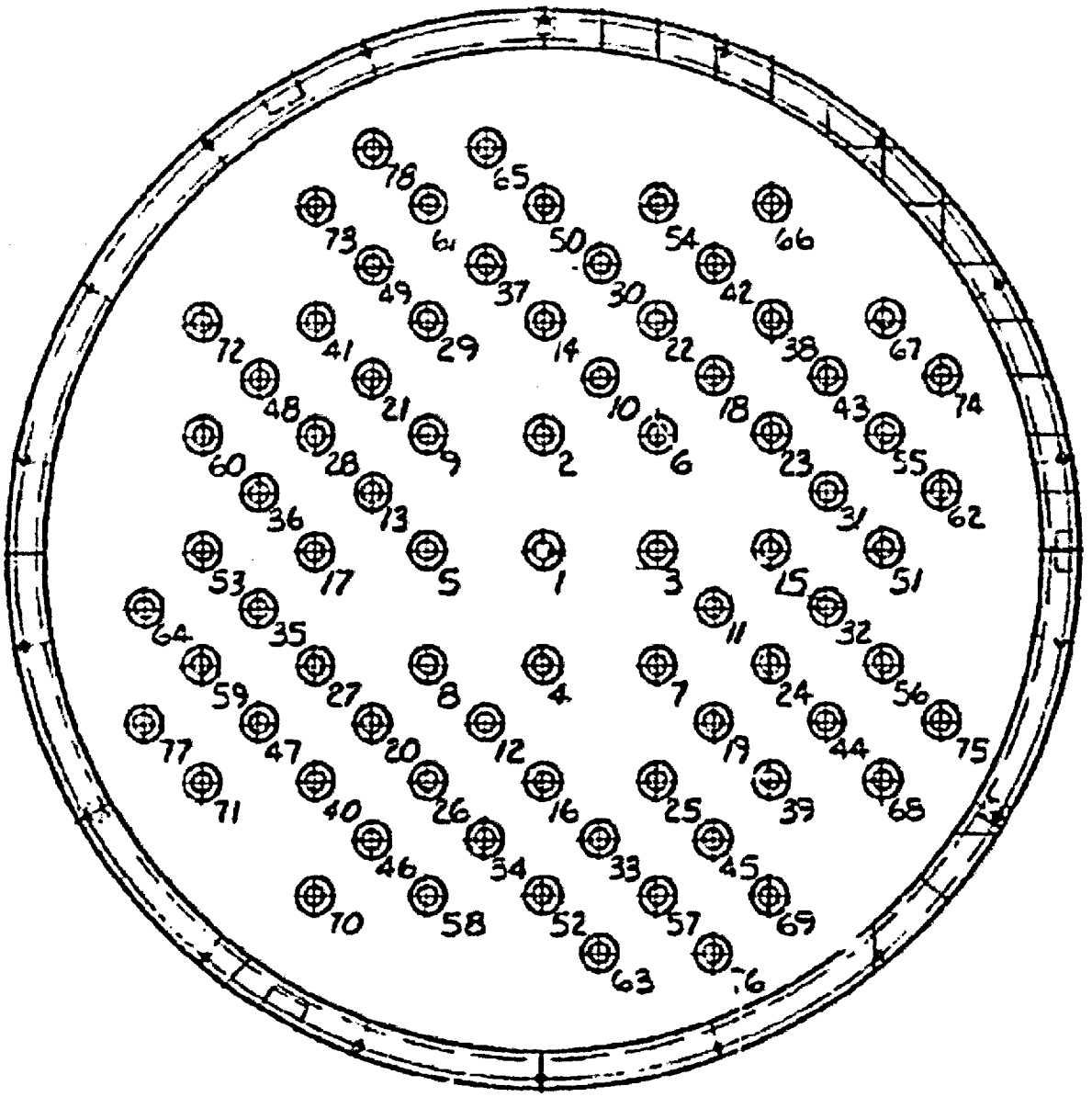


Figure 1-2 Location of Head Penetrations for Byron and Braidwood Units 1 and 2 [1A, 2A, 3A, 4A]

2 HISTORY OF CRACKING IN HEAD PENETRATIONS

In September of 1991, leakage was reported from the reactor vessel CRDM head penetration region of a French plant, Bugey Unit 3. Bugey 3 is a 920 megawatt three-loop Pressurized Water Reactor (PWR) plant which had just completed its tenth fuel cycle. The leak occurred during a post ten year hydrotest conducted at a pressure of approximately 3000 psi (204 bar) and a temperature of 194°F (90°C). The leak rate was estimated to be approximately 0.7 liter/hour. The location of the leak was subsequently established on a peripheral penetration with an active control rod (H-14), as seen in Figure 2-1.

The control rod drive mechanism and thermal sleeve were removed from this location to allow further examination. A study of the head penetration revealed the presence of longitudinal cracks near the head penetration attachment weld. Penetrant and ultrasonic testing confirmed the cracks. The cracked penetration was fabricated from Alloy 600 bar stock (SB-166), and has an outside diameter of 4 inches (10.16 cm) and an inside diameter of 2.75 inches (7.0 cm).

As a result of this finding, all of the control rod drive mechanisms and thermal sleeves at Bugey 3 were removed for inspection of the head penetrations. Only two penetrations were found to have cracks, as shown in Figure 2-1.

An inspection of a sample of penetrations at three additional plants were planned and conducted during the winter of 1991-92. These plants were Bugey 4, Fessenheim 1, and Paluel 3. The three outermost rows of penetrations at each of these plants were examined, and further cracking was found in two of the three plants.

At Bugey 4, eight of the 64 penetrations examined were found to contain axial cracks, while only one of the 26 penetrations examined at Fessenheim 1 was cracked. The locations of all the cracked penetrations are shown in Figure 2-1. At the time, none of the 17 CRDM penetrations inspected at Paluel 3 showed indications of cracking, however subsequent inspections of the French plants have confirmed at least one crack in each operating plant.

Thus far, the cracking in reactor vessel heads not designed by Babcock and Wilcox (B&W) has been consistent in both its location and extent. All cracks discovered by nondestructive examination have been oriented axially, and have been located in the bottom portion of the penetration in the vicinity of the partial penetration attachment weld to the vessel head as shown schematically in Figure 1-1.

One small, outside diameter initiated, circumferential flaw was found during destructive examination at Bugey 3. The flaw was found to have resulted from Primary Water Stress Corrosion Cracking (PWSCC) as a consequence of leakage of the PWR water from an axial through-wall crack into the annulus between the penetration and head.

Since November 2000, leaks were discovered in a total of 29 CRDM nozzles at seven Babcock & Wilcox designed plants:

- Oconee 1 (1 leaking nozzle)

- Oconee 2 (4 leaking nozzles)
- Oconee 3 (9 leaking nozzles)
- ANO-1 (1 leaking nozzle)
- Crystal River Unit 3 (1 leaking nozzle)
- Three Mile Island 1 (5 leaking nozzles)
- Davis Besse (8 leaking nozzles)

In addition, five of the eight smaller diameter thermocouple nozzles at Oconee 1, and all eight at Three Mile Island 1, were discovered to have leaks. All of these leaks were first detected during visual inspections of the top surface of the vessel heads for boric acid crystal deposits. In all cases, except Davis Besse, the quantity of boric acid crystals at each nozzle location was small (<1 in^3).

Destructive examinations of several specimens from cracked Oconee 1 and 3 nozzles showed that the leaks were the result of Primary Water Stress Corrosion Cracking (PWSCC). Non-destructive examinations of the leaking CRDM nozzles showed that most of the cracks were axially oriented, originating on the outside surface of the nozzles below the J-groove weld and propagating primarily in the nozzle base material to an elevation above the top of the J-groove weld. Leakage could then pass through the annulus to the top of the head where it was detected by visual inspection. In some cases the cracks initiated in the weld metal or propagated into the weld metal, and in a few cases the cracks propagated through the nozzle wall thickness to the inside surface.

In addition to the predominantly axial cracks, several nozzles had cracks on the outside surface of the nozzle approximately following the weld contour above or below the J-groove weld. At least eight of these nozzles (three in Oconee 3, one in Oconee 2, one in Crystal River 3, and three in Davis Besse) were found to have cracks approximately following the weld contour just above the J-groove weld. Two of the nozzles had relatively short and shallow cracks. Two of these nozzles had cracks either through-wall or essentially through-wall over an arc length of about 165° around the nozzle centered approximately about the nozzle uphill side. Cracks which follow the weld contour are a greater concern than axial cracks in that they raise the potential for a nozzle to be ejected if a through-wall crack extends more than about [ ]^{a,c,e}

Seventeen additional non-leaking Oconee 1 and nine non-leaking Oconee 3 CRDM nozzles were inspected by eddy current, ultrasonic testing, or eddy current and ultrasonic testing to assess the extent of the condition of non-leaking nozzles in the vessel head. No significant cracking was found in any of these additional nozzles.

The experience at Oconee, Three Mile Island, Crystal River, Davis Besse, and ANO-1 differs from previous industry experience in that the cracking appears to initiate primarily on the outside surface of the nozzle below the weld rather than on the nozzle Inside Diameter (ID) surface. Five of the nozzles had also developed OD-initiated flaws approximately following the contour of the top of the J-groove weld. These CRDM tubes have shown no pattern of cracking, whereas the previous CRDM tubes were cracking only in the outermost three rows.

The cracking has now been confirmed to be primary water stress corrosion cracking. Relatively high residual stresses are produced in the outermost CRDM penetrations due to the welding process. Other important factors which affect this process are temperature and time, with higher temperatures and longer times being more detrimental.

All three Nuclear Steam Supply System (NSSS) Owners Groups submitted safety assessments to the USNRC between 1993 and 1994 in response to the leakage observed in Bugey Unit 3. The analyses demonstrated that CRDM nozzles are capable of accommodating long through-wall axial flaws and the resulting leakage. The analyses also demonstrated that the CRDM nozzles are capable of accommodating significant circumferential flaws above the J-groove weld. After reviewing the safety assessment submitted by the industry and examining international inspection findings, the USNRC concluded that CRDM nozzle and weld cracking observed to that time in Pressurized Water Reactor (PWR) facilities was not an immediate safety concern.

USNRC issued Generic Letter (GL) 97-01, "Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations," on April 1, 1997. Responses to GL 97-01 were predicated on the development of susceptibility ranking models to relate the operating conditions for each plant to the plant's relative susceptibility to PWSCC. The industry committed to surface examinations (i.e., eddy current) of the vessel head penetration nozzles for plants with the highest relative susceptibility ranking.

In response to the inspection findings at Oconee in November 2000 and because existing requirements in the ASME Code and NRC regulations do not adequately address inspections of RPV head penetrations for degradation due to PWSCC, the NRC then issued Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles," dated August 3, 2001. In response to the bulletin, plans for inspecting the vessel head penetration nozzles and/or the outside surface of the reactor vessel head to determine whether the nozzles were leaking was provided by the industry.

On March 18, 2002, the NRC issued Bulletin 2002-01 in response to the head degradation found at Davis-Besse Nuclear Power Station, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," which requested that information be provided on the reactor vessel head inspection and maintenance programs, the material condition of the reactor vessel heads, and the boric acid inspection programs.

As a result of the circumferential cracking of vessel head penetration nozzles at Oconee Nuclear Station 3 and other PWR facilities, the vessel head material degradation at Davis-Besse, and NRC review of the responses to NRC Bulletins 2001-01 and 2002-01, NRC has a number of concerns about the inspection requirements and programs for RPV head and VHP nozzles. Based on the experience and information currently available concerning cracking and degradation, until there is a better understanding of the wastage phenomenon and wastage rates, it may be necessary for inspection programs that rely on visual examinations to be supplemented with additional measures (e.g., volumetric and surface examinations) to demonstrate compliance with applicable regulations. The NRC issued Bulletin 2002-02, "Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs," dated August 9, 2002, requested that information be

provided on the inspection programs and any plans to supplement existing visual inspections with additional measures (e.g., volumetric and surface examinations).

Inspections performed at several PWR plants in late 2002 found leakage and cracks in nozzles or J-groove welds that have required repairs or prompted the replacement of the RPV head. In addition, as discussed in NRC Information Notice 2003-02, "Recent Experience with Reactor Coolant System Leakage and Boric Acid Corrosion," issued on January 16, 2003, leakage has recently occurred at some plants from connections above the RPV head and has required additional assessments and inspections to ensure that the leakage has not caused significant degradation of RPV heads.

Revising the ASME Code and subsequently the NRC regulations will take several years. The resulting inspection plans and responses to the NRC bulletins have provided reasonable assurance of adequate protection of public health and safety for the near term operating cycles, but cannot be relied upon to do so for the entire interim period until NRC regulations are revised. Consequently, it is necessary to establish a minimum set of RPV head inspection requirements, as a supplement to existing inspection and other requirements in the ASME Code and NRC regulations, through the issuance of NRC Order EA-03-009 on February 11, 2003. The first revised Order EA-03-009 was issued on February 20, 2004 to revise certain aspects of the original order in response to some of the common issues emerging from the numerous relaxation requests from the original order.

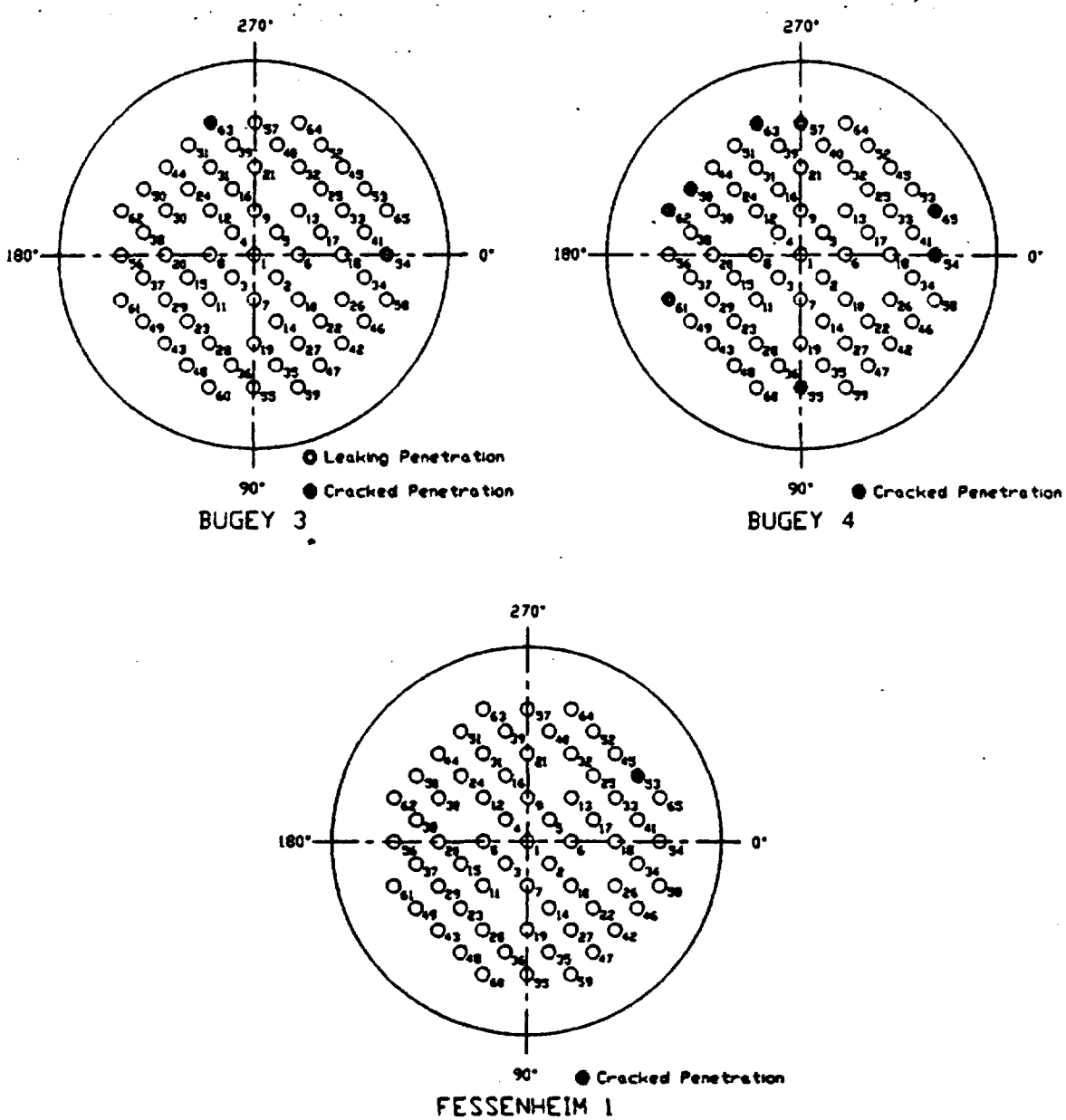


Figure 2-1 EDF Plant R/V Closure Head CRDM Penetrations – Penetrations with Cracking

3 OVERALL TECHNICAL APPROACH

The primary goal of this work is to provide technical justification for the continued safe operation of Byron and Braidwood Units 1 and 2 in the event that cracking is discovered during in-service inspections of the Alloy 600 reactor vessel upper head penetrations.

3.1 PENETRATION STRESS ANALYSIS

Three-dimensional elastic-plastic finite element stress analyses applicable to Byron and Braidwood Units 1 and 2 were performed in [6]. The results from these analyses were used to determine the stresses in the head penetration region for Byron and Braidwood Units 1 and 2. The analyses considered the pressure loads associated with steady state operation, as well as the residual stresses that are produced by the fabrication process.

A number of rows of penetrations, including those nearest the head flange, which is the region where cracking has been discovered in other non-B&W design plants, were analyzed using the finite element analysis method. In addition, several other rows of penetrations and the center CRDM penetrations were analyzed to provide additional results, so a trend can be established as a function of radial location. The calculated stresses as well as field-measured deformation have been found to be more severe at the outermost location. The stress analysis will be used to provide input directly to the crack growth analysis.

The stress analysis provides the key input to the flaw tolerance evaluation, which is described below.

3.2 FLAW TOLERANCE APPROACH

A flaw tolerance approach has been developed to allow continued safe operation until an appropriate time for repair, or the end of plant life. The approach is based on the prediction of future growth of detected flaws, to ensure that such flaws would remain stable.

If an indication is discovered during in-service inspection, its size can be compared with the flaw size considered as allowable for continued service. This "allowable" flaw size is determined from the actual loading (including mechanical and residual loads) on the head penetration for Byron and Braidwood Units 1 and 2. Acceptance criteria are discussed in Section 6.5.

The time for the observed crack to reach the allowable crack size determines the length of time the plant can remain online before repair, if required. For the crack growth calculation, a best estimate is needed and no additional margins are necessary.

The results of the evaluation are presented in terms of simple flaw tolerance charts. The charts graphically show the time required to reach the allowable length or depth, which represents additional service life before repair. This result is a function of the loading on the particular head penetration as well as the circumferential location of the crack in the penetration nozzle.

Schematic drawings of the head penetration flaw tolerance charts are presented as Figure 3-1. This type of chart can be used to provide estimates of the remaining service life before a leak would develop from an observed crack. For example, if a part-through flaw was discovered, the user would refer to Figure 3-1, to determine the time (t_P) which would be remaining before the crack would penetrate the wall or reach the allowable depth (t_a) (e.g. a/t = 0.75).

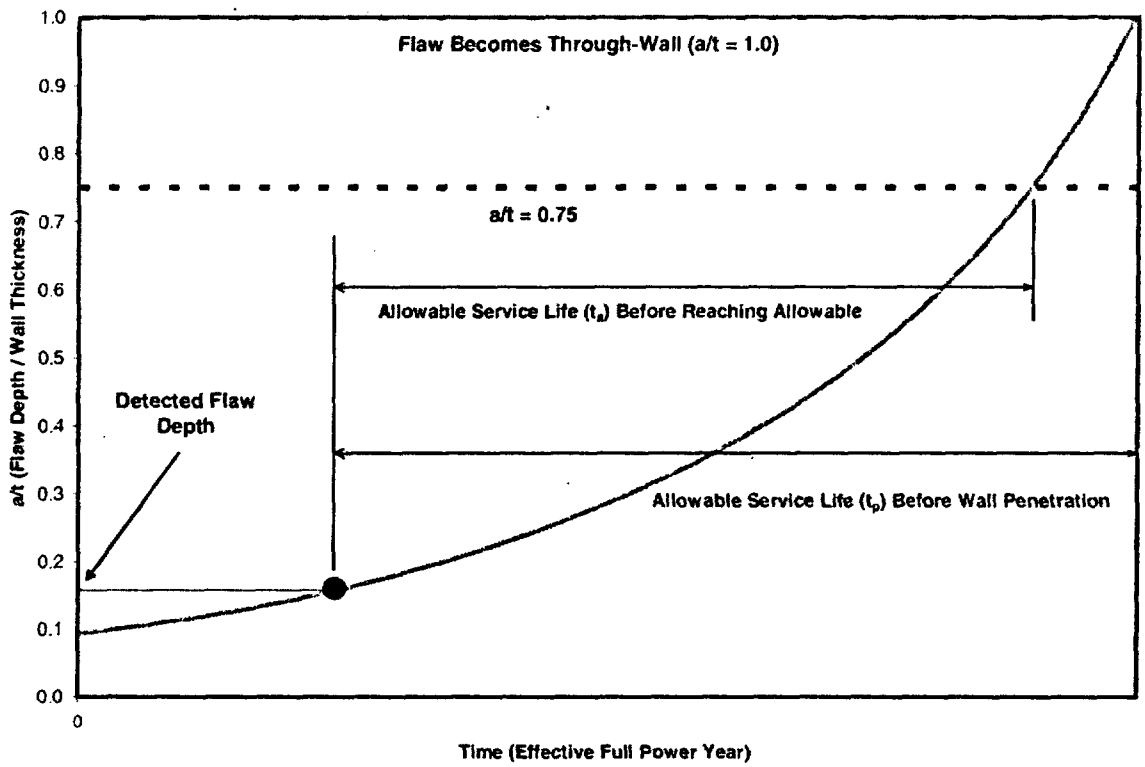


Figure 3-1 Schematic of a Head Penetration Flaw Growth Chart for Part-Through Flaws

4 MATERIAL PROPERTIES, FABRICATION HISTORY AND CRACK GROWTH PREDICTION

4.1 MATERIALS AND FABRICATION

The reactor vessels for Byron and Braidwood Units 1 and 2 were manufactured from material produced by Babcock and Wilcox. The carbon content and mechanical properties of the Alloy 600 material used to fabricate the Byron and Braidwood Units 1 and 2 vessels are provided in Tables 4-1, 4-2, 4-3, and 4-4 [7]. Figures 4-1 and 4-2 illustrate the yield strengths and carbon content, based on percent of heats, of the head adapter penetrations in the Byron and Braidwood Units 1 and 2 vessels relative to a sample of the French head penetrations which have experienced cracking. The head adapter penetrations in Byron and Braidwood Units 1 and 2 are similar in carbon content, but in general lower in yield strength relative to those on the French vessels. These are only some of the significant factors contributing to the material resistance to PWSCC in the head penetrations.

4.2 CRACK GROWTH PREDICTION

The cracks in the penetration region have been determined to result from primary water stress corrosion cracking in the Alloy 600 base metal and, in some cases, the Alloy 182 weld metal. There are a number of available measurements of static load crack growth rates in primary water environment, and in this section the available results will be compared and a representative growth rate established.

Direct measurements of Stress Corrosion Cracking (SCC) growth rates in Alloy 600 are relatively rare. Also, care should be used when interpreting the results because the materials may be excessively cold worked, or the loading applied may be near or exceeding the limit load of the penetration nozzle, meaning there will be an interaction between tearing and crack growth. In these cases the crack growth rates may not be representative of service conditions.

The effort to develop a reliable crack growth rate model for Alloy 600 began in the spring of 1992, when the Westinghouse Owners Group began to develop a safety case to support continued operation of plants. At the time, there was no available crack growth rate data for head penetration materials, and only a few publications existed on growth rates of Alloy 600 in any product form.

The best available publication at that time was that of Peter Scott of Framatome, who had developed a growth rate model for PWR steam generator materials [8]. His model was based on a study of results obtained by McIlree, Rebak and Smialowska [9] who had tested short steam generator tubes which had been flattened into thin compact specimens.

An equation was fitted to the data of reference [9] for the results obtained in water chemistries that fell within the standard specification for PWR primary water. Results for chemistries outside the specification were not used. The following equation was fitted to the data at 330°C (626°F):

$$\frac{da}{dt} = 2.8 \times 10^{-11} (K - 9)^{1.16} \text{ m/sec} \tag{4-1}$$

where:

K is in MPa$\sqrt{m}$

The next step was to correct these results for the effects of cold work. Based on work by Cassagne and Gelpi [10], Scott concluded that dividing the above equation by a factor of 10 would be appropriate for noncold-worked material. The crack growth law for 330°C (626°F) then becomes:

$$\frac{da}{dt} = 2.8 \times 10^{-12} (K - 9)^{1.16} \text{ m/sec} \tag{4-2}$$

Scott further corrected this law for the effects of temperature. This forms the basis for the PWR Materials Reliability Program (MRP) recommended crack growth rate (CGR) curve for the evaluation of SCC where a power-law dependence on stress intensity factor was assumed [11A]. The MRP recommended CGR curve was used in this report for determining the primary water stress corrosion crack growth rate and a brief discussion on this recommended curve is as follows:

The EPRI-MRP crack growth review team, an international panel of experts in the area of SCC crack growth, provided input to the MRP in its development of the recommended CGR curve. This group met to review the available worldwide data on October 2-4, 2001, in Airlie, Virginia. The PWR Materials Reliability Program (MRP) has developed a recommended crack growth rate (CGR) curve for primary water stress corrosion cracking (PWSCC) of Alloy 600 materials. [

]a,c,e

[

]a,c,e

There is a general agreement that crack growth in Alloy 600 materials in the primary water environment can be modeled using a power-law dependence on stress intensity factor with differences in temperature accounted for by an activation energy (Arrhenius) model for thermally controlled processes. Figure 4-3 shows the recommended CGR curve along with the laboratory data from Huntington materials used to develop the curve.

[

]a,c,e

[redacted]

The MRP crack growth curve was structured to bound 75 percent of the 26 heats for which test results were available. Fits were done on the results for each heat, and the constant term was determined for each heat. This was done to eliminate the concern that the curve might be biased from a large number of results from a single heat. The 75th percentile was then determined from these results. The MRP expert panel on crack growth endorsed the resulting curve unanimously in a meeting on March 6th and 7th 2002. This approach is consistent with the Section XI flaw evaluation philosophy, which is to make a best estimate prediction of future growth of a flaw. Margins are incorporated in the allowable flaw sizes. The entire data set is shown in Figure 4-3, where the data have been adjusted to a single temperature of 325°C.

The applicability of the MRP recommended model to head penetrations was recently confirmed by two independent approaches. The first was a collection of all available data from Standard Steel and Huntington Alloys materials tested over the past ten years [11A]. The results are shown in Figure 4-3, along with the Scott model for the test temperature.

A second independent set of data were used to validate the model, and these data were obtained from the two inspections carried out on penetration no. 75 of D. C. Cook Unit 2, which was first found to be cracked in 1994 [11M]. The plant operated for one fuel cycle before the penetration was repaired in 1996 and the flaw was measured again before being repaired. These results were used to estimate the PWSCC growth rate for both the length of the flaw and its depth. These two points are also shown in Figure 4-4, and are consistent with the laboratory data for Huntington materials. In fact, Figure 4-4 demonstrates that the MRP model is nearly an upper bound for these materials. The D. C. Cook Unit 2 penetrations were made from Huntington materials.

Since the applicable temperature range for the Byron and Braidwood Units 1 and 2 upper head region is between 547°F and 558°F, the upper bound temperature of 558°F is used as the bounding upper head temperature for Byron and Braidwood Units 1 and 2. A temperature adjustment on the crack growth rate is necessary since the crack growth rate is strongly affected by temperature. The temperature correction was obtained from study of both laboratory and field data for stress corrosion crack growth rates for Alloy 600 in primary water environments. The available data showing the effect of temperature are summarized in Figure 4-5. Most of the results shown here are from steam generator tube materials, with several sets of data from operating plants, and results from two heats of materials tested in a laboratory [11B].

Study of the data shown in Figure 4-5 results in an activation energy of 31-33 Kcal/mole, which can then be used to adjust for the lower operating temperature. This value is slightly lower than the generally accepted activation energy of 44-50 Kcal/mole used to characterize the effect of temperature on crack initiation, but the trend of the actual data for many different sources is unmistakable.

[

]a,c,e Therefore the following crack growth rate model was used in the crack growth calculation for both Byron and Braidwood Units 1 and 2 head penetrations.

$$\frac{da}{dt} = 5.88 \times 10^{-13} (K - 9)^{1.16} \text{ m/sec}$$

where:

K = applied stress intensity factor, in $MPa\sqrt{m}$

This equation implies a threshold for cracking susceptibility, $K_{ISCC} = 9\ MPa\sqrt{m}$. The crack growth rate is applicable to propagation in both axial and circumferential directions.

Table 4-1 Byron Unit 1 R/V Head Adapter Material Information [7]

a,c,e

Table 4-2 Byron Unit 2 R/V Head Adapter Material Information [7]

a,c,e

Table 4-3 Braidwood Unit 1 R/V Head Adapter Material Information [7]

a,c,e

Table 4-4 Braidwood Unit 2 R/V Head Adapter Material Information [7]

a,c,e

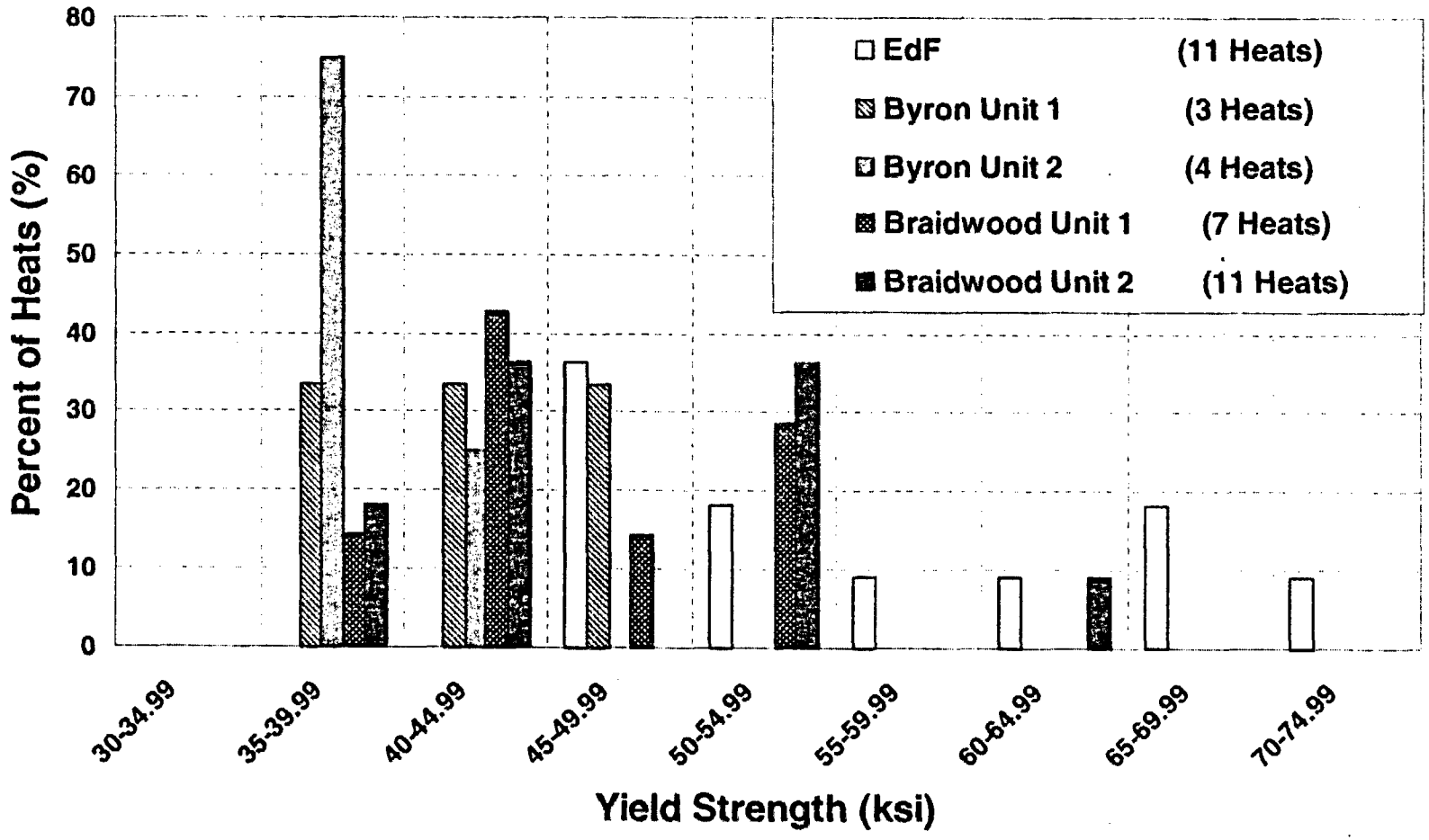


Figure 4-1 Yield Strength of the Various Heats of Alloy 600 Used in Fabricating the Byron and Braidwood Units 1 and 2 and French HeadPenetrations

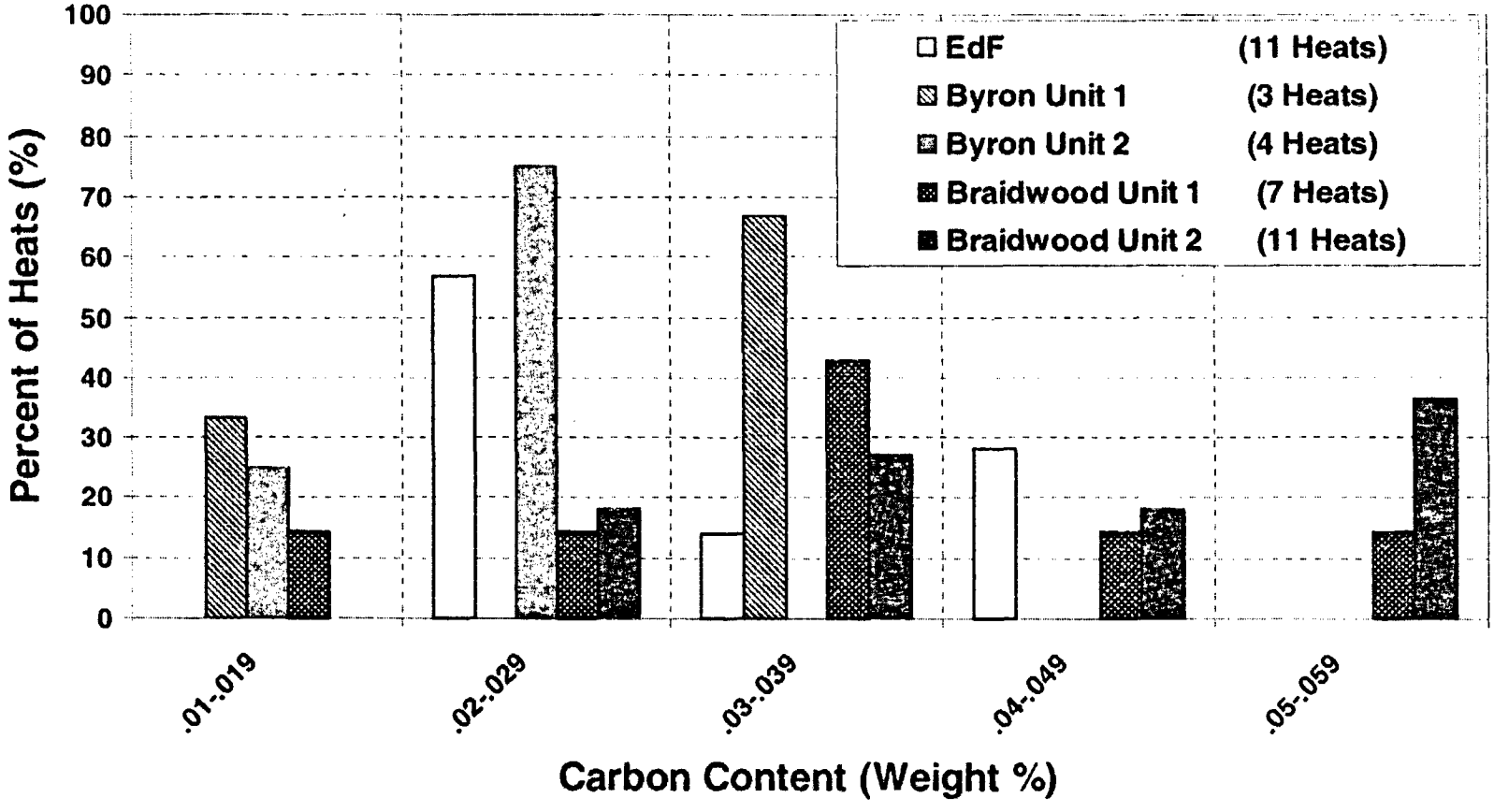


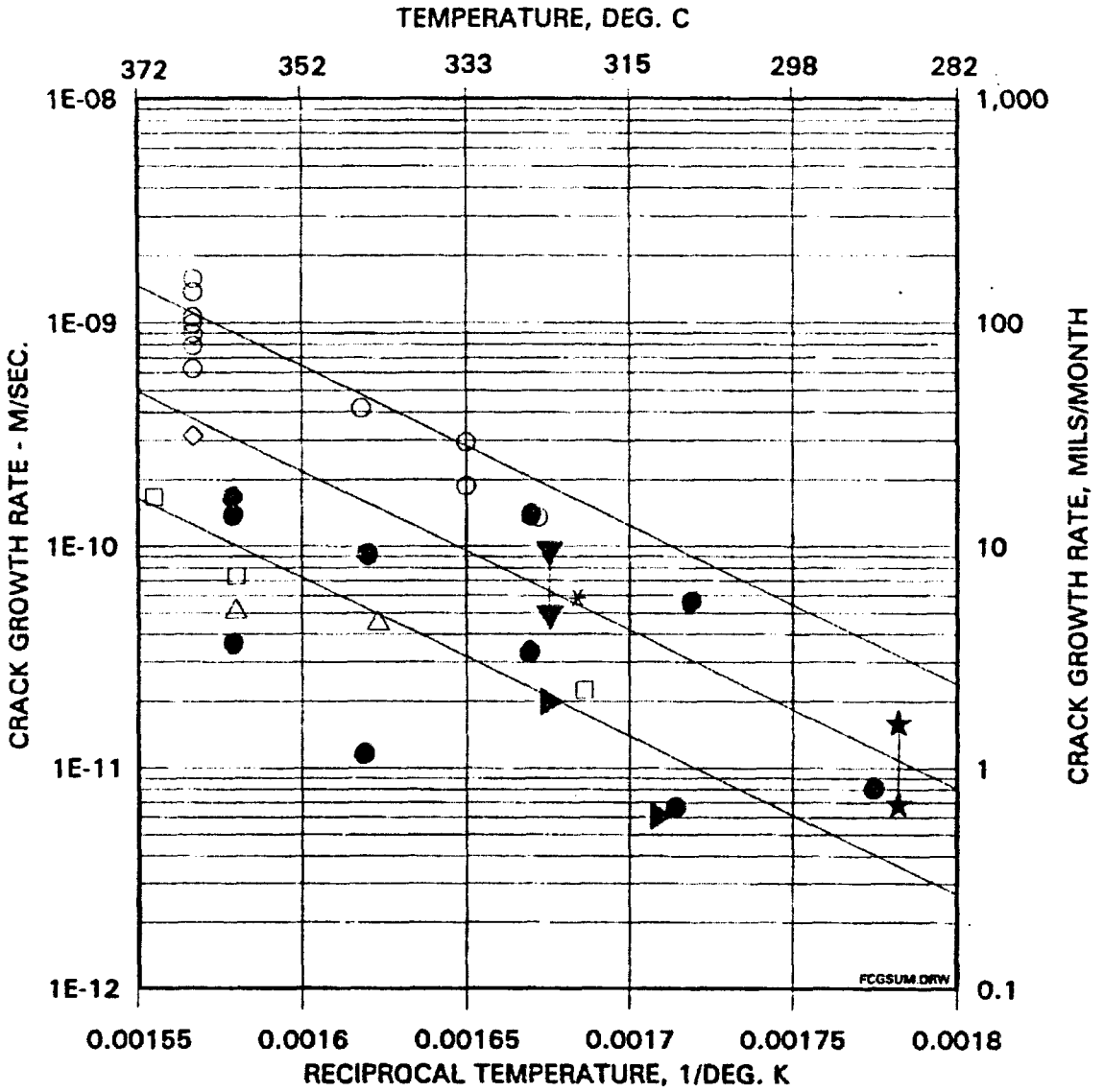
Figure 4-2 **Carbon Content of the Various Heats of Alloy 600 Used in Fabricating the Byron and Braidwood Units 1 and 2 and French Head Penetration**

a,c,e

Figure 4-3 Screened Laboratory Data for Alloy 600 with the MRP Recommended Curve (Note that the Modified Scott Model is also Shown)

Figure 4-4 Model for PWSCC Growth Rates in Alloy 600 in Primary Water Environments (325°C), With Supporting Data from Standard Steel, Huntington, and Sandvik Materials

Note that the data have been normalized to a temperature of 325°C (617°F). The actual test temperatures are listed in parenthesis after the caption. For example, the Huntington data were obtained at temperature ranging from 315°C to 331°C (599°F to 628°F).



Note: All symbols are for steam generator materials, except the solid circles, which are head penetration laboratory data.

Figure 4-5 Summary of Temperature Effects on PWSCC Growth Rates for Alloy 600 in Primary Water

5 STRESS ANALYSIS

5.1 OBJECTIVES OF THE ANALYSIS

The objective of this analysis was to obtain accurate stresses in each CRDM and its immediate vicinity. To do so, it requires a three dimensional analysis which considers all the pertinent loadings on the penetration [6]. The stress analyses were performed for Byron and Braidwood Units 1 and 2. An investigation of deformations at the lower end of the housing was also performed using the model. Five CRDM locations were considered: 0 degree (penetration no. 1), 25.4 degrees (penetration nos. 22 through 29), 42.8 degrees (penetration nos. 62 through 65), 43.8 degrees (penetration nos. 66 through 73), and 47.0 degrees (penetration nos. 74 through 78).

The analyses were used to provide information for the flaw tolerance evaluation, which follows in Section 6. Also, the results of the stress analysis were compared to the findings from service experience, to help assess the causes of the cracking which has been observed.

5.2 MODEL

A three-dimensional finite element model comprised of isoparametric brick and wedge elements was used to obtain the stresses and deflections. Views of CRDM model is shown in Figure 5-1. Taking advantage of the symmetry of the vessel head, only half of the CRDM penetrations were modeled. Similarly, only half of the center penetration was modeled.

In the models, the lower portion of the Control Rod Drive Mechanism (CRDM) penetration nozzle, the adjacent section of the vessel closure head, and the joining weld were modeled. The vessel to penetration nozzle weld was simulated with two weld passes. The penetration nozzle, weld metal, cladding and the vessel head shell were modeled in accordance with the relevant materials.

The only loads used in the analysis are the steady state operating loads. External loads, such as seismic loads, have been studied and have no impact since the penetration nozzles are captured by the full thickness of the reactor vessel head into which the penetrations are shrunk fit during construction. In addition, the duration of the seismic loading is very short and will not have any significant impact on the overall primary stress corrosion crack (PWSCC) growth. The area of interest is in the penetration near the attachment weld, which is unaffected by these external loads.

5.3 STRESS ANALYSIS RESULTS – OUTERMOST CRDM PENETRATION (47.0°)

Figure 5-2 presents the hoop and axial stresses for the steady state condition for the outermost CRDM penetration.

The hoop stresses for steady state operation are much greater than the axial stresses. This is consistent with the field findings, where the cracks discovered are generally oriented axially. Typically, in-service cracks will orient themselves perpendicular to the largest stress component. Also it should be noted from Figure 5-2 that the highest tensile hoop stresses are at the uphill side

and downhill side locations rather than midway around the penetration, where they are compressive. This is consistent with finding the axial cracks only at the uphill side and downhill side locations. It is these steady state stresses that will be used to predict crack extension in the penetrations, as will be discussed further in Section 6.

These stress findings also support the safety argument that cracks are unlikely to propagate in the circumferential direction, because the axial stresses are relatively low. This is illustrated in a cut taken along the plane of the top of the attachment weld, as shown in Figure 5-7. Note the area of compressive axial stress near mid-wall of the penetration, which extends for nearly the entire circumference.

5.4 STRESS ANALYSIS RESULTS – INTERMEDIATE CRDM PENETRATIONS

The stresses in these penetrations are similar in character. Figures 5-3, 5-4, and 5-5 show the results for the 43.8 degree, 42.8 degree, and 25.4 degree CRDM penetrations respectively. As with the outermost housing, the hoop stresses for steady state operation are greater than the axial stresses.

5.5 STRESS ANALYSIS RESULTS – CENTER CRDM PENETRATION

Figure 5-6 shows the hoop and axial stresses at steady state for the center CRDM penetration. The tube hoop stresses near the weld are generally lower than the tube hoop stresses at the downhill side or uphill side locations of the outer head penetration.

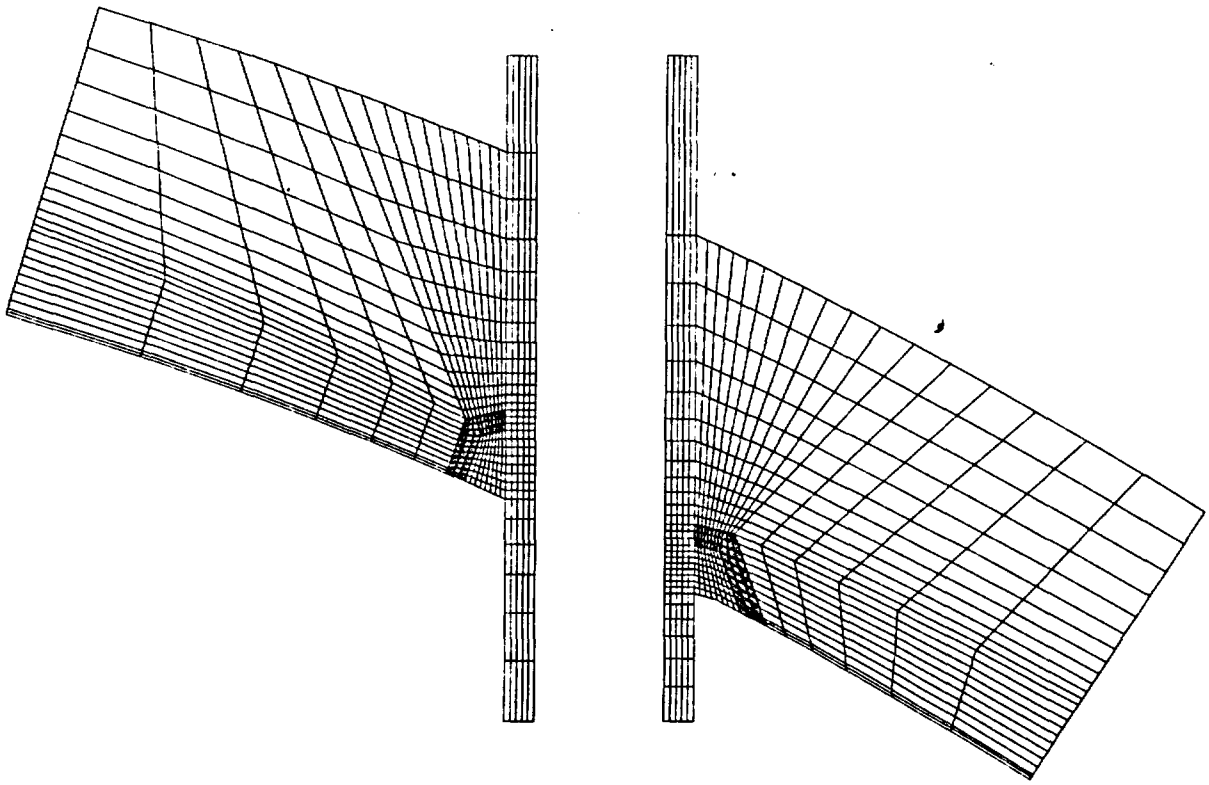
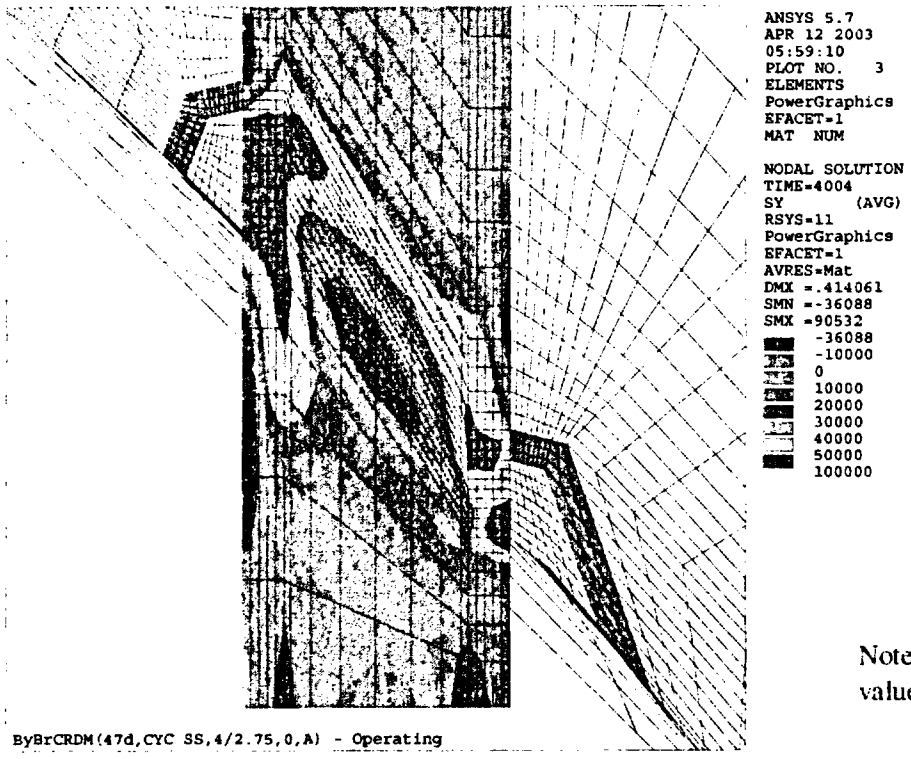
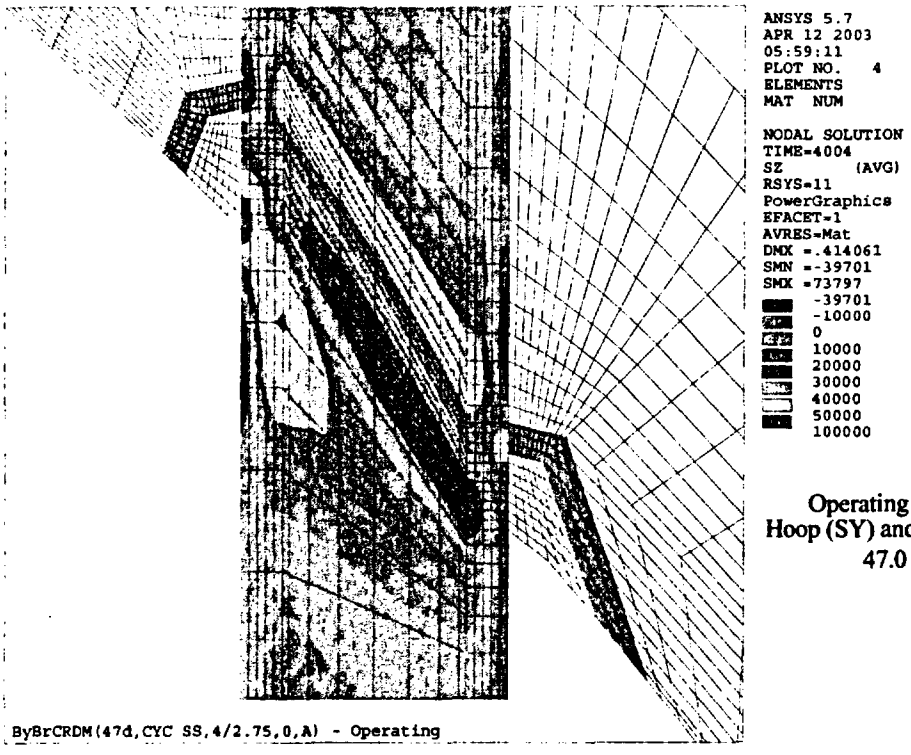


Figure 5-1 Finite Element Model of CRDM Penetration

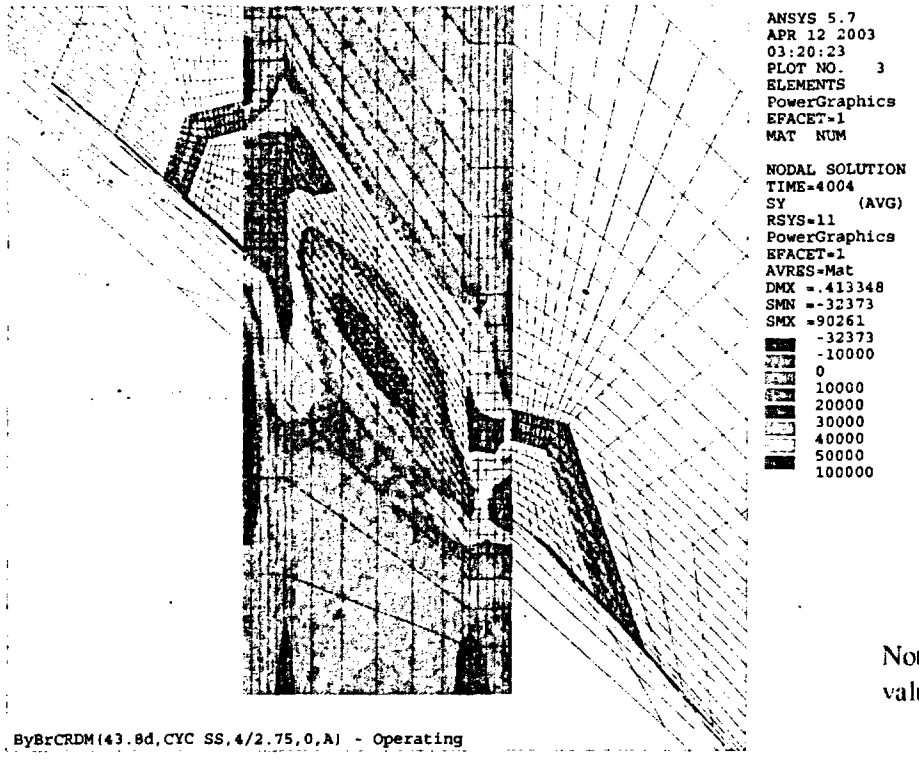


Note: The magnitude of the stress values shown is in psi

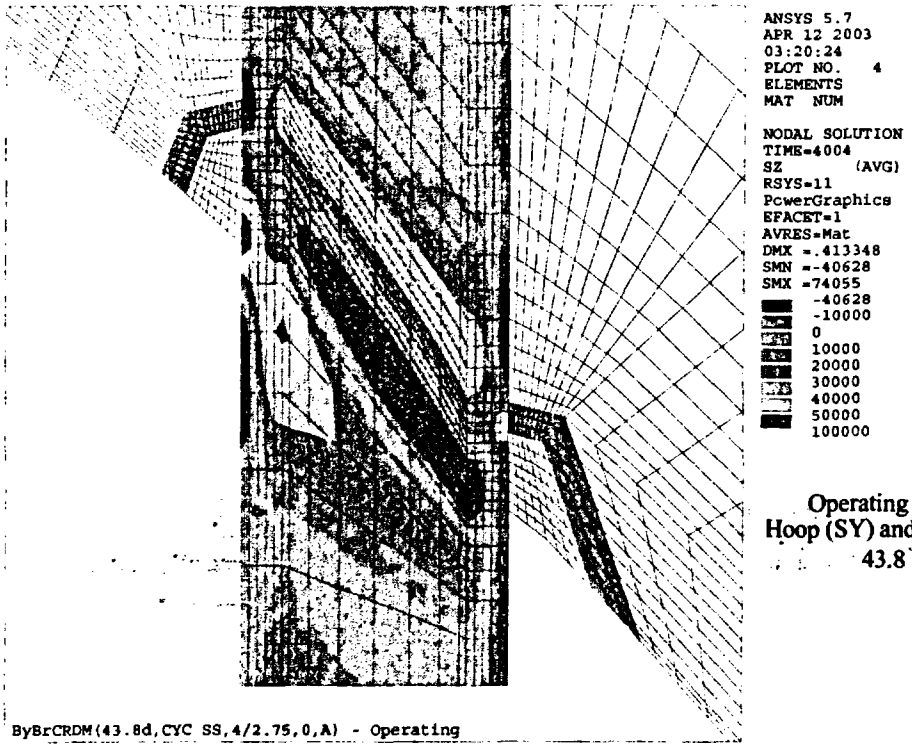


Operating plus Residual
Hoop (SY) and Axial (SZ) Stress
47.0 CRDM

Figure 5-2 Stress Distribution at Steady State Conditions: Outermost CRDM Penetration Nozzle (47.0 Degrees) (Hoop Stress is the Top Figure, Axial Stress is the Bottom Figure)

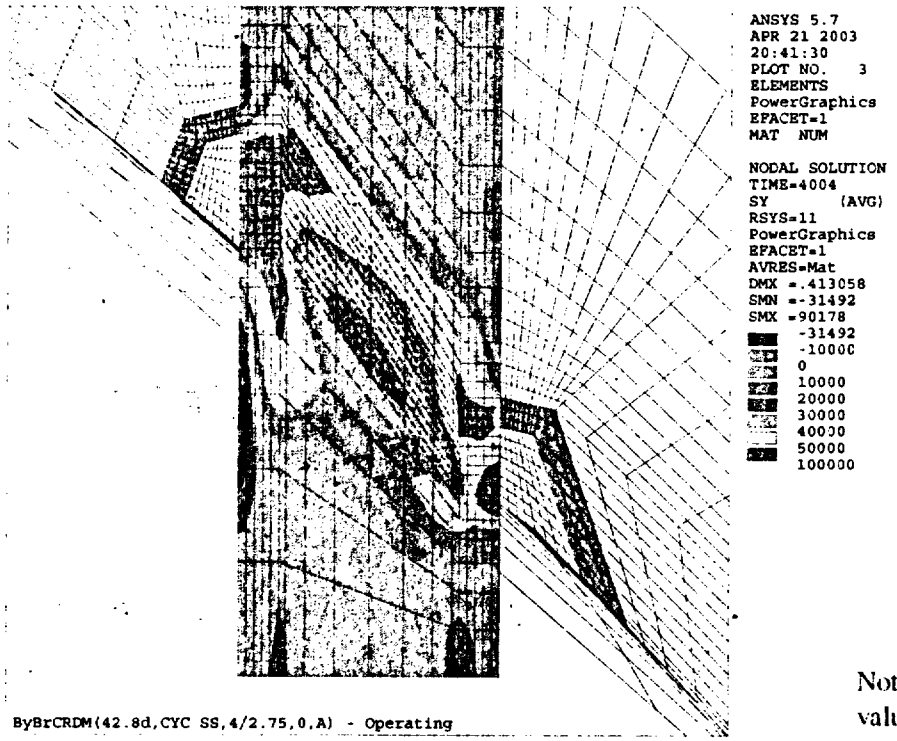


Note: The magnitude of the stress values shown is in psi

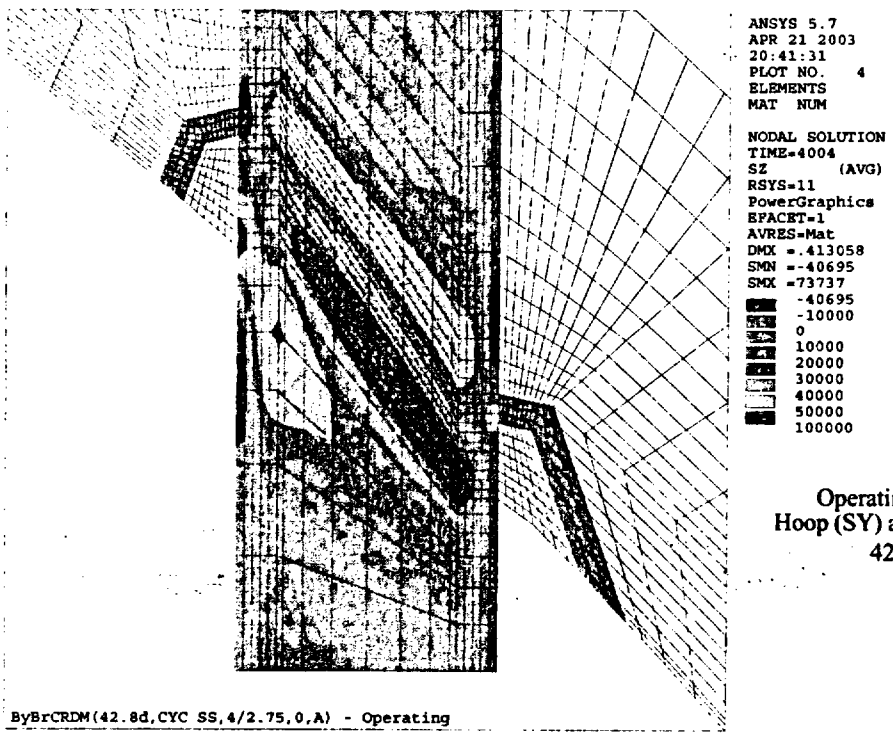


Operating plus Residual Hoop (SY) and Axial (SZ) Stress 43.8° CRDM

Figure 5-3 Stress Distribution at Steady State Conditions for the 43.8 Degrees CRDM Penetration (Hoop Stress is the Top Figure; Axial Stress is the Bottom Figure)

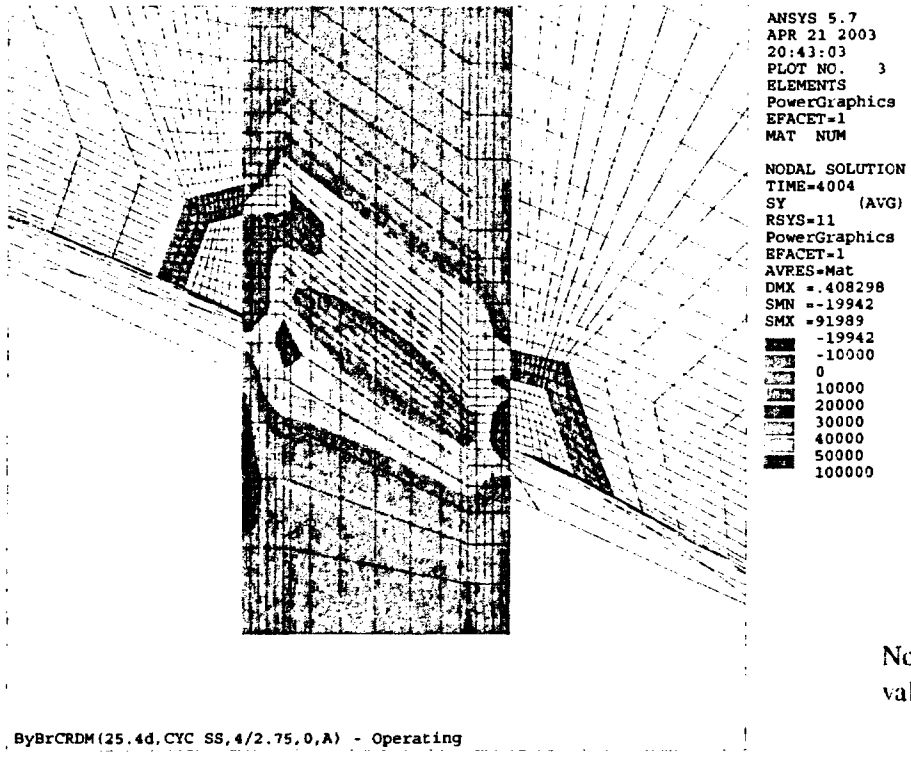


Note: The magnitude of the stress values shown is in psi

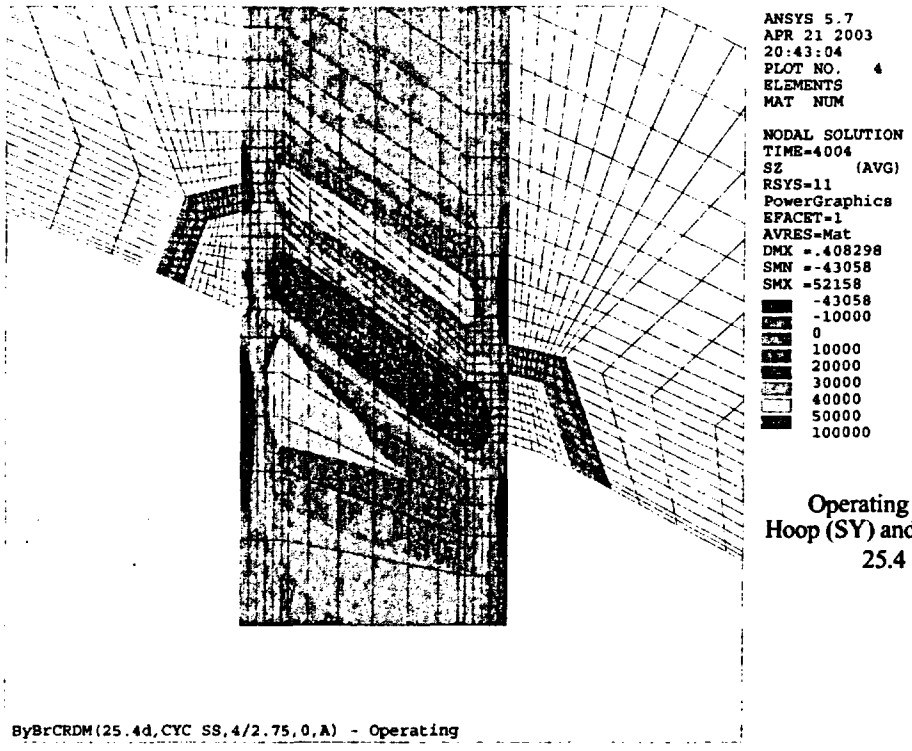


Operating plus Residual
Hoop (SY) and Axial (SZ) Stress
42.8 CRDM

Figure 5-4 Stress Distribution at Steady State Conditions for the 42.8 Degrees CRDM Penetration (Hoop Stress is the Top Figure; Axial Stress is the Bottom Figure)

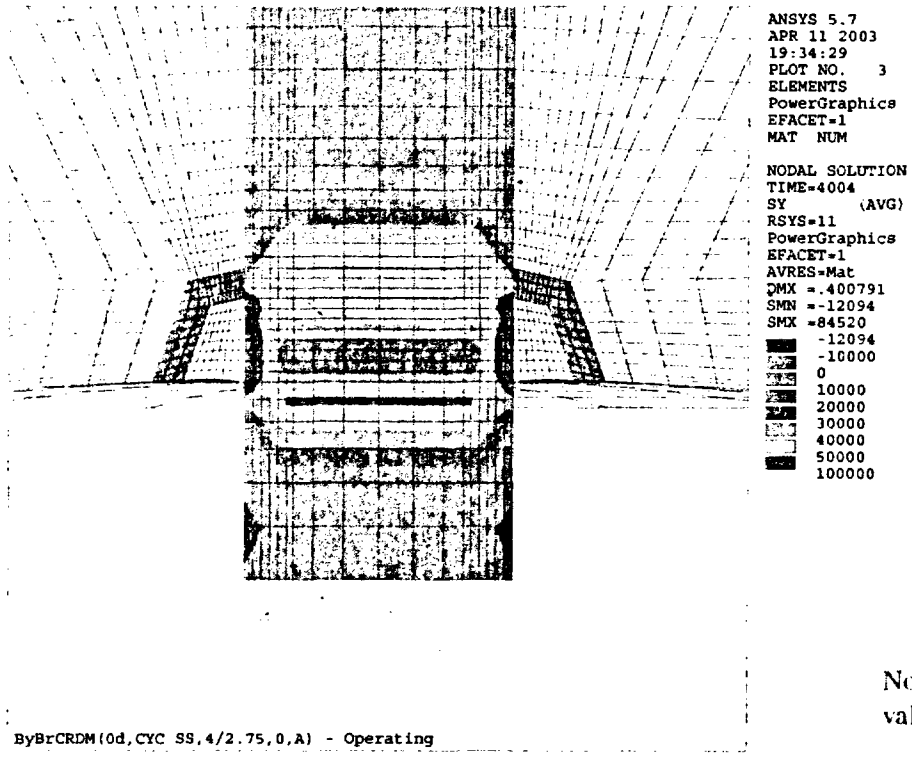


Note: The magnitude of the stress values shown is in psi

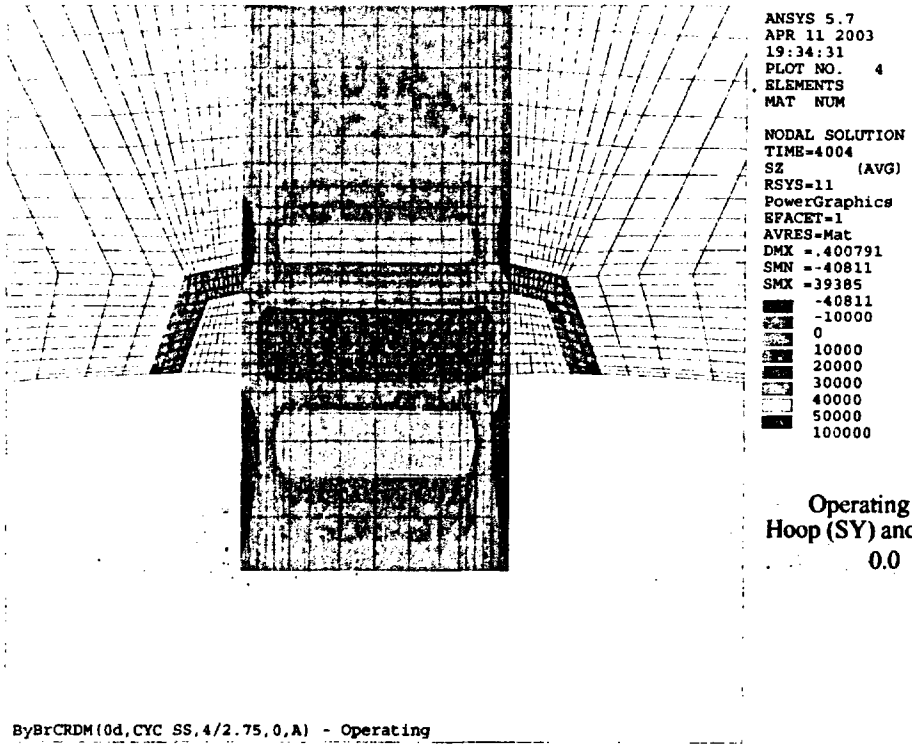


Operating plus Residual
Hoop (SY) and Axial (SZ) Stress
25.4 CRDM

Figure 5-5 Stress Distribution at Steady State Conditions for the 25.4 Degrees CRDM Penetration (Hoop Stress is the Top Figure; Axial Stress is the Bottom Figure)

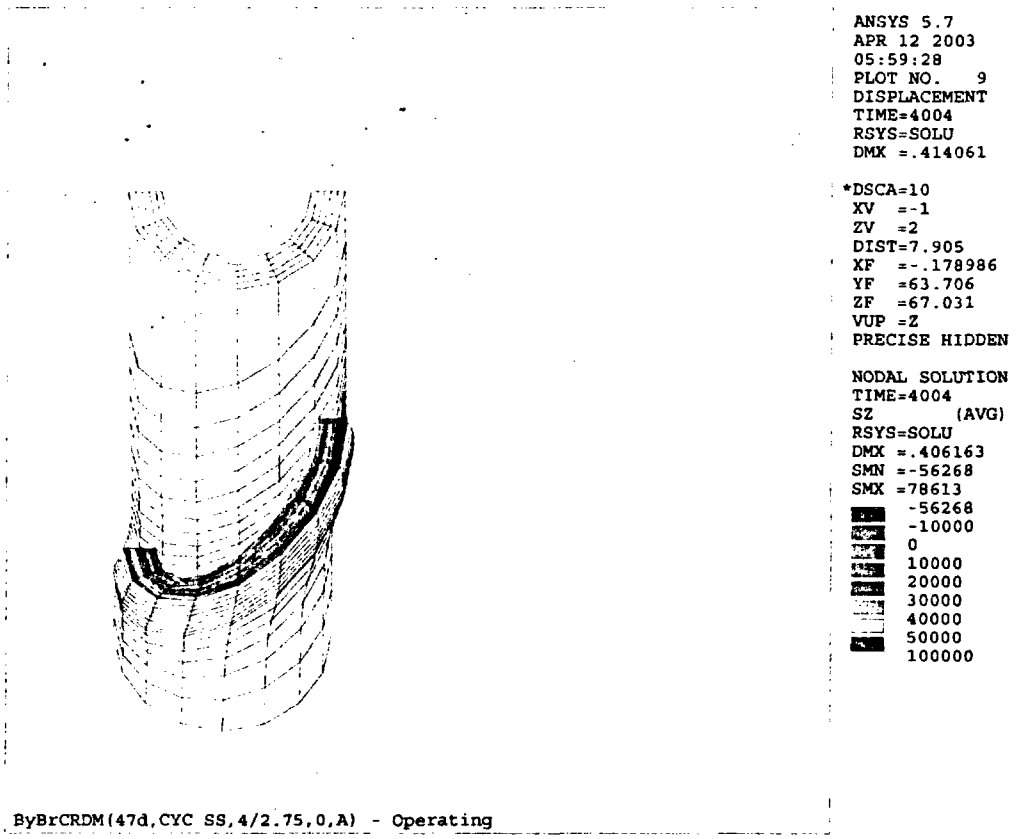


Note: The magnitude of the stress values shown is in psi



Operating plus Residual
Hoop (SY) and Axial (SZ) Stress
0.0 CRDM

Figure 5-6 Stress Distribution at Steady State Conditions for the Center CRDM Penetration (Hoop Stress is the Top Figure; Axial Stress is the Bottom Figure)



Note: The magnitude of the stress values shown is in psi

Figure 5-7 Axial Stress Distribution at Steady State Conditions for the Outermost CRDM Penetration (47.0 Degrees), Along a Plane Oriented Parallel to, and Just Above, the Attachment Weld

6 FLAW TOLERANCE CHARTS

6.1 INTRODUCTION

The flaw tolerance charts were developed using the stress analysis of each of the penetration locations as discussed in Section 5. The crack growth law developed for Byron and Braidwood Units 1 and 2 in Section 4.2 was used for each case, and several flaw tolerance charts were developed for each penetration location. The first series of charts characterizes the growth of a part through flaw and is used in predicting remaining service life of the penetration nozzle. The second series of charts, which characterizes the growth of a through-wall flaw below the J-groove weld, can be used to determine the minimum required inspection coverage to ensure that any flaws initiated below the weld in the un-inspected region of the penetration nozzle would not reach the bottom of the weld before the next inspection. All service lives resulting from these calculations are in Effective Full Power Years (EFPY), since crack growth will only occur at operating temperatures.

6.2 OVERALL APPROACH

The results of the three-dimensional stress analysis of the penetration locations were used directly in the flaw tolerance evaluation.

The crack growth evaluation for the part-through flaws was based on the worst stress distribution through the penetration wall at the location of interest of the penetration. The highest stressed location was found to be in the immediate vicinity of the weld for both the center and outermost penetrations.

The stress profile was represented by a cubic polynomial:

$$\sigma(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3 \tag{6-1}$$

where:

x = the coordinate distance into the nozzle wall
σ = stress perpendicular to the plane of the crack
A_j = coefficients of the cubic polynomial fit

For the surface flaw with length six times its depth, the stress intensity factor expression of Raju and Newman [12A, 12B] was used. The stress intensity factor $K_I(\Phi)$ can be calculated anywhere along the crack front. The point of maximum crack depth is represented by $\Phi = 0$, and this location was also found to be the point of maximum K_I for the cases considered here. The following expression is used for calculating $K_I(\Phi)$, where Φ is the angular location around the crack. The units of $K_I(\Phi)$ are ksi$\sqrt{\text{in}}$.

$$K_I(\Phi) = \left[\frac{\pi a}{Q}\right]^{0.5} \sum_{j=0}^{3} G_j\left(a/c,\ a/t,\ t/R,\ \Phi\right) A_j a^j \tag{6-2}$$

The boundary correction factors $G_0(\Phi)$, $G_1(\Phi)$, $G_2(\Phi)$ and $G_3(\Phi)$ are obtained by the procedure outlined in reference [12A, 12B]. The dimension "a" is the crack depth, and "c" is the semi crack length, while "t" is the wall thickness. "R" is the inside radius of the tube, and "Q" is the shape factor.

[

]a,c,e

For the prediction of crack growth for a circumferential through-wall flaw in the head penetration along a plane above the attachment weld, an expression first presented by Hiser [12D] was used. The stress intensity factor for a circumferential through-wall flaw was developed using finite element modeling by Structural Integrity Associates (SIA), and these results were merged with results obtained by Richard Bass of Oak Ridge National Labs (ORNL), as shown in Figure 6-1. The equation of the stress intensity factor is simply a function of the crack half angle, and is given below:

$$K_I = 3.476x - 6.619\times10^{-2}\,x^2 + 4.733\times10^{-4}\,x^3 - 1.445\times10^{-6}\,x^4 + 1.790\times10^{-9}\,x^5 \qquad (6\text{-}4)$$

In this equation, x is the crack half angle in degrees and K_I is in ksi$\sqrt{\text{in}}$.

[

]a,c,e

[ ]a,c,e

6.3 AXIAL FLAW PROPAGATION

CRDM Surface Flaws

The results of the calculated growth for inside surface flaws growing through the wall thickness of the CRDM penetration nozzles are shown in Figures 6-2 through 6-7. For outside surface flaws, the results are shown in Figures 6-8 and 6-9. Based on the discussion in MRP-55 report [11A], the use of stress intensity factors less than 15 MPa$\sqrt{m}$ involves assumption not currently substantiated by actual CGR data for CRDM nozzle materials. Therefore, these crack growth curves begin at a flaw depth that result in a stress intensity factor of 15 MPa$\sqrt{m}$, which exceeds the threshold value of 9 MPa$\sqrt{m}$. This may result in curves with different initial flaw sizes, as seen for example in Figure 6-3. Note that results are only provided for the uphill and downhill sides of each penetration nozzle. The stresses for the regions 90 degrees from these locations are in general much lower. If flaws are found in such a location, the results for either the uphill or downhill location, whichever is closer, can be conservatively used.

Each of these figures allows the future allowable service time to be estimated graphically, as discussed in Section 3. Results are shown for each of the penetration nozzles analyzed in each of these figures. The stresses are much higher near the weld than at 0.5 inch below or above it, so separate figures have been provided for these three regions. For more than 0.5 inch below the weld, the crack growth will eventually come to rest since the stresses are compressive as shown in the hoop stress plots for the CRDM nozzles in Appendix A. Also, the stresses are different on the downhill side of the penetration as opposed to the uphill side, so these two cross sections have also been treated separately.

Example problems are provided in section 7 for a range of possible flaw types.

Inspection Coverage of RPV Head Penetration Below the Weld

As a result of the First Revised NRC Order EA-03-009 issued on February 2004, most of the power plants in the United States have encountered problems with the required inspection coverage of the head penetrations below the weld. To support the submittal of relaxation request in the event that the required inspection coverage below the attachment weld cannot be achieved, a series of axial through-wall crack growth below the weld charts for the downhill side were prepared for each of the penetrations evaluated. The charts are shown in Figures 6-11 through 6-15.

There is nearly universal agreement that high stresses, on the order of the material yield strength, are necessary to initiate Primary Water Stress Corrosion Cracking (PWSCC). There is no known case of stress corrosion cracking of Alloy 600 below the yield stress [13, 14]. Typical yield strengths for wrought Alloy 600 head penetration nozzles are in the range of 37 ksi to 65 ksi. Weld metal yield strengths are generally higher. The yield strength of the head penetration nozzles for Byron and Braidwood Units 1 and 2 varies from 36.5 ksi to 60.5 ksi [7]. In addition,

the stress level of 20 ksi has been determined as a value below which PWSCC initiation is extremely unlikely [14].

In each of the figures, the location of the upper extremity of the postulated through-wall crack is identified on the charts by the distance measured from the bottom of weld. Although the assumption of any PWSCC crack initiation in the region of the penetration nozzle with a stress level less than 20 ksi is very conservative, nevertheless, the lower extremity of the initial through-wall flaw is conservatively postulated to be located on the penetration nozzle where either the inside or the outside surface hoop stress drops below 0 ksi. The time duration required for the upper extremity of an axial through-wall flaw to reach the bottom of the weld can be determined from these charts as illustrated in Example 5 of section 7.

6.4 CIRCUMFERENTIAL FLAW PROPAGATION

Since circumferentially oriented flaws have been found at five plants (Bugey 3, Oconee 2, Crystal River 3, Davis Besse, and Oconee 3), it is important to consider the possibility of crack extension in the circumferential direction. The first case was discovered as part of the destructive examination of the tube with the most extensive circumferential cracking at Bugey 3. The crack was found to have extended to a depth of 0.0886 in (2.25 mm) in a wall thickness of 0.6299 in (16 mm). The flaw was found at the outside surface of the penetration (number 54) at the downhill side location, just above the weld.

The circumferential flaws in Oconee Unit 3 were discovered during the process of repairing a number of axial flaws, whereas the circumferential flaw in Oconee Unit 2 and Crystal River Unit 3 were discovered by UT. Experience gained from these findings has enabled the development of UT procedures capable of detecting circumferential flaws reliably.

To investigate this issue completely, a series of crack growth calculations were carried out for a postulated surface circumferential flaw located just above the head penetration weld, in a plane parallel to the weld itself. [

]a,c,e

]^{a,c,e} The results of this calculation are shown in Figure 6-16. From this figure, it can be seen that the time required for propagation of a circumferential flaw to a point where the integrity of the CRDM penetration nozzle would be affected [ ]^{a,c,e} would be about 62 years. Due to the conservatism in the calculations, i.e. the time period for a surface flaw to become a through-wall flaw was conservatively ignored and therefore the service life is likely to be even longer. In addition, due to uncertainties in the exact composition of the chemical environment in contact with the nozzle OD, a multiplicative factor of 2.0 is used in the Crack Growth Rate (CGR) for all circumferential surface flaws on the OD of the head penetration nozzles located above the elevation of the J-groove weld.

6.5 FLAW ACCEPTANCE CRITERIA

Now that the projected crack growth curves have been developed, the question remains as to what flaw size would be acceptable for further service.

Acceptance criteria have been developed for indications found during inspection of reactor vessel upper head penetration as part of an industry program coordinated by NEI (formerly NUMARC). In developing the enclosed acceptance criteria, the approach used was very similar to that used by Section XI, in that an industry consensus was reached using input from both operating utility technical staff and each of the three PWR vendors. The criteria developed are applicable to all PWR plant designs.

Since the discovery of the leaks at Oconee and ANO-1, the acceptance criteria have been revised slightly to cover flaws on the outside diameter of the penetration below the attachment weld, and flaws in the attachment weld. These revised criteria have been formally endorsed by the NRC [15], and are used in these evaluations. Portions of the acceptance criteria will be noted below.

The criteria presented herein are limits on flaw sizes, which are acceptable. The criteria are to be applied to inspection results. It should be noted that determination of the future service during which the criteria are satisfied is plant-specific and dependent on flaw geometry and loading conditions.

It has been previously demonstrated by each of the owners groups that the penetration nozzles are very tolerant of flaws and there is only a small likelihood of flaw extensions to larger sizes. Therefore, it was concluded that complete fracture of the penetration nozzle is highly unlikely. The approach used here is more conservative than that used in Section XI applications where the acceptable flaw size is calculated by placing a margin on the critical flaw size. For the current application, the critical flaw size would be far too large to allow a practical application of the approach used in Section XI applications, so protection against leakage is the priority.

The acceptance criteria presented herein apply to all the flaw types regardless of orientation and shape. Similar to the approach used in Section XI, flaws are first characterized according to established rules and then compared with acceptance criteria.

Flaw Characterization

Flaws detected must be characterized by the flaw length and preferably flaw depth. The proximity rules of Section XI for considering flaws as separate, may be used directly (Section XI, Figure IWA 3400-1). This figure is reproduced here as Figure 6-17.

When a flaw is detected, its projections in both the axial and circumferential directions must be determined. Note that the axial direction is always the same for each penetration, but the circumferential direction will be different depending on the angle of intersection of the penetration nozzle with the vessel head. The "circumferential" direction of interest here is along the top of the attachment weld, as illustrated in Figure 6-18. It is this angle which will change for each penetration nozzle and the top of the attachment weld is also the plane which could cause separation of the penetration nozzle from the vessel head. The location of the flaw relative to both the top and bottom of the partial penetration attachment weld must also be determined since a potential leak path exists when a flaw propagates through the penetration nozzle wall and up the penetration nozzle past the attachment weld. Schematic of a typical weld geometry is shown in Figure 6-19.

Flaw Acceptance Criteria

The maximum allowable depth (a_f) for axial flaws on the inside surface of the penetration nozzle, at or above the weld is 75 percent of the penetration wall thickness. The term a_f is defined as the maximum size to which the detected flaw is calculated to grow in a specified time period. This 75 percent limitation was selected to be consistent with the maximum acceptable flaw depth in Section XI and to provide an additional margin against through wall penetration. There is no concern about separation of the penetration nozzle from the vessel head, unless the flaw is above the attachment weld and oriented circumferentially.

Axial inside surface flaws found below the weld are acceptable regardless of depth as long as their upper extremity does not reach the bottom of the weld during the period of service until the next inspection. Axial flaws that extend above the weld are limited to 75 percent of the wall thickness.

Axial flaws on the outside surface of the penetration nozzle below the attachment weld are acceptable regardless of depth, as long as they do not extend into the attachment weld during the

period of service until next inspection. Outside surface flaws above the attachment weld must be evaluated on a case by case basis, and must be discussed with the regulatory authority.

Circumferential flaws located below the weld are acceptable regardless of their depth, provided the length is less than 75 percent of the penetration nozzle circumference for the period of service until the next inspection. Circumferential flaws detected in this area have no structural significance except that loose parts must be avoided. To this end, intersecting axial and circumferential flaws shall be removed or repaired. Circumferential flaws at and above the weld must be discussed with the regulatory authority on a case by case basis.

Surface flaws located in the attachment welds themselves are not acceptable regardless of their depth. This is because the crack growth rate of the weld material is several times faster than that of the Alloy 600 material, and also because depth sizing capability does not yet exist for indications in the attachment weld.

The flaw acceptance criteria are summarized in Table 6-1. Flaws that exceed these criteria must be repaired unless analytically justified for further service. These criteria have been reviewed and endorsed by the NRC, as documented in references [15, 16, 17] and are also shown in Table IWB-3663-1 in the 2004 Edition of the ASME Code [18].

It is expected that the use of these criteria and crack growth curves will provide conservative predictions of the allowable service time.

Table 6-1 Summary of Reactor Vessel Head Penetration Flaw Acceptance Criteria

Location	Axial		Circumferential	
	a_f	ℓ	a_f	ℓ
Below Weld (ID)	t	no limit	t	0.75 circ.
At and Above Weld (ID)	0.75 t	no limit	repair	repair
Below Weld (OD)	t	no limit	t	0.75 circ.
Above Weld (OD)	repair	repair	repair	repair

Note: Surface flaws of any size in the attachment weld are not acceptable.

a_f = Flaw Depth
ℓ = Flaw Length
t = Wall Thickness

Table 6-2 Byron and Braidwood Units 1 and 2 Penetration Geometries [1C, 2C, 3C, 4C]

Penetration Type	Wall Thickness (in.)	Penetration OD (in.)
CRDM	0.625	4.000

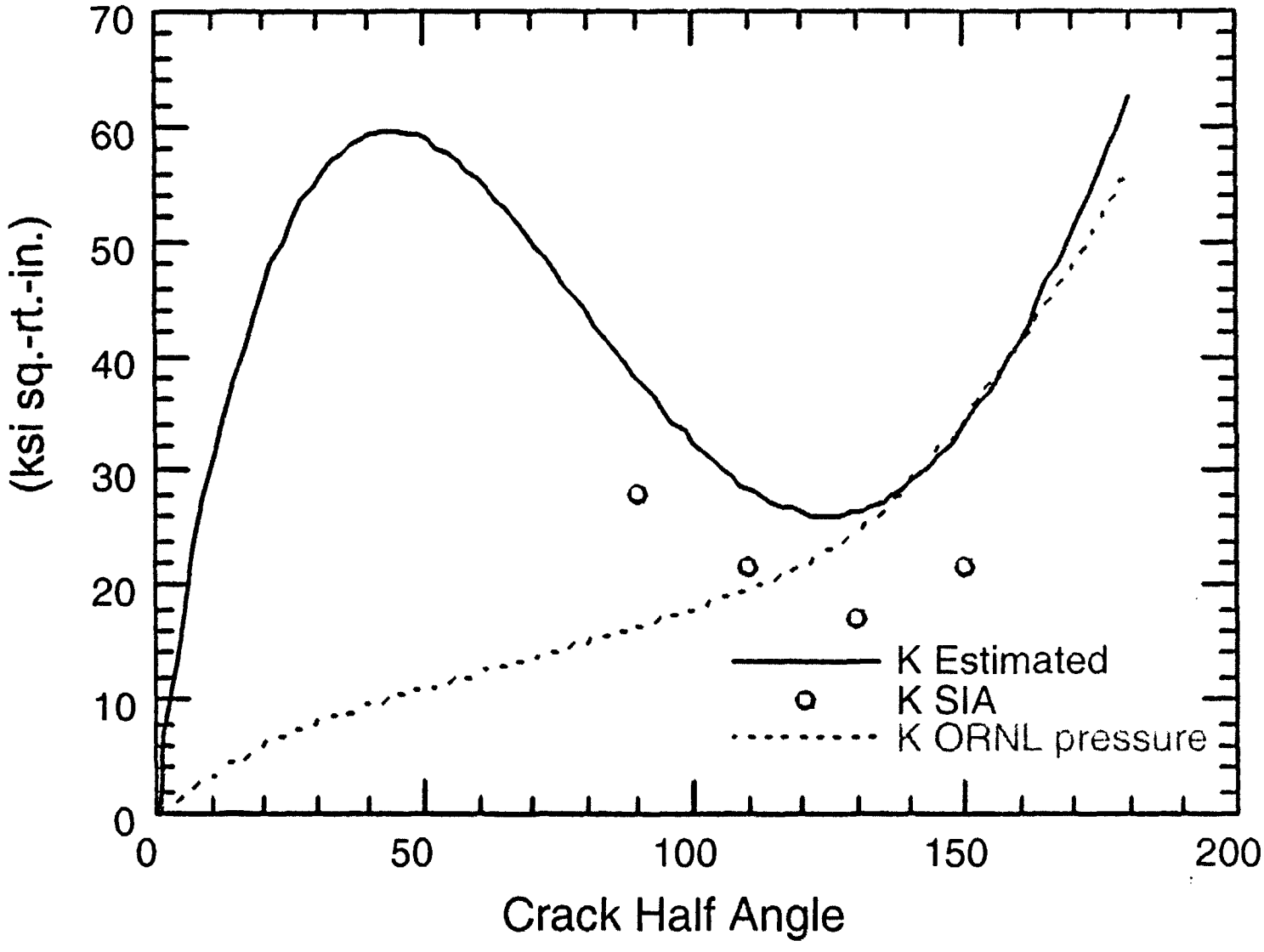


Figure 6-1 Stress Intensity Factor for a Through-Wall Circumferential Flaw in a Head Penetration

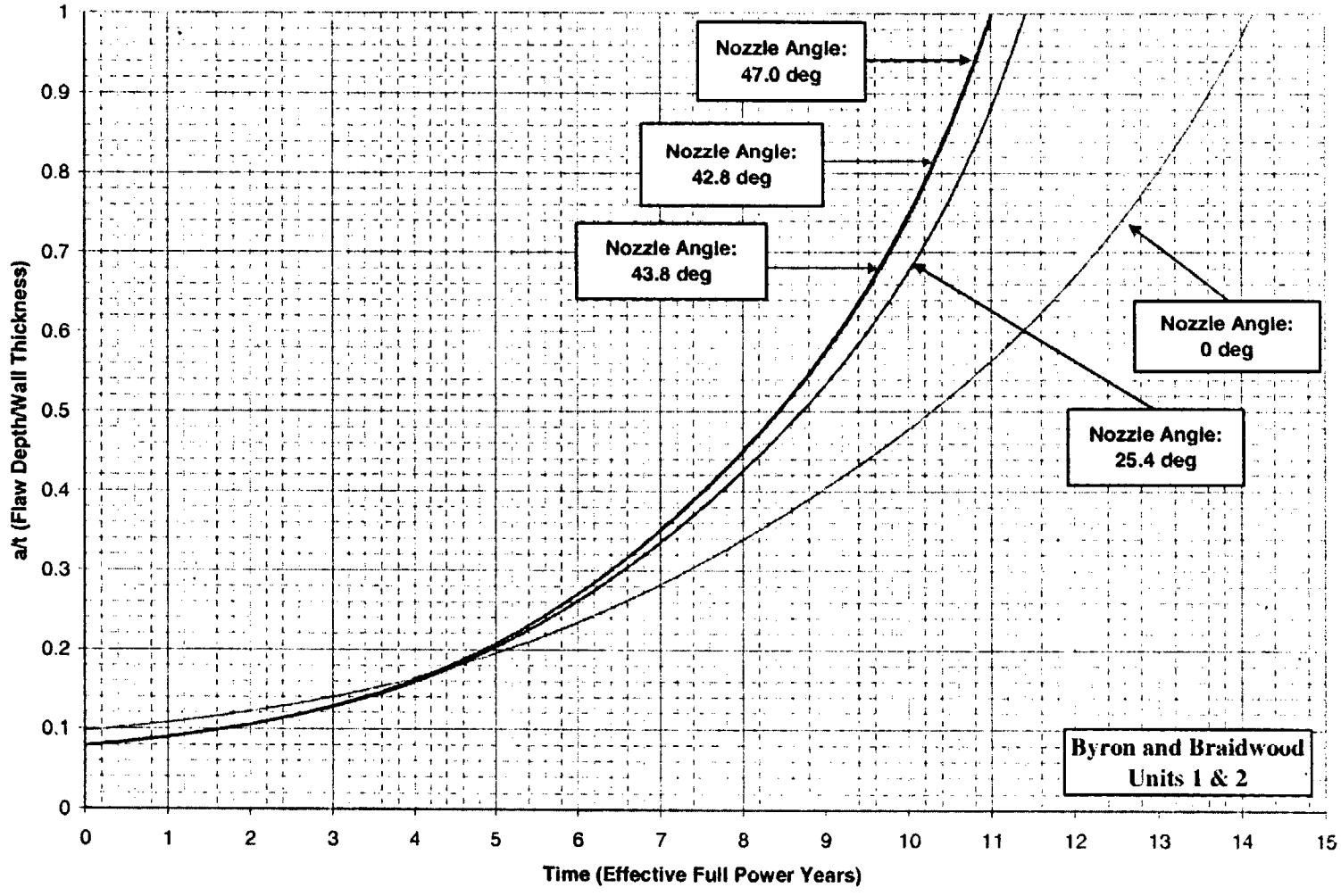


Figure 6-2 **Inside, Longitudinal Surface Flaws, .5" Below the Attachment Weld, Nozzle Uphill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2**

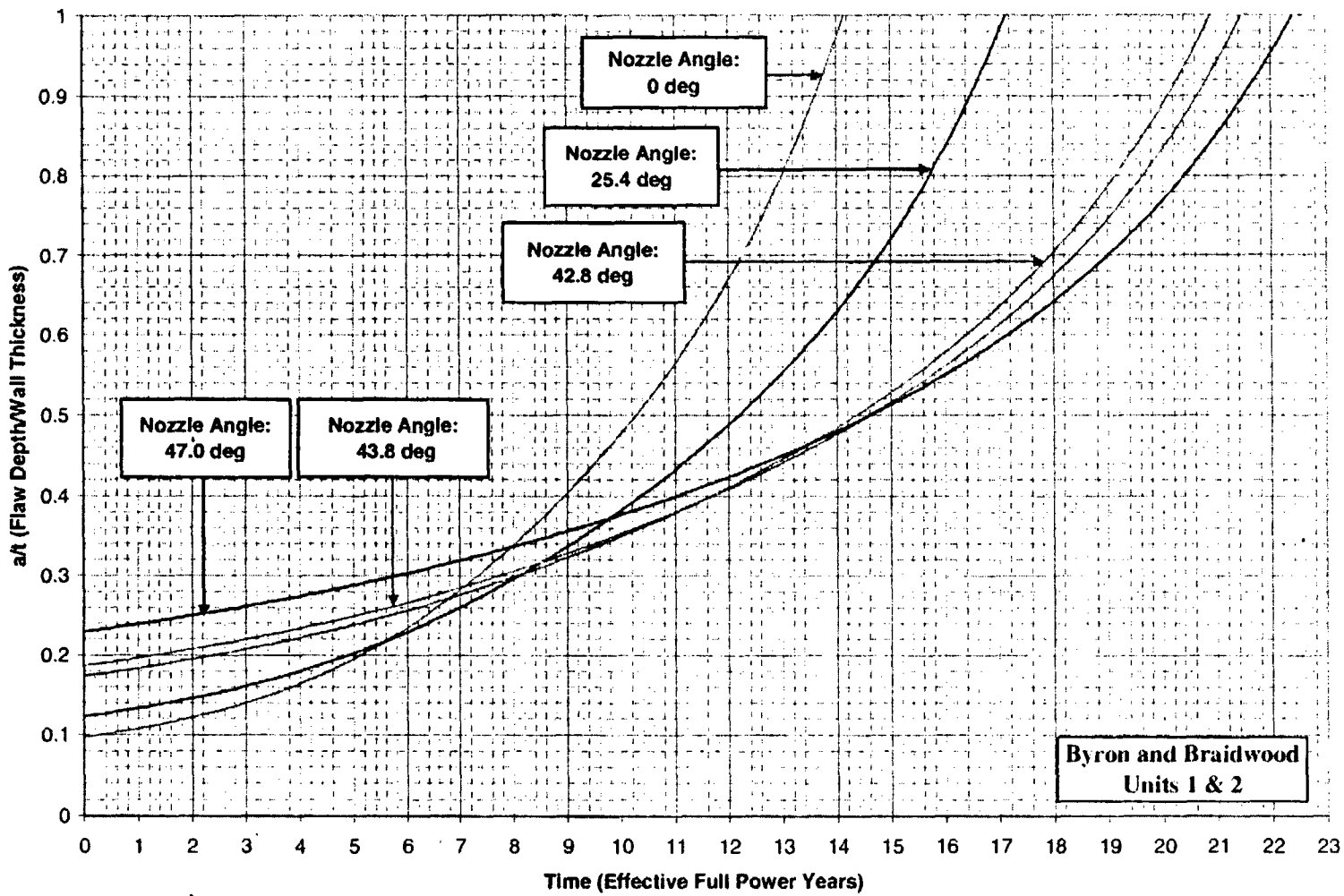


Figure 6-3 **Inside, Longitudinal Surface Flaws, .5" Below the Attachment Weld, Nozzle Downhill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2**

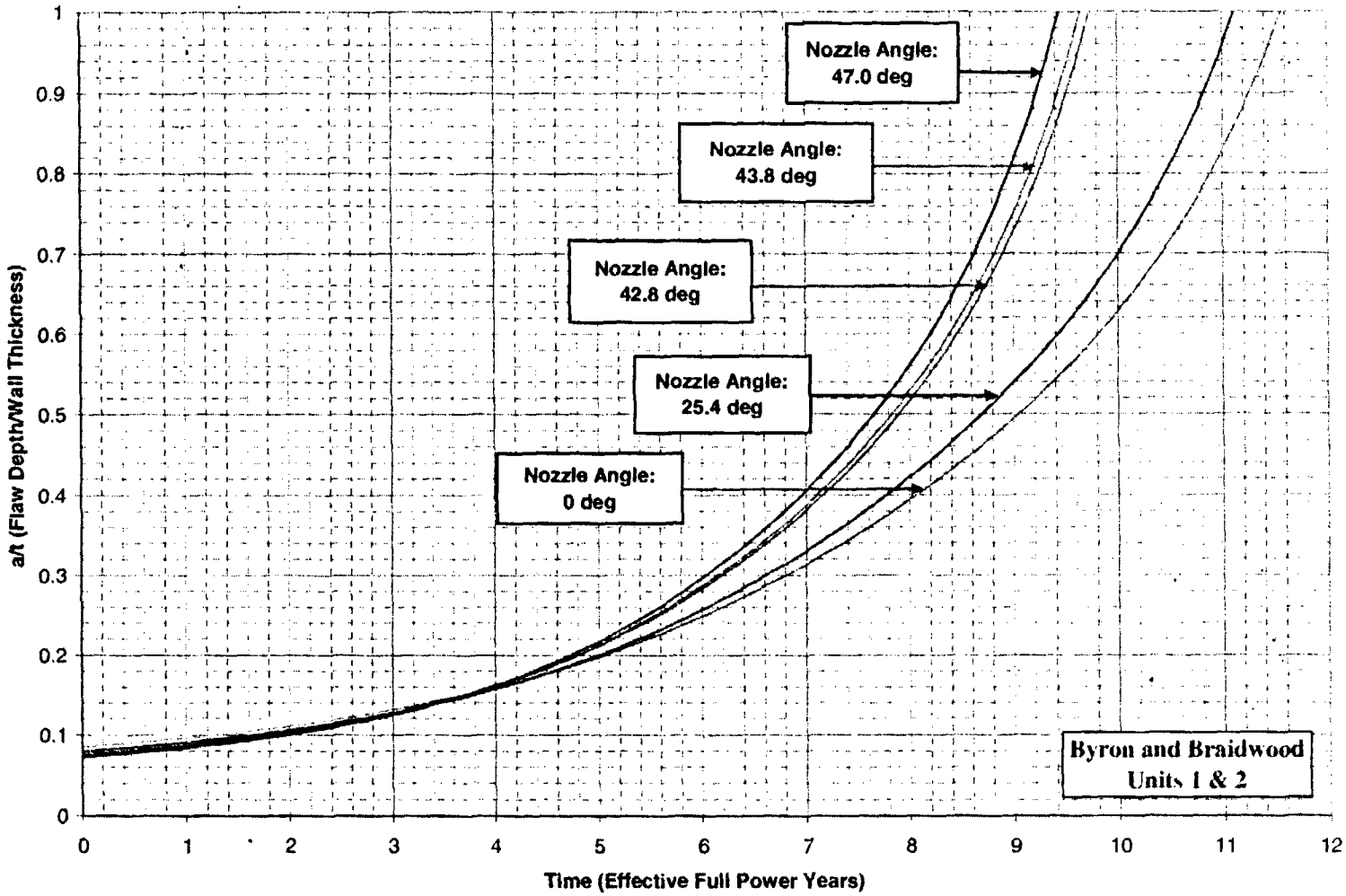


Figure 6-4 **Inside, Longitudinal Surface Flaws, At the Attachment Weld, Nozzle Uphill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2**

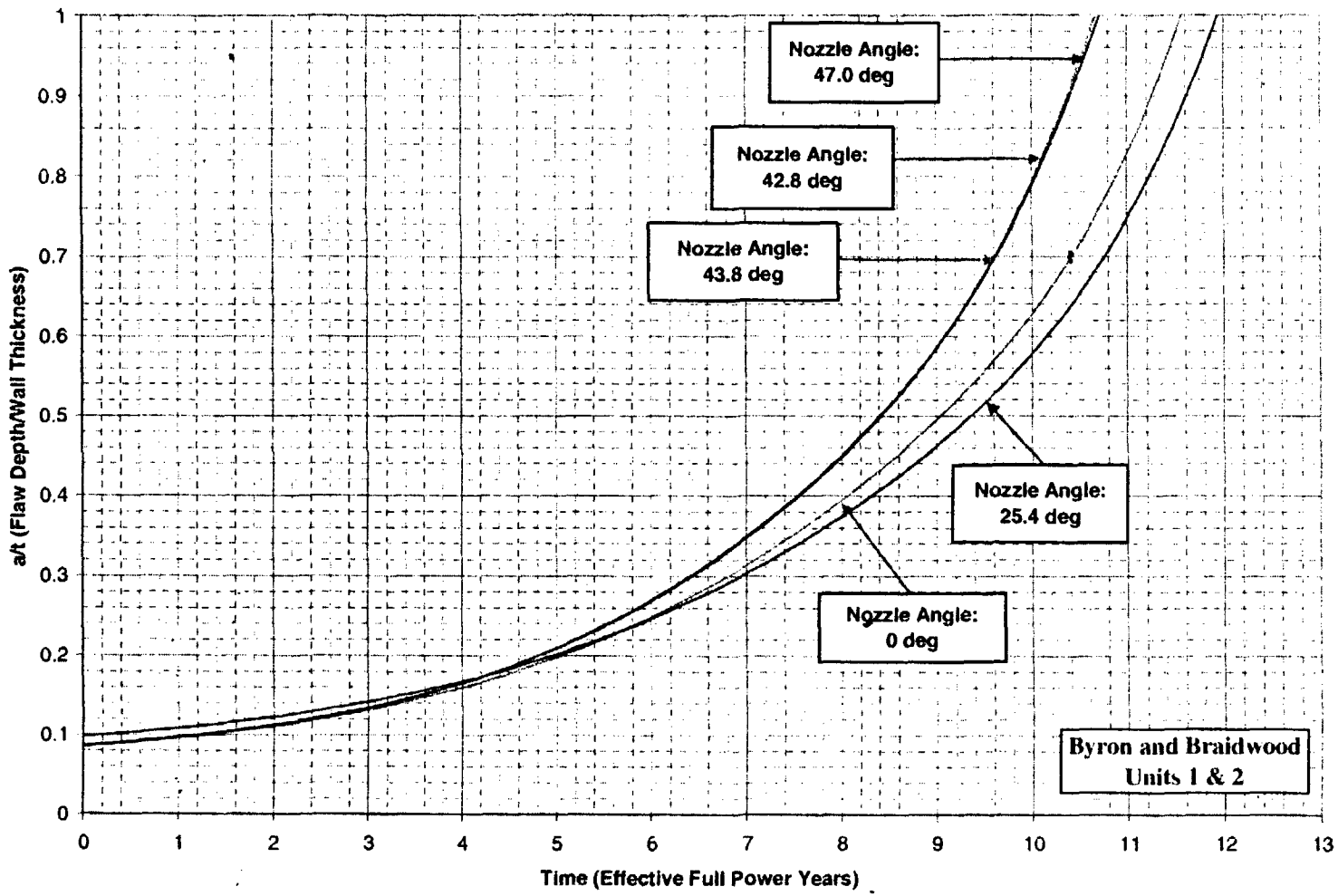


Figure 6-5 **Inside, Longitudinal Surface Flaws, At the Attachment Weld, Nozzle Downhill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2**

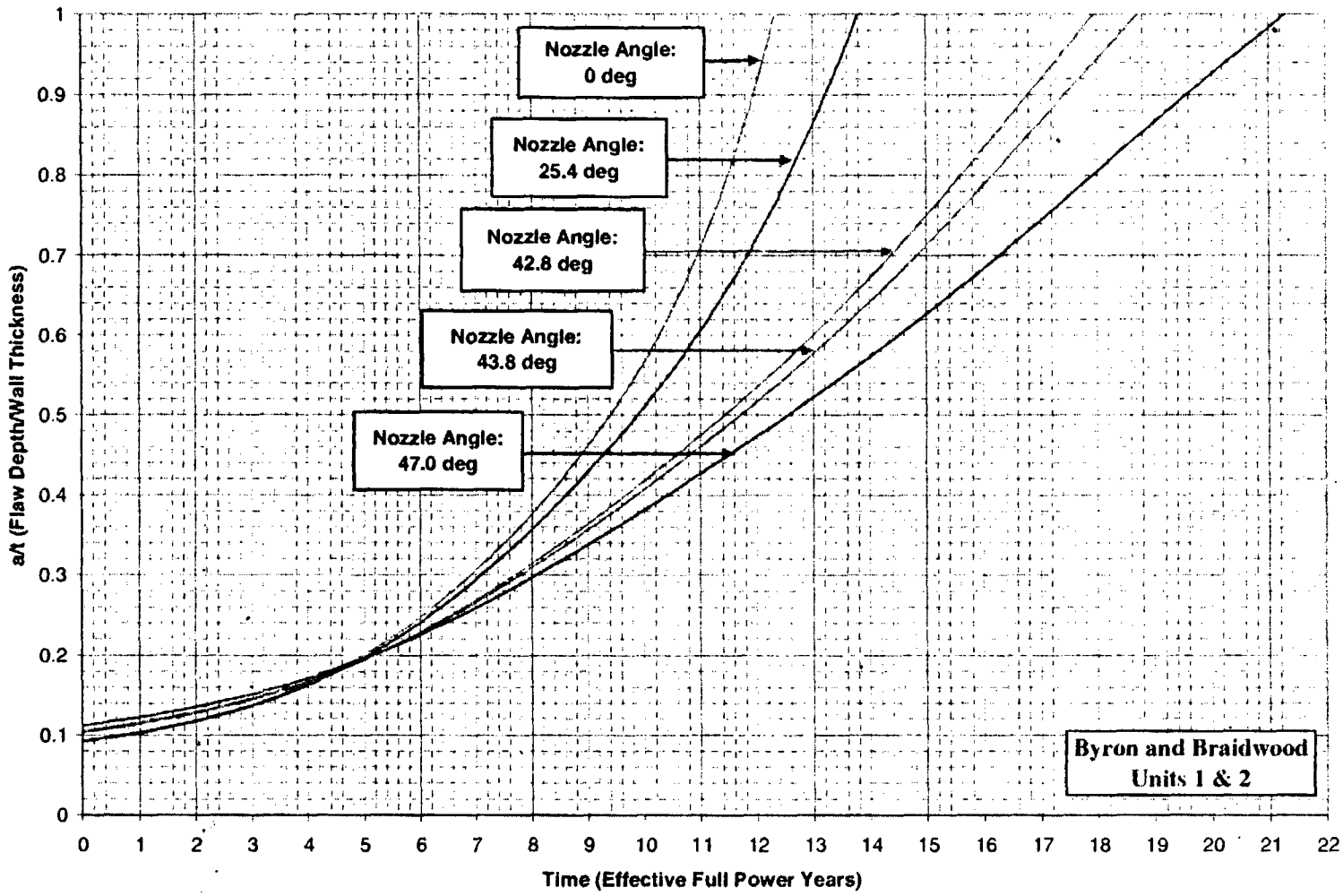


Figure 6-6 **Inside, Longitudinal Surface Flaws, .5" Above the Attachment Weld, Nozzle Uphill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2**

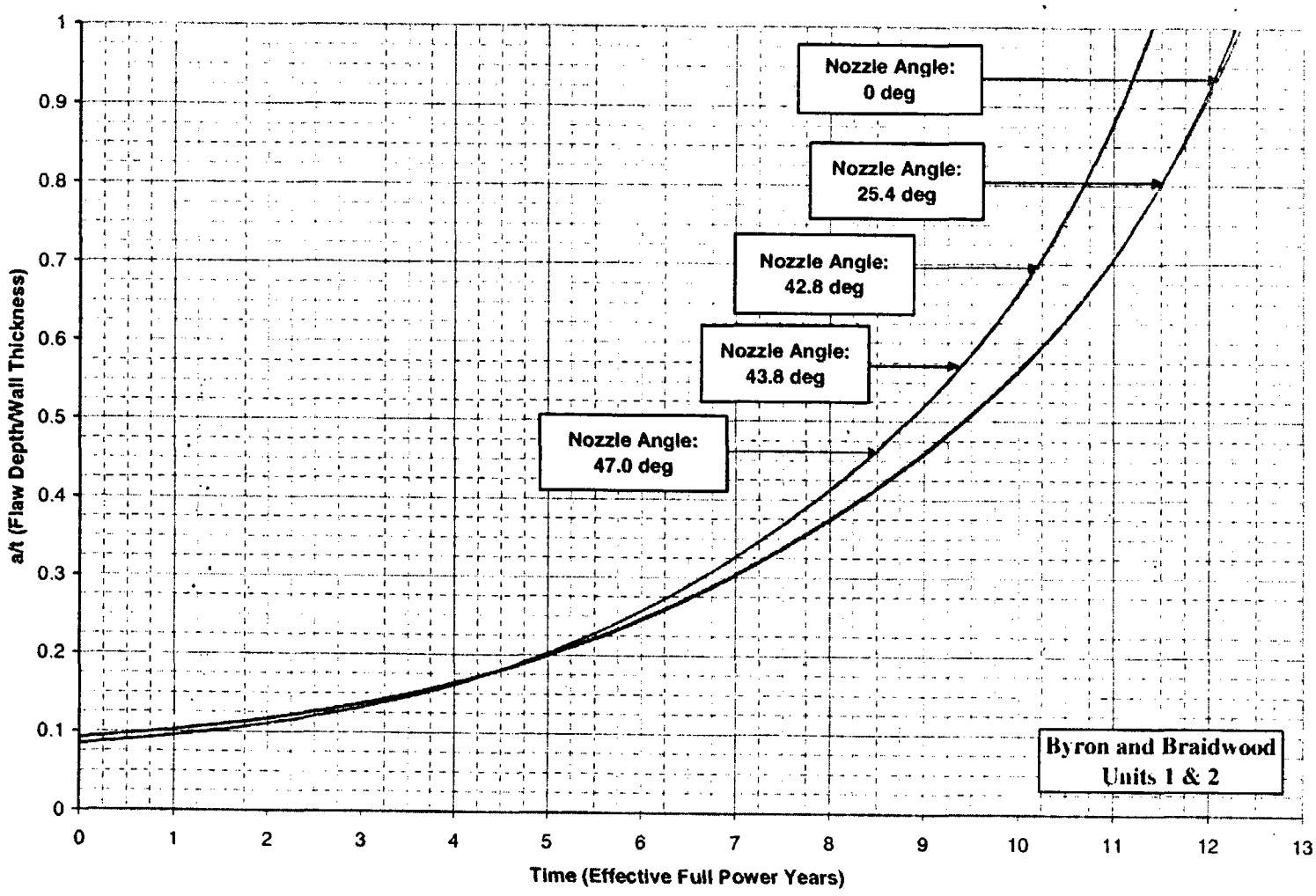


Figure 6-7 **Inside, Longitudinal Surface Flaws, .5" Above the Attachment Weld, Nozzle Downhill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2**

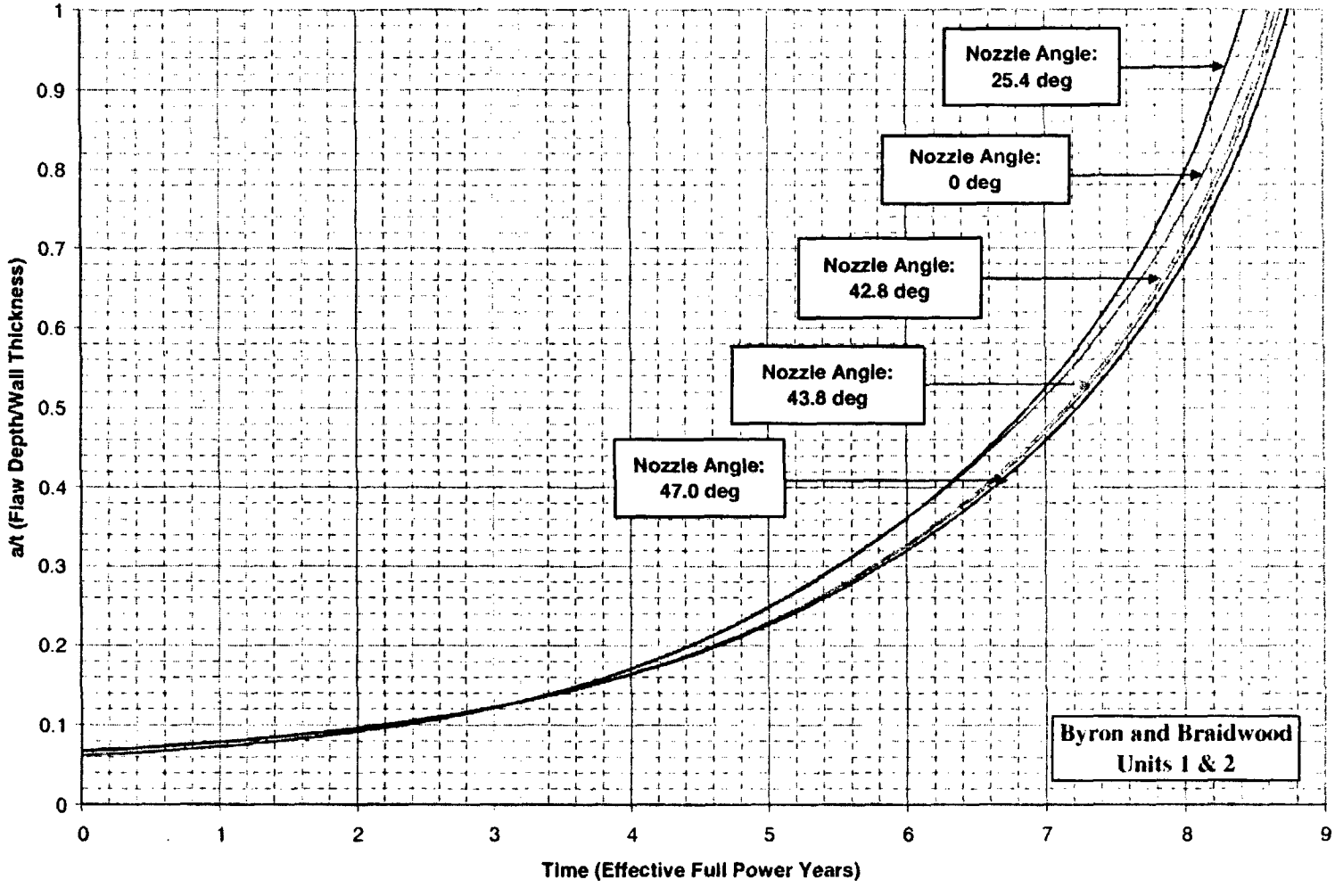


Figure 6-8 **Outside, Longitudinal Surface Flaws, Below the Attachment Weld, Nozzle Uphill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2**

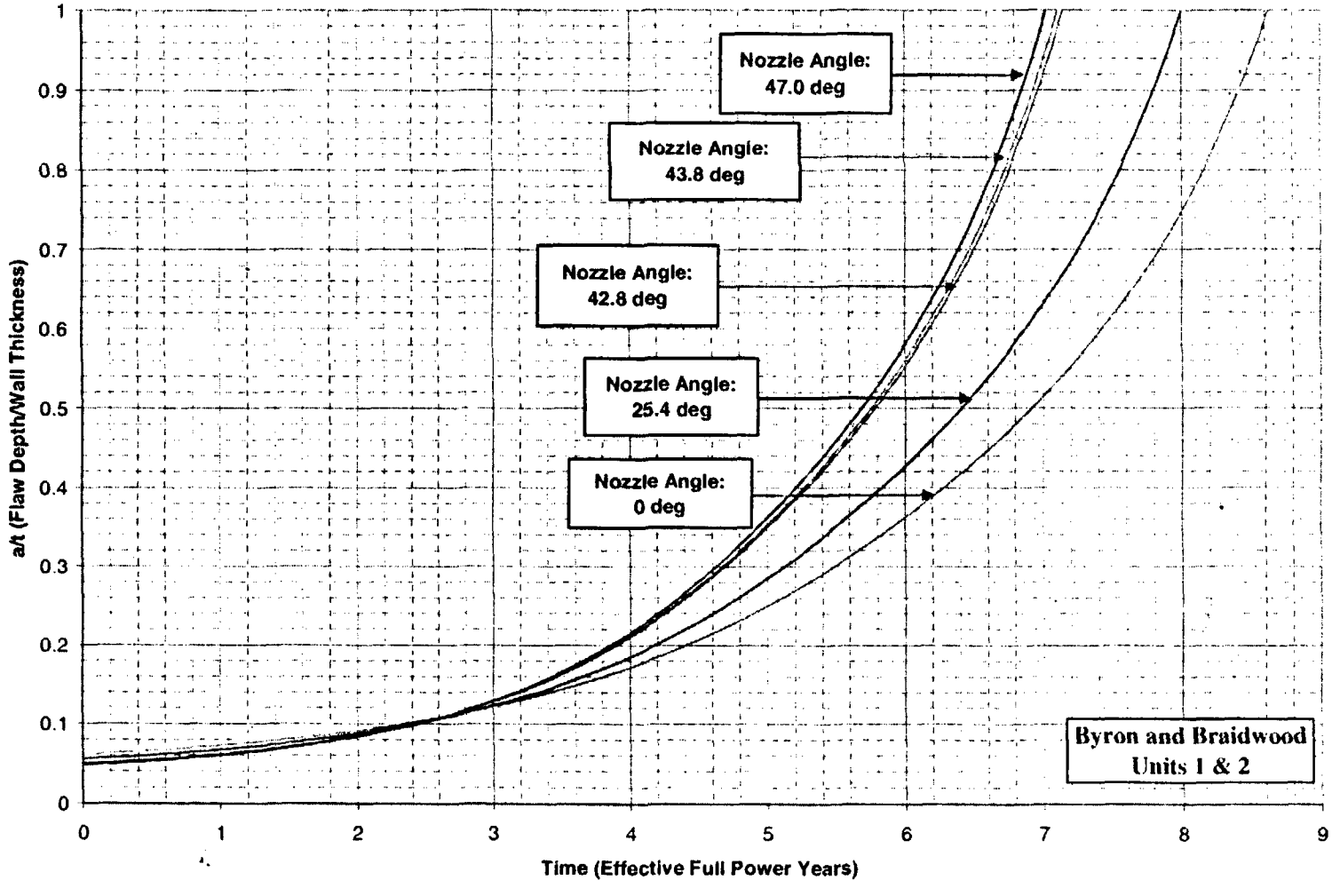


Figure 6-9 **Outside, Longitudinal Surface Flaws, Below the Attachment Weld, Nozzle Downhill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2**

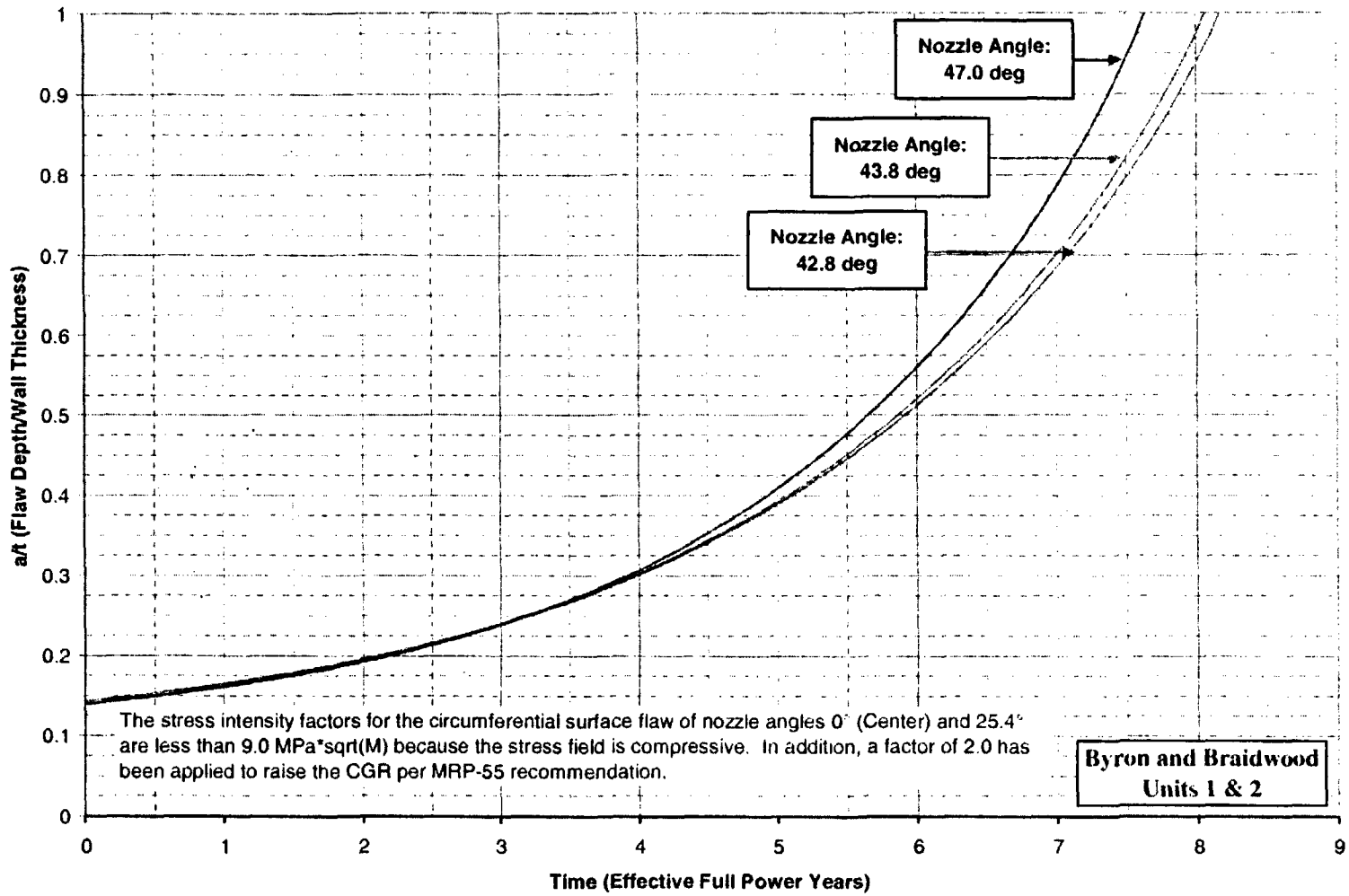


Figure 6-10 Outside, Circumferential Surface Flaws, Along the Top of the Attachment Weld - Crack Growth Predictions for Byron and Braidwood Units 1 and 2 (MRP Factor of 2.0 Included)

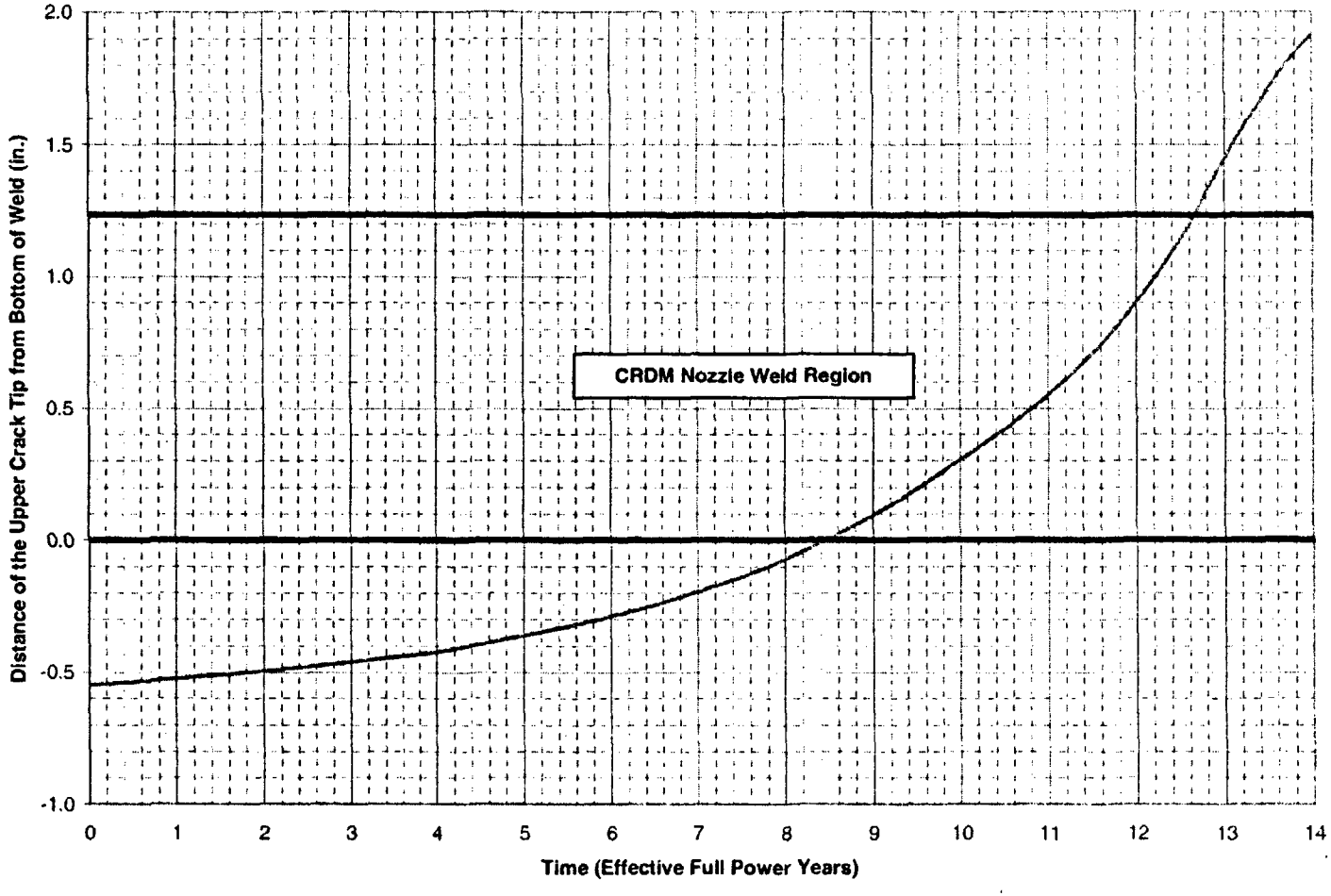


Figure 6-11 Through-Wall Longitudinal Flaws Located in the Center CRDM (0.0 Degrees) Penetration - Crack Growth Predictions for Byron and Braidwood Units 1 and 2

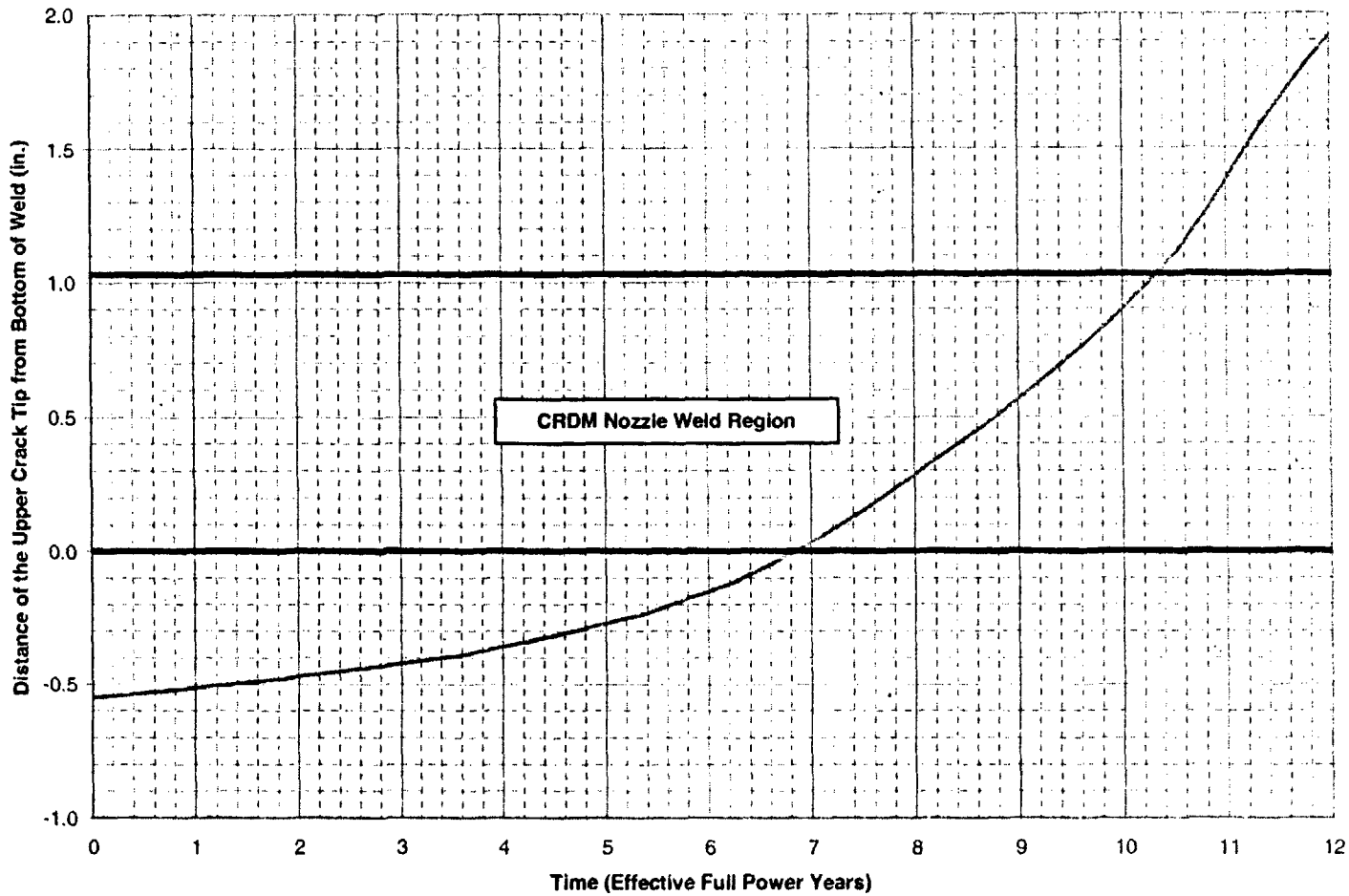


Figure 6-12 Through-Wall Longitudinal Flaws Located in the 25.4 Degrees CRDM Row of Penetrations, Downhill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2

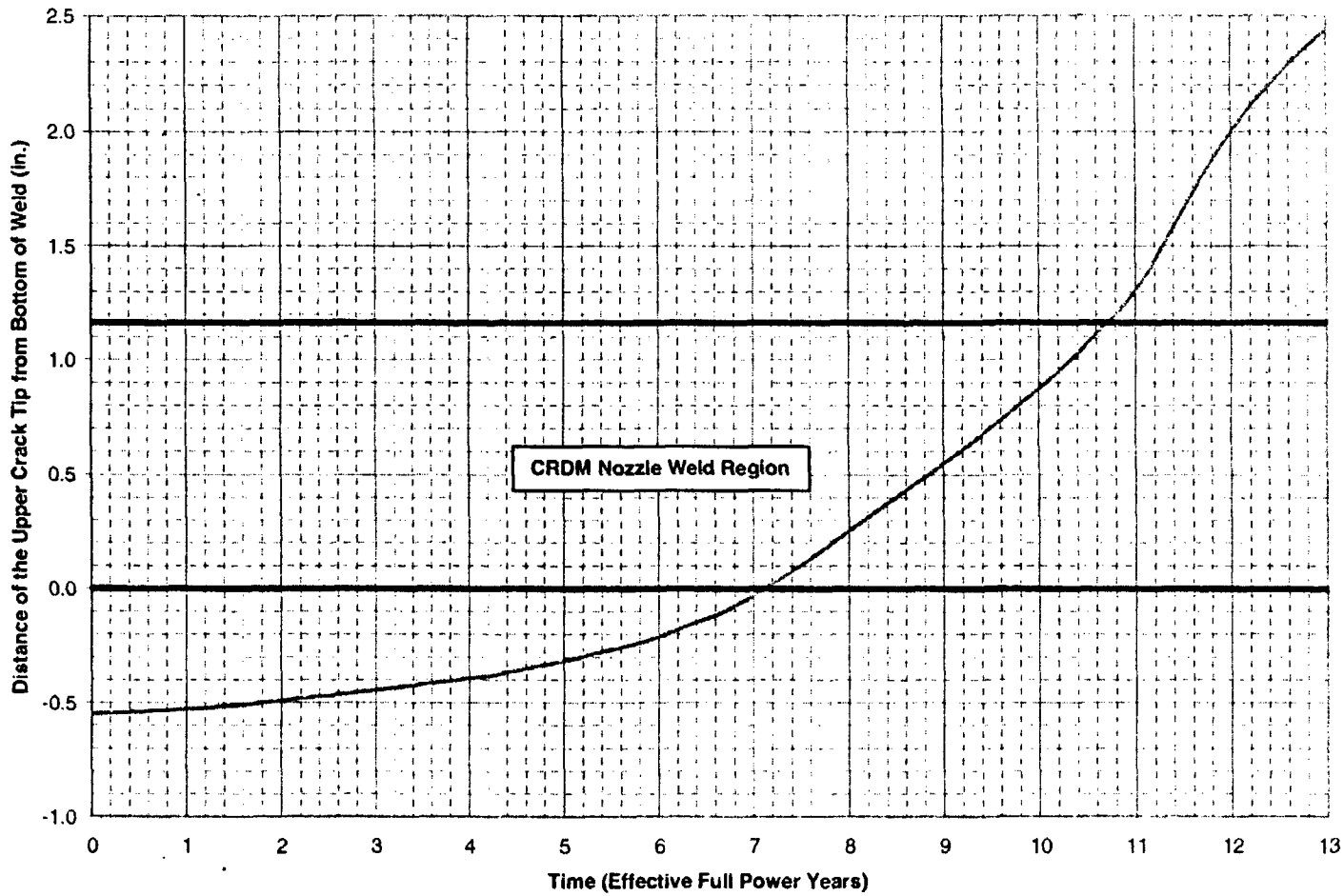


Figure 6-13 Through-Wall Longitudinal Flaws Located in the 42.8 Degrees CRDM Row of Penetrations, Downhill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2

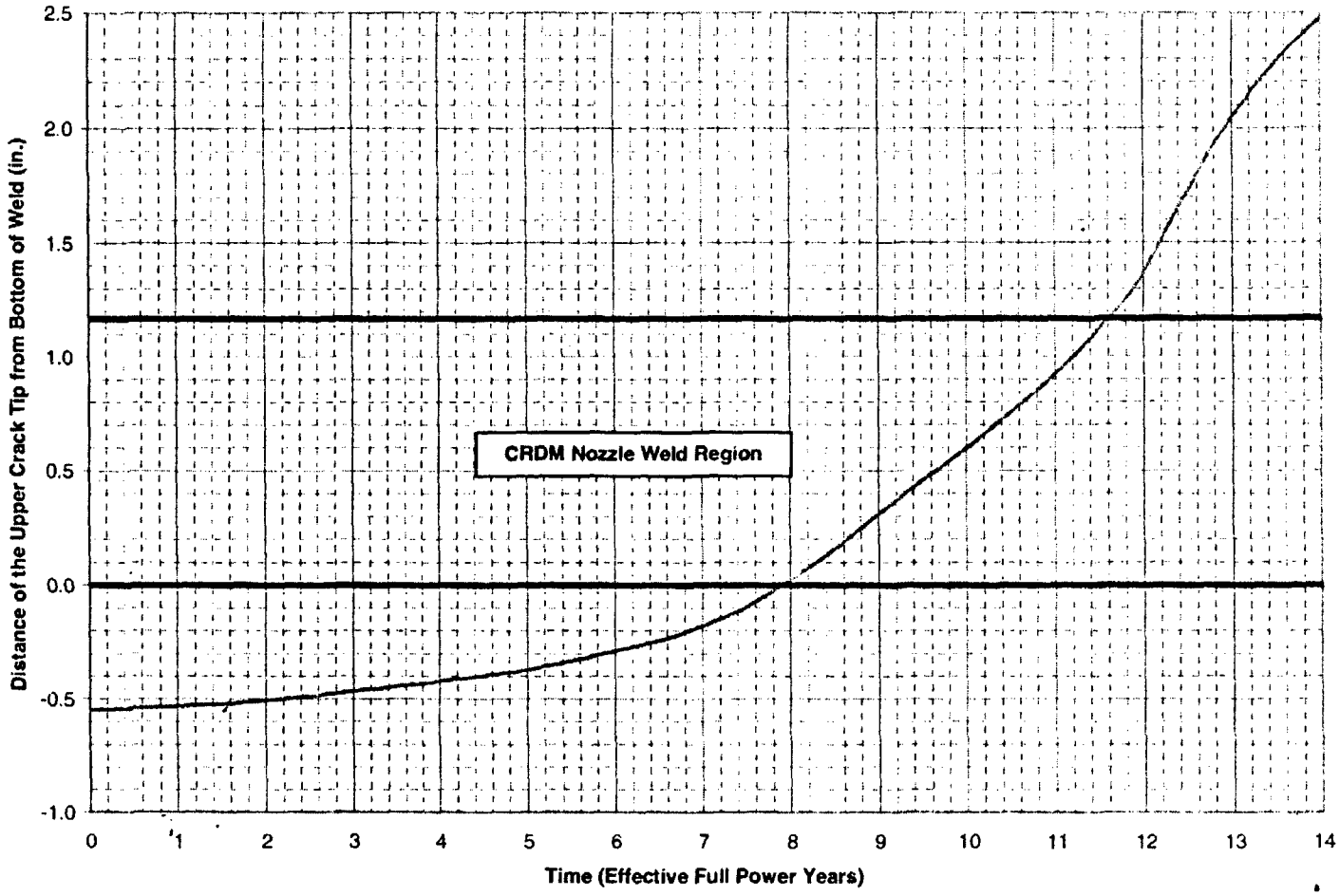


Figure 6-14 Through-Wall Longitudinal Flaws Located in the 43.8 Degrees CRDM Row of Penetrations, Downhill Side - Crack Growth Predictions for Byron and Braidwood Unit1 and 2

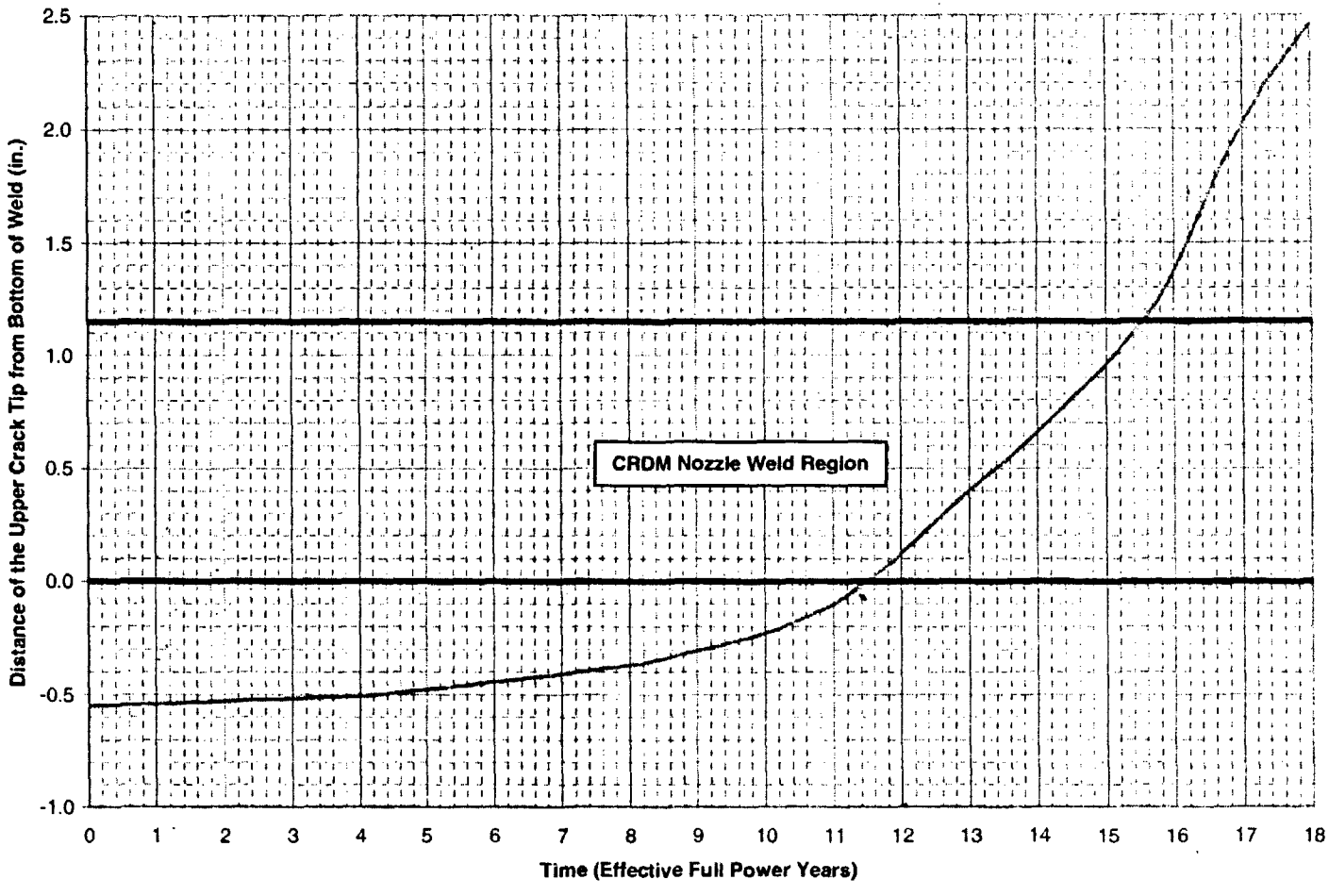


Figure 6-15 Through-Wall Longitudinal Flaws Located in the 47.0 Degrees CRDM Row of Penetrations, Downhill Side - Crack Growth Predictions for Byron and Braidwood Units 1 and 2

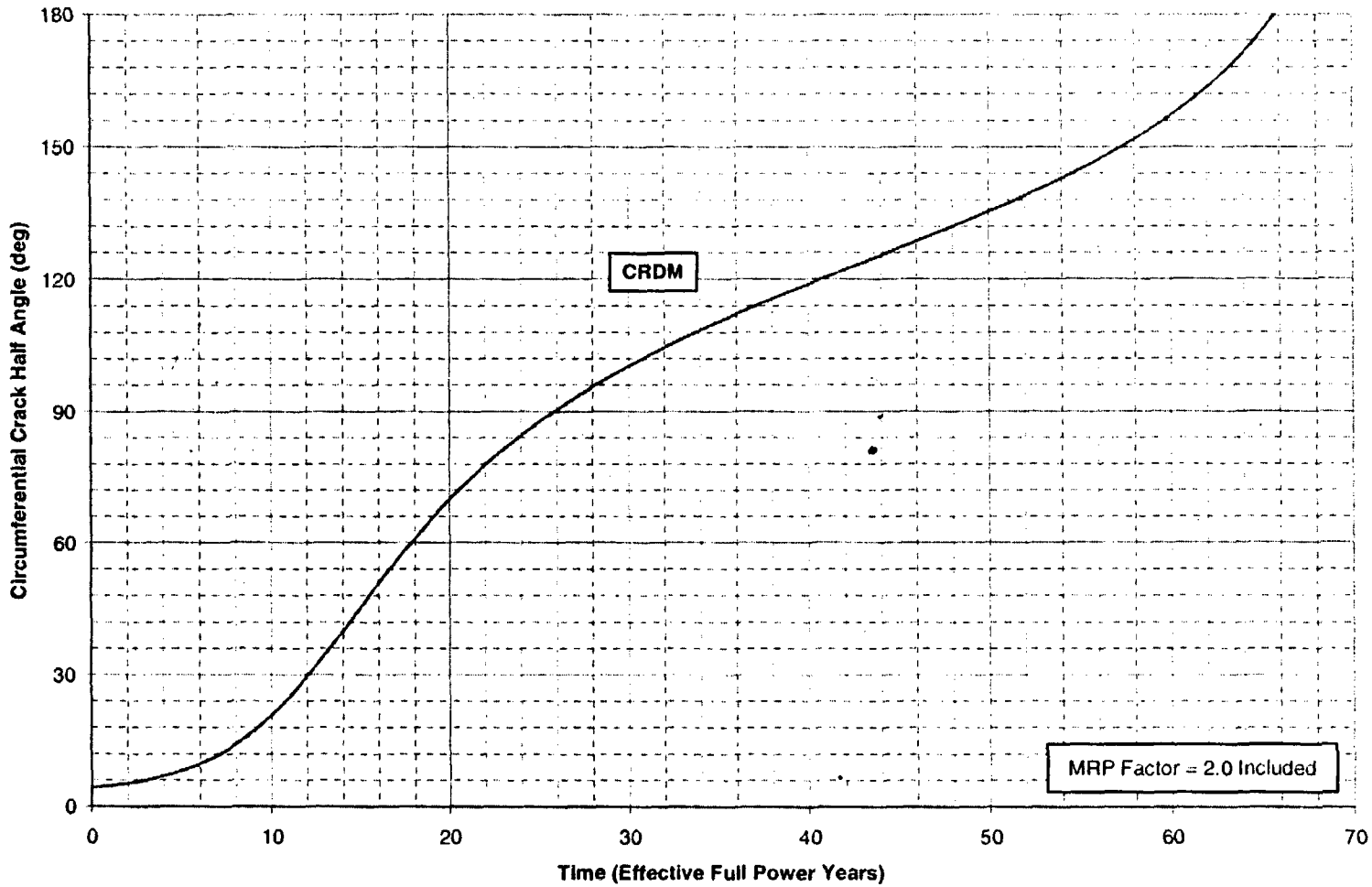


Figure 6-16 Through-Wall Circumferential Flaws Near the Top of the Attachment Weld for CRDM Nozzles - Crack Growth Predictions for Byron and Braidwood Units 1 and 2 (MRP Factor of 2.0 Included)

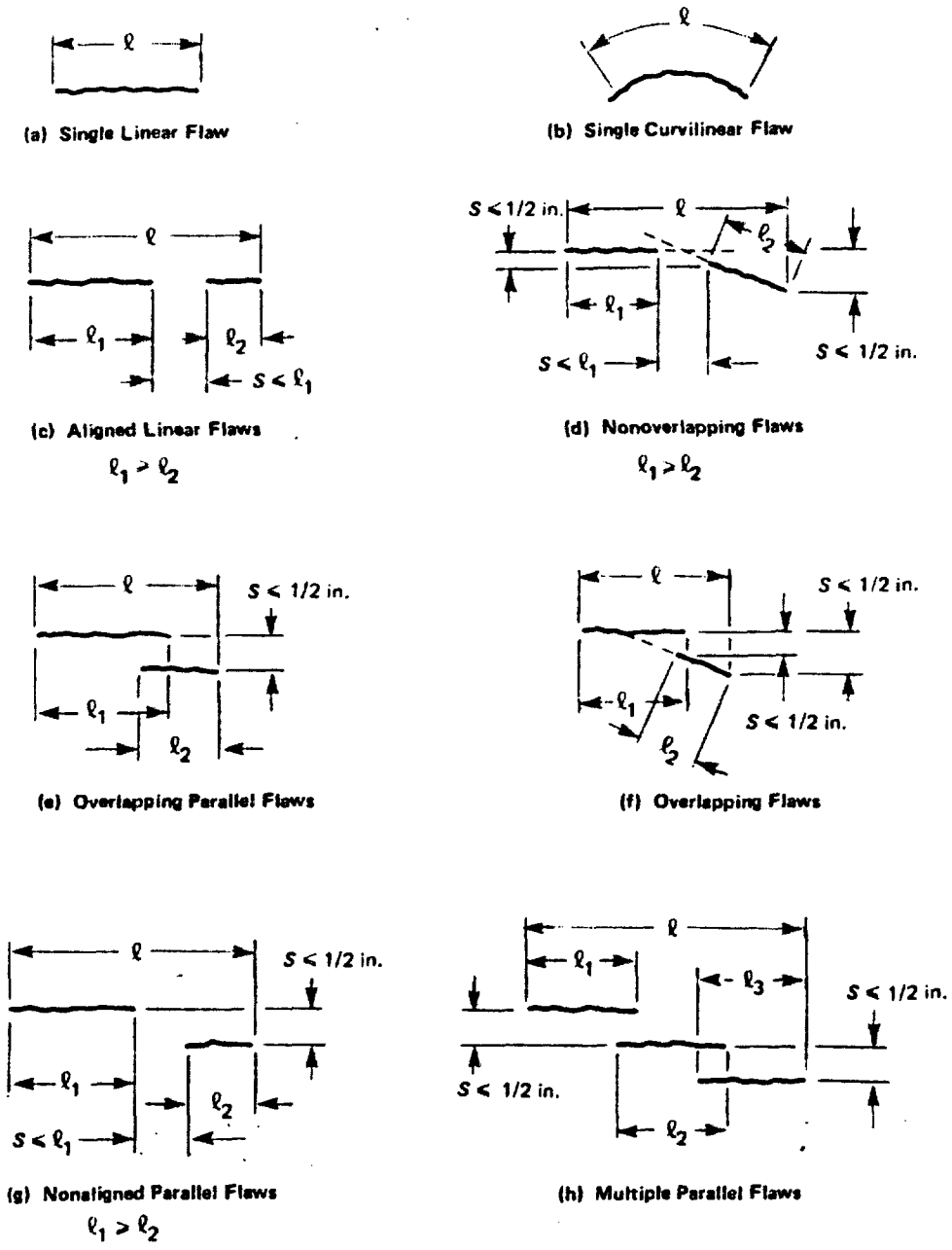


Figure 6-17 Section XI Flaw Proximity Rules for Surface Flaws (Figure IWA-3400-1)

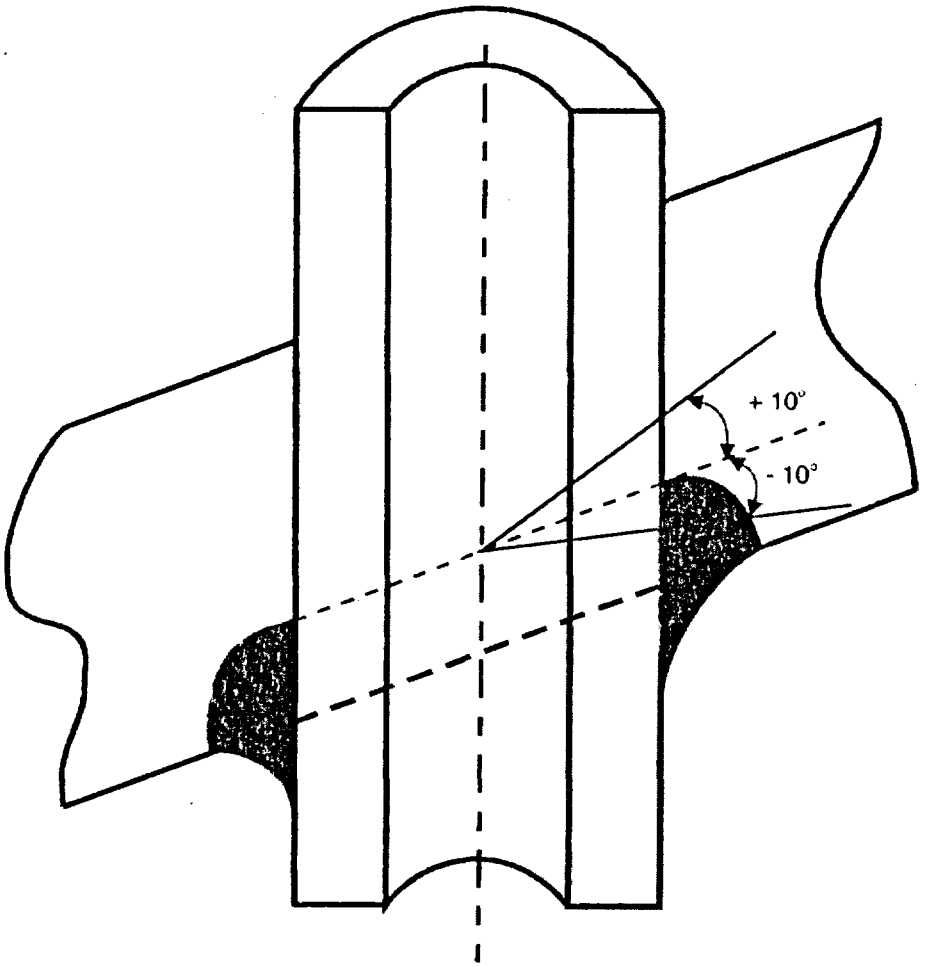


Figure 6-18 Definition of "Circumferential"

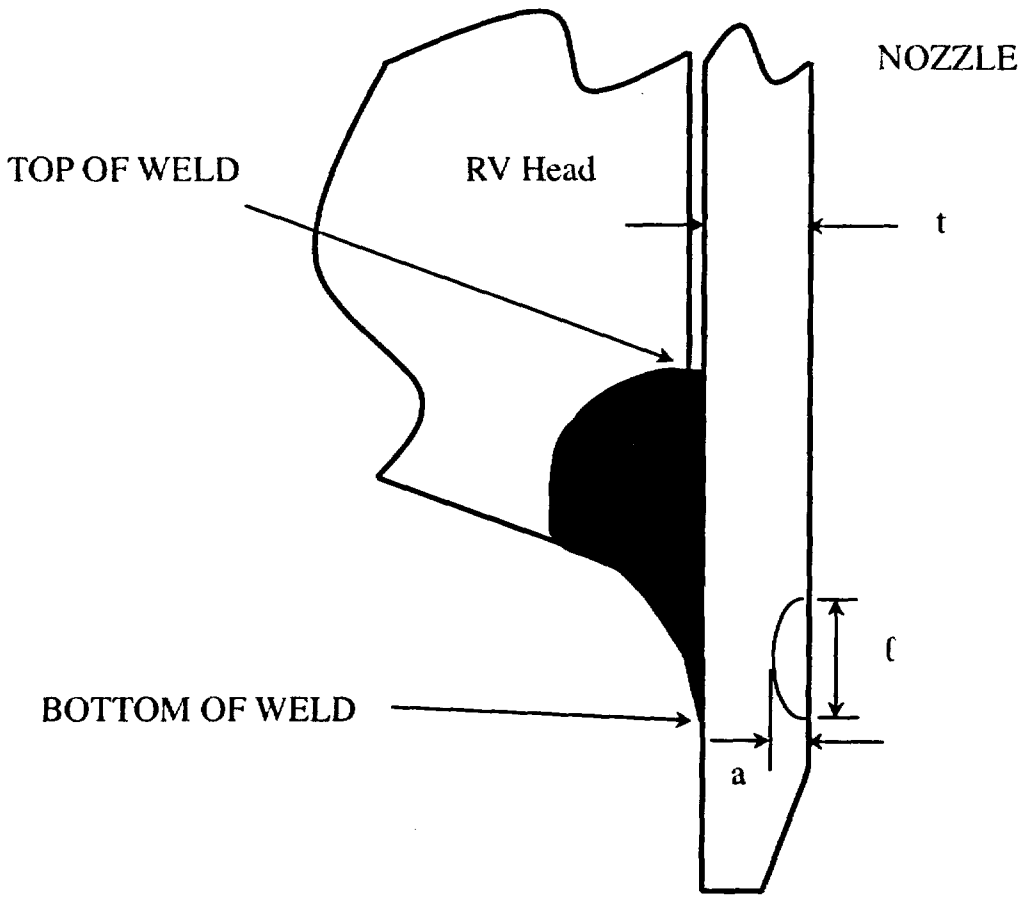


Figure 6-19 Schematic of Head Penetration Geometry

7 SUMMARY AND EXAMPLE PROBLEMS

An extensive evaluation has been carried out to characterize the loadings and stresses, which exist in the head penetrations at Byron and Braidwood Units 1 and 2 reactor vessel head. Three-dimensional finite element models were constructed [6], and all pertinent loadings on the penetrations were analyzed. These loadings included internal pressure and thermal expansion effects typical of steady state operation. In addition, residual stresses due to the welding of the penetrations to the vessel head were considered.

Results of the analyses reported here are consistent with the axial orientation and location of flaws which have been found in service in a number of plants and that the largest stress component is the hoop stress, and the maximum stresses were found to exist at the attachment weld. The most important loading conditions were found to be those which exist on the penetration for the majority of the time, which are the steady state loading and the residual stresses.

These stresses are important because the cracking observed to date in operating plants has been determined to result from primary water stress corrosion cracking (PWSCC). These stresses were used in the fracture calculations to predict the future growth of flaws postulated to exist in the head penetrations. A crack growth law was developed specifically for the bounding operating temperature of the head at Byron and Braidwood Units 1 and 2 reactor pressure vessels, based on the EPRI recommendation, which is consistent with laboratory data as well as crack growth results for operating plants.

The crack growth predictions contained in Section 6 show that the future growth of cracks which might be found in the penetrations will be typically moderate, however, a number of effective full power years would be required for any significant extensions. The propagation of circumferential flaws is much slower than that of axial flaws since the stresses responsible for cracking in the circumferential direction (axial stresses) are relatively small compare to the hoop stresses responsible for cracking in the axial direction.

7.1 SAFETY ASSESSMENT

It is appropriate to examine the safety consequences of an indication which might be found. The indication, even if it were to propagate through the penetration nozzle wall, would have only minor consequences, since the pressure boundary would not be broken, unless it were to propagate above the weld.

Further propagation of the indication would not change its orientation, since the hoop stresses in the penetration nozzle are much larger than the axial stresses. Therefore, it is extremely unlikely that the head penetration would be severed.

If the indication were to propagate to a position above the weld, a leak could result, but the magnitude of such a leak would be very small, because the crack could not open significantly due to the tight fit between the penetration nozzle and the vessel head. Such a leak would have no immediate impact on the structural integrity of the system, but could lead to wastage in the

ferritic steel of the vessel head, as the borated primary water concentrates due to evaporation. Davis Besse has demonstrated the consequence of ignoring such leaks.

Any indication is unlikely to propagate very far up the penetration nozzle above the weld, because the hoop stresses decrease in this direction, and this will cause it to slow down, and to stop before it reaches the outside surface of the head.

The high likelihood that the indication will not propagate up the penetration nozzle beyond the vessel head ensures that no catastrophic failure of the head penetration will occur, since the indication will be enveloped in the vessel head itself, which precludes the opening of the crack and limits leakage.

It should be noted that the objective of the acceptance criteria shown in Table 6-1 is to prevent leakage. Therefore, even though a small leak may have no immediate impact on the structural integrity of the system, it is not acceptable to the NRC and nozzle repair is required.

7.2 EXAMPLE PROBLEMS

The flaw tolerance charts in Figures 6-2 through 6-16 can be used with the acceptance criteria of Section 6.5 to determine the available service life for Byron and Braidwood Units 1 and 2. In this section, the guidelines on using the flaw tolerance charts and a few examples will be presented to illustrate the use of these charts. The example cases are listed in Table 7-1.

Guidelines on Using Flaw Tolerance Charts

Several guidelines are provided below to facilitate the use of flaw tolerance charts.

1. If a flaw is found in a penetration nozzle for which no specific analysis was performed and there is an uniform "trend" in the crack growth as a function of penetration nozzle angle, interpolation between penetration nozzles is the best approach.

For example in Figure 6-4, it can be seen that the slope of the crack growth curve is steeper as the penetration nozzle angle increases. That means if the initial flaw depth is the same for all the penetration nozzles, the time required to reach a given flaw depth is shorter as the penetration nozzle angle increases. In this case, a trend in the crack growth exists as a function of penetration nozzle angle.

2. If a flaw is found in a penetration nozzle for which no specific analysis was performed and there is no apparent trend in the crack growth as a function of penetration nozzle angle, the result for the penetration nozzle with the closest angle should be used.

3. If a flaw is found which has a depth smaller than any depth shown for the penetration nozzle angle of interest, the initial flaw depth should be assumed to be the same as the smallest depth analyzed for that particular penetration nozzle.

4. The flaw evaluation charts are applicable for aspect ratio of 6 or less. Consult with Westinghouse if the as-found flaw has an aspect ratio larger than 6.0.

5. All references to service life are in Effective Full Power Years (EFPY).

6. Results are only provided for the uphill and downhill sides of the selected penetration nozzles. If flaws are found in locations between the uphill and downhill side, use the results for either the uphill or downhill location, whichever is closer.

7. As shown in Example 4, flaws whose upper extremities grow within 0.5 inch below the weld can use both the "0.5 inch below the attachment weld" and "at the attachment weld" flaw tolerance charts. To avoid the use of these two charts, the "at the attachment weld" charts may solely be used in determining the service life. This shall provide a conservative estimate of the crack growth due to a larger stress field.

Example Problems

Example 1. Determine the service life of an axially oriented inside surface flaw whose upper extremity is located 1.25" below the weld on the uphill side of penetration no. 22. First, the penetration locality angle is obtained from Table 1-1 and, in this case, the locality angle is 25.4 degrees. The initial flaw depth, $a_{initial}$, is 0.078" and the initial flaw length, $2c_{initial}$, is 0.195". Assuming that the initial aspect ratio of 2.5:1 is maintained throughout the time that the inside surface flaw becomes a through-wall flaw, the final length of the flaw ($2c_{final}$) will be: 0.625" x 2.5 = 1.563". The upper extremity of the flaw is now located 1.25" – (1.563" – 0.195") / 2 = 0.566" below the weld and validates the use of a single crack growth curve, which is applicable to flaws located 0.5 inch below the attachment weld. The crack growth curve for the 25.4 degrees nozzle angle of Figure 6-2 is applicable and Figure 6-2 has been reproduced as Figure 7-1. The flaw is initially 12.5 percent of the wall thickness, and a straight line is drawn horizontally at a/t = 0.125 that intersects the crack growth curve. Using the acceptance criteria in Table 6-1, the service life can then be determined as the remaining time for this flaw to grow to the limit of 100 percent of the wall thickness or approximately 8.5 years (labeled as "Service Life" in Figure 7-1)

Example 2. In this case, the flaw is identical in size to that used in Example 1, but located on the outside surface and on the downhill side of penetration no. 22. This flaw, just as the flaw in Example 1, will not propagate within 0.5 inch below the bottom of the weld region. The applicable curve to use is Figure 6-9. The ratio a/t and initial reference time are likewise found using the same approach as used in Example 1. Using the acceptance criteria in Table 6-1, the determination of service life is illustrated in Figure 7-2, where we can see that the result is approximately 5 years.

Example 3. An axial inside surface flaw is located at the weld and on the downhill side of penetration no. 74. The initial length of the flaw is 0.250" and the initial depth is 0.05". From Table 1-1, the angle of this penetration nozzle is 47.0 degrees. The applicable curve is Figure 6-5 and is reproduced here as Figure 7-3. In this case, the initial flaw depth is 8.0 percent of the wall thickness. The initial reference time can be found by drawing a horizontal line at a/t = 0.08.

Since the as-found flaw depth is less than in Figure 6-5, the first analyzed flaw depth can be conservatively used. As a result, the initial reference time can be set at 0 years as shown in Figure 7-3. Using the acceptance criteria in Table 6-1, the allowable service life can then be determined as the time for the flaw to reach a depth of 75 percent of the wall thickness. The final reference time is found through a horizontal line drawn at a/t = 0.75. The service life can be determined through the intersection points of these lines and the crack growth curve. The resulting service life is approximately 9.8 years, as shown in Figure 7-3.

Example 4. In this case, we have postulated an axial inside surface flaw with an upper extremity located 1.0 inch below the attachment weld on the uphill side of penetration no. 74 (47.0 degrees). The flaw has an initial depth of 0.079" and an initial length of 0.395". Assuming that the initial aspect ratio of 0.395" / 0.079" or 5:1 is maintained as the flaw propagates into the nozzle wall, the final length of a through-wall flaw would be 0.625" x 5 = 3.125" long. The location of the upper extremity of this flaw would have reached within 0.5 inch below the weld as it propagates into the nozzle wall (1.0" – ((3.125" / 2) – (0.395" / 2)) = -0.365"). Therefore the evaluation will require the use of two flaw charts. The first step is to estimate the time required for the initial flaw to grow to within 0.5 inch from the weld. This can be accomplished with the use of Figure 6-2 and is reproduced here as Figure 7-4a. The upper extremity is 1 inch below the weld and is assumed to grow until the upper extremity is 0.5 inches below the weld. The final half-length of the flaw when it reaches 0.5 inches below the weld will be the sum of the initial half-length and the 0.5 inches it has grown or 0.395" / 2 + 0.5" = 0.6975". Multiplying this by two and then dividing by the aspect ratio, 5, gives the flaw depth when the upper extremity is 0.5 inches below the weld: 2 x 0.6975" / 5.0 = 0.279". Figure 7-4a can be used to find the time it takes to grow from 12.6% through-wall (a/t = 0.079" / 0.625" = 0.126) to 44.6% through-wall (a/t = 0.279" /0.625" = 0.446). The time is estimated as 5.0 years. Using the flaw depth calculated previously (a/t = 0.446) as the initial flaw depth, the curves in Figure 6-4 reproduced here as Figure 7-4b for inside surface flaws at the weld can be used to determine the remaining service time before the flaw depth reaches the allowable flaw size (a/t = 0.75). Using the acceptance criteria in Table 6-1, Figure 7-4b shows an additional 1.5 years of service life for a total of 6.5 years.

As shown above, flaws whose upper extremities grow within 0.5 inch below weld require the use of both the "0.5 inch below the attachment weld" and "at the attachment weld" flaw tolerance charts. To avoid the use of these two charts, the "at the attachment weld" chart may solely be used in determining the service life. This shall provide a conservative estimate of the crack growth due to the higher stress field.

Example 5. This case is an axial through-wall flaw with its upper extremity located 0.40 inches below the weld region of penetration no. 62. Similarly, this would be the case where inspection can only be performed from 2 inch above the J-weld to only 0.40 inches below the weld on the downhill side. The objective is to determine the remaining service life for a flaw in the un-inspected region below the weld to reach the bottom of the J-weld. The angle of the penetration nozzle is 42.8 degrees as shown in Table 1-1. The crack growth curve of Figure 6-13 is applicable and has been reproduced as Figure 7-5. The initial reference time is found by drawing a horizontal line 0.40 inches below the line representing the bottom of the weld, then dropping a vertical line to the horizontal axis. The final reference time is found by drawing a vertical line

where the crack growth curve intersects the bottom of the weld horizontal line. If inspection can only be performed from 2 inch above the J-weld to only 0.4 inches below the weld, it would take approximately 3.2 years for a flaw in the un-inspected region below the weld to reach the weld bottom.

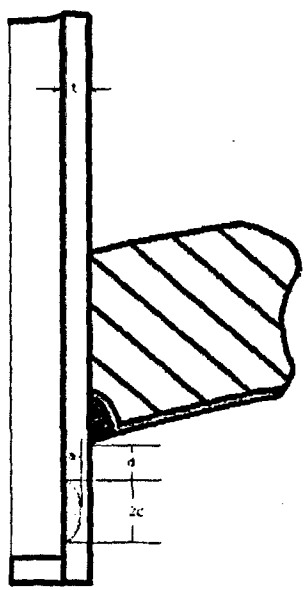
Table 7-1Example Problem Inputs: Initial Flaw Sizes and Locations

Example No.	Orientation	Vertical Location	Circumferential Location	Penetration Row	Length	Depth	Penetration No.	Source Figure
1	Axial - Inside Surface	1.25" Below Weld	Uphill	25.4°	0.195"	0.078"	. 22	6-2
2	Axial - Outside Surface	1.25" Below Weld	Downhill	25.4°	0.195"	0.078"	22	6-9
3	Axial - Inside Surface	At Weld	Downhill	47.0°	0.250"	0.05"	74	6-5
4	Axial - Inside Surface	1.0" Below Weld	Uphill	47.0°	0.395"	0.079"	74	6-2, 6-4
5	Axial Through-Wall	0.40" Below Weld	Downhill	42.8°	--	--	62	6-13

Example No.	Orientation	Crack Tip Location (d)	Circumferential Location	Penetration Row	Length (2c)	Depth (a)	Wall Thickness	a/t	Penetration No.	Source Figure
1	Axial – Inside Surface	1.25" Below Weld	Uphill	25.4°	0.195"	0.078"	0.625"	0.125	22	6-2

Locality Angle from Table 1-1:

Nozzle No.	Angle
22	25.4



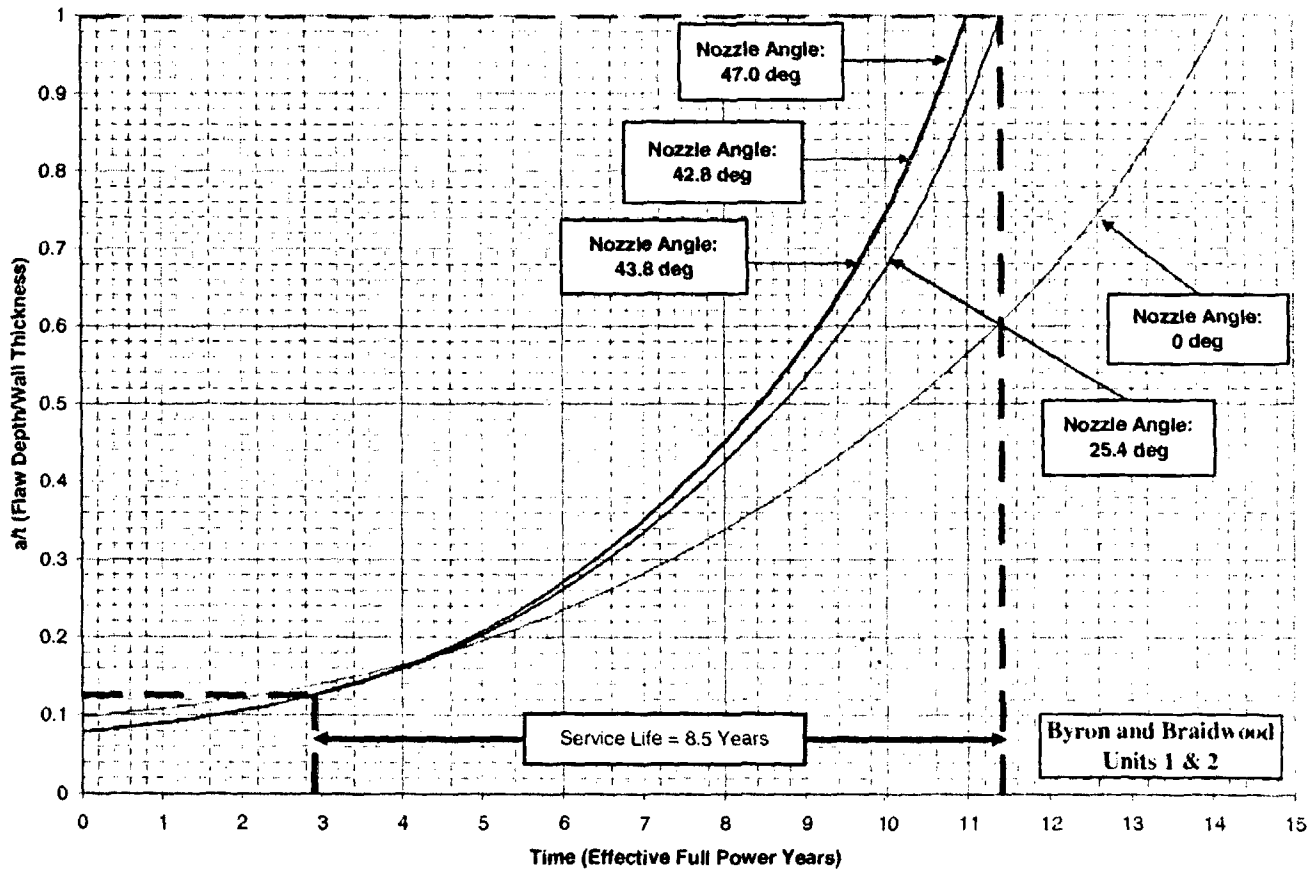
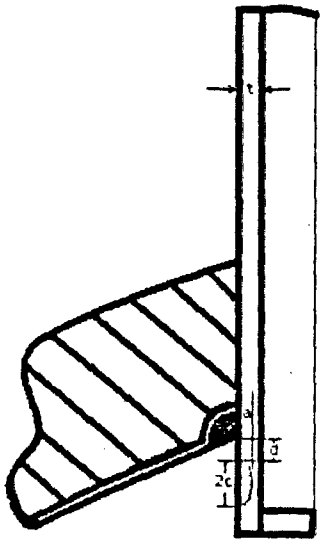


Figure 7-1 Example Problem 1

Example No.	Orientation	Crack Tip Location (d)	Circumferential Location	Penetration Row	Length (2c)	Depth (a)	Wall Thickness	a/t	Penetration No.	Source Figure
2	Axial – Outside Surface	1.25" Below Weld	Downhill	25.4°	0.195"	0.078"	0.625"	0.125	22	6-9

Locality Angle from Table 1-1:

Nozzle No.	Angle
22	25.4



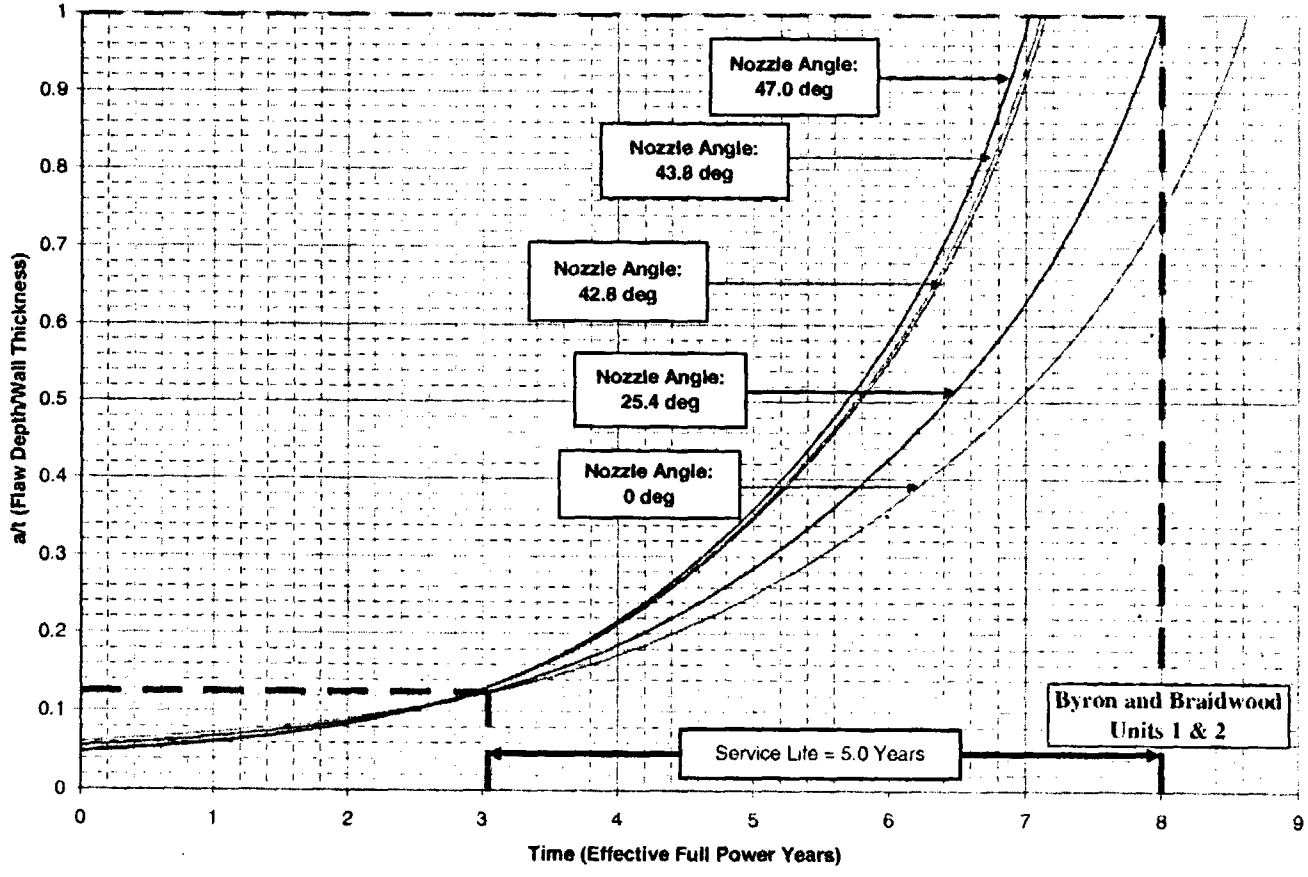
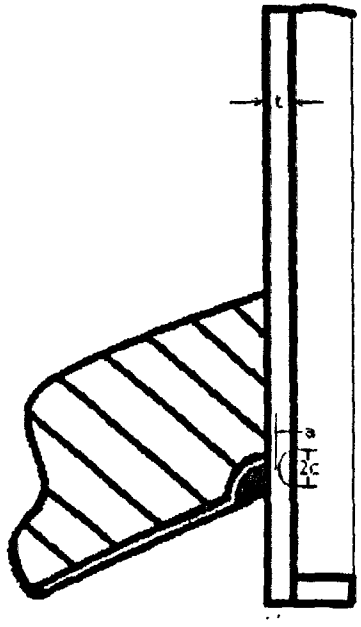


Figure 7-2 Example Problem 2

Example No.	Orientation	Crack Tip Location (d)	Circumferential Location	Penetration Row	Length (2c)	Depth (a)	Wall Thickness	a/t	Penetration No.	Source Figure
3	Axial – Inside Surface	At Weld	Downhill	47.0°	0.250"	0.05"	0.625"	0.08	74	6-5

Locality Angle from Table 1-1:

Nozzle No.	Angle
74	47.0



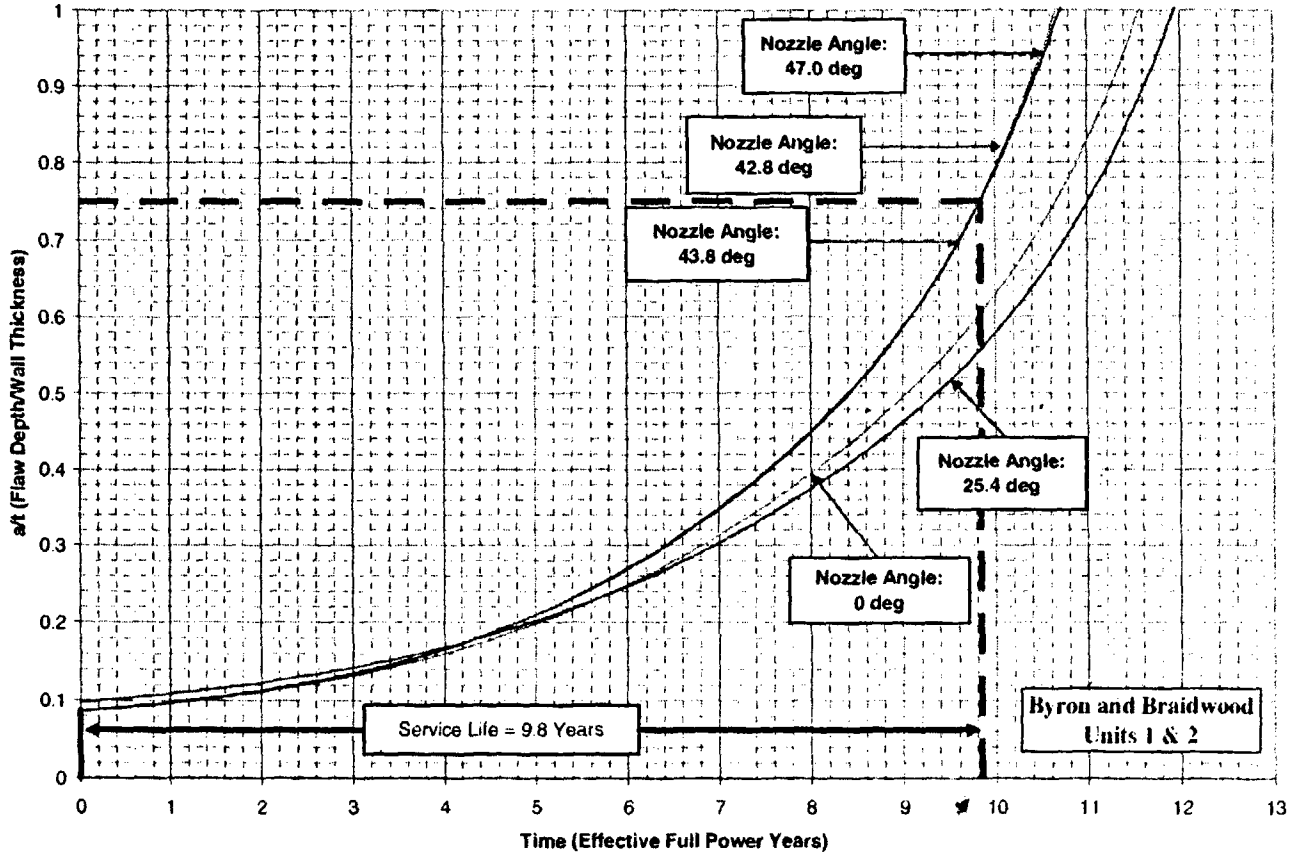
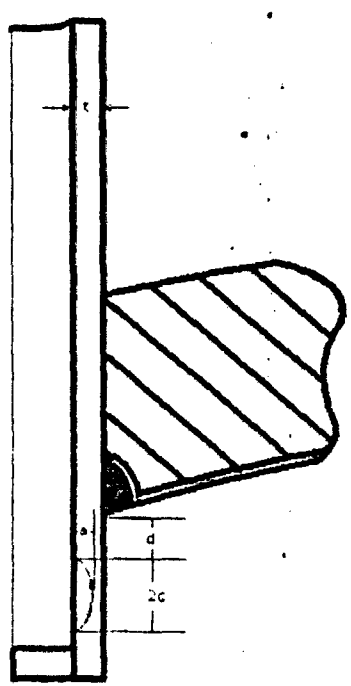


Figure 7-3 Example Problem 3

Example No.	Orientation	Crack Tip Location (d)	Circumferential Location	Penetration Row	Length (2c)	Depth (a)	Wall Thickness	a/t	Penetration No.	Source Figure
4	Axial – Inside Surface	1.00" Below Weld	Uphill	47.0°	0.395"	0.079"	0.625"	0.126	74	6-2, 6-4

Locality Angle from Table 1-1:

Nozzle No.	Angle
74	47.0



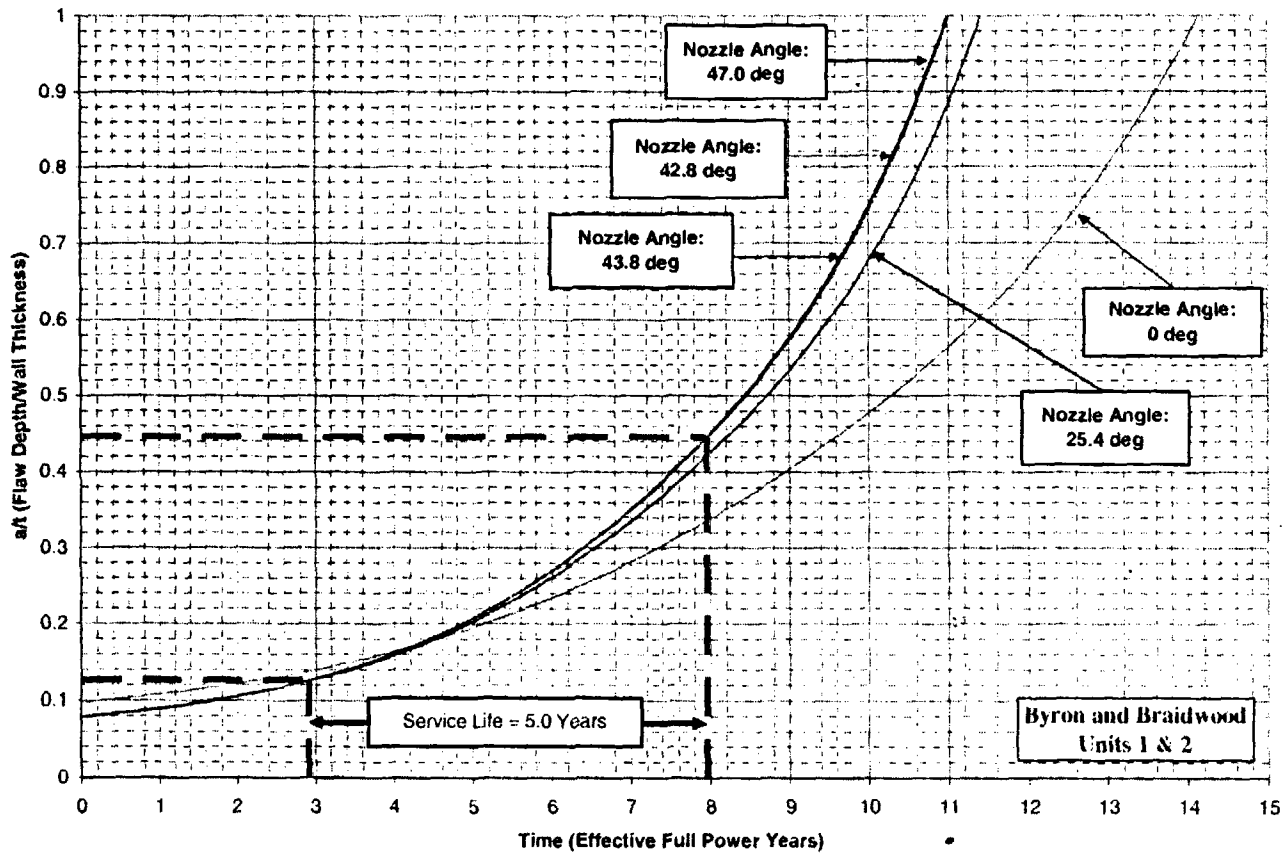
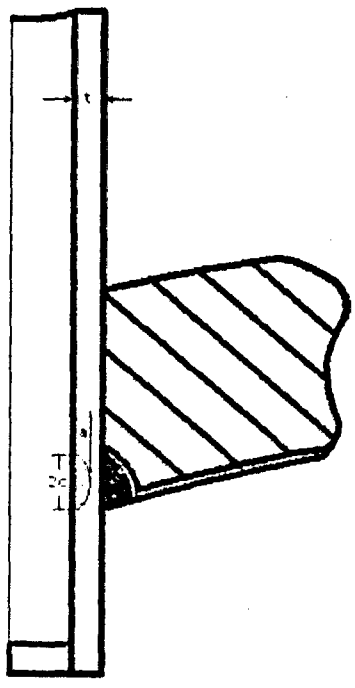


Figure 7-4a Example Problem 4 (See also Figure 7-4b)

Example No.	Orientation	Crack Tip Location (d)	Circumferential Location	Penetration Row	Length (2c)	Depth (a)	Wall Thickness	a/t	Penetration No.	Source Figure
4	Axial – Inside Surface	1.00" Below Weld	Uphill	47.0°	0.395"	0.079"	0.625"	0.126	74	6-2, 6-4

Locality Angle from Table 1-1:

Nozzle No.	Angle
74	47.0



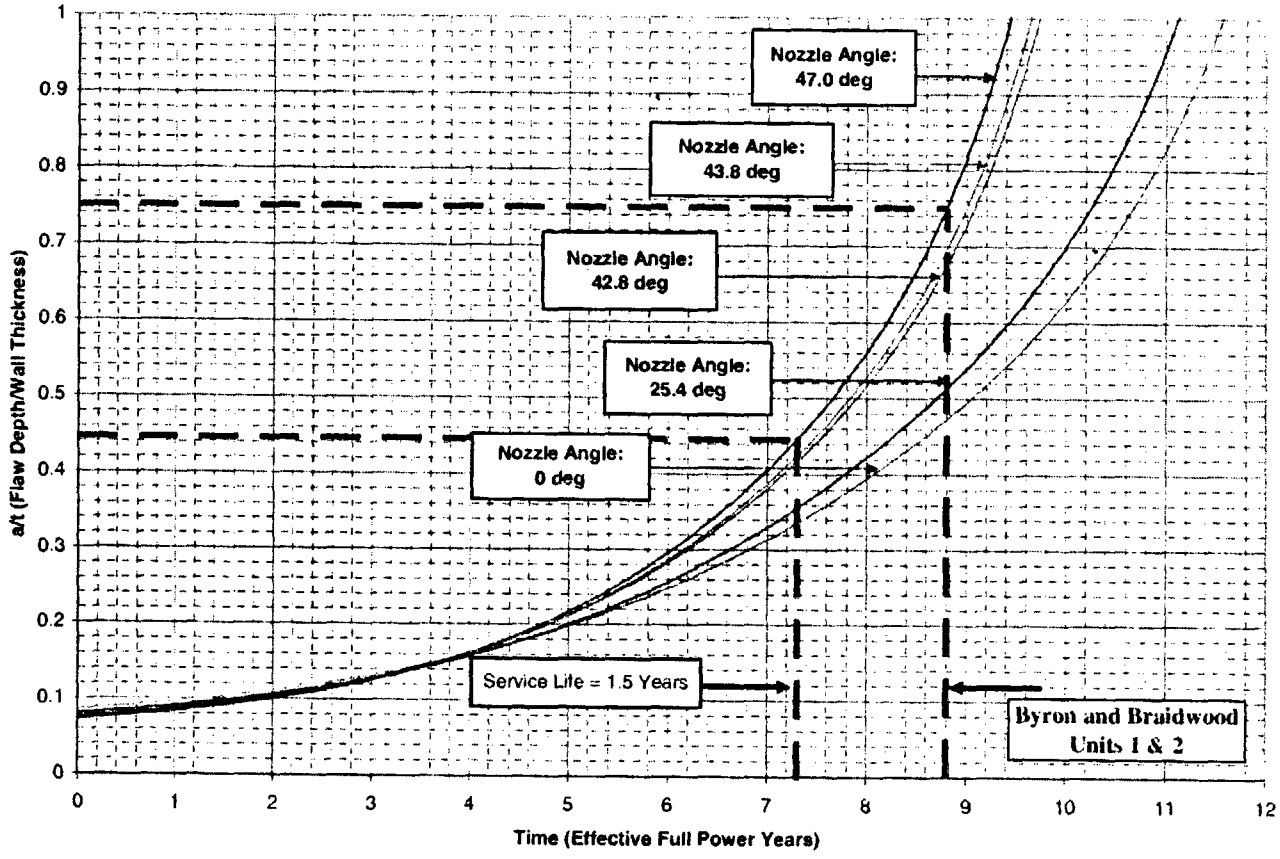
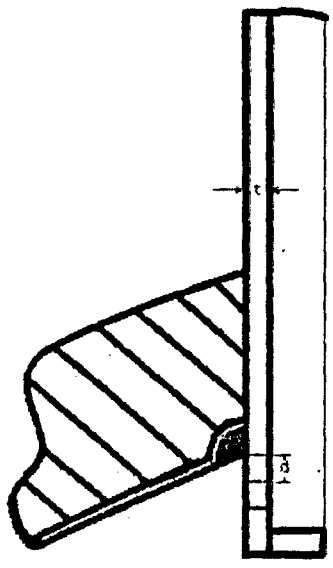


Figure 7-4b Example Problem 4 (See also Figure 7-4a)

Example No.	Orientation	Crack Tip Location (d)	Circumferential Location	Penetration Row	Length (2c)	Depth (a)	Wall Thickness	a/t	Penetration No.	Source Figure
5	Axial – Through-Wall	0.4" Below Weld	Downhill	42.8°	N/A	N/A	0.625"	N/A	62	6-13

Locality Angle from Table 1-1:

Nozzle No.	Angle
62	42.8



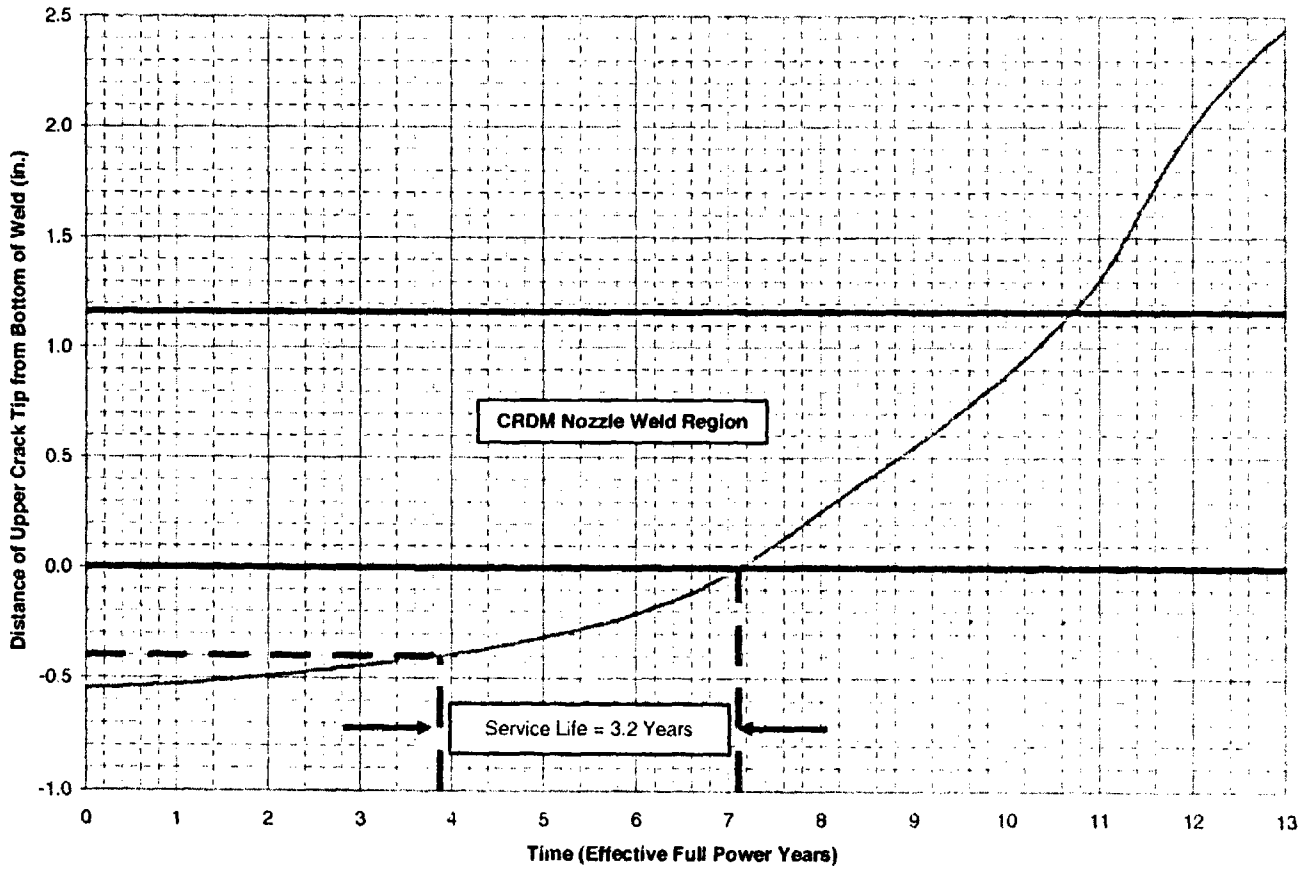


Figure 7-5 Example Problem 5

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1C. Babcock and Wilcox Drawing No. 184577-E, Revision 2, "Control Rod Mech. Housing" (Byron Unit 1).

2A. Babcock and Wilcox Drawing No. 185283-E, Revision 1, "Closure Head Sub-Assembly Sheet #1" (Byron Unit 2).

2B. Babcock and Wilcox Drawing No. 185282-E, Revision 0, "Closure Head Assembly" (Byron Unit 2).

2C. Babcock and Wilcox Drawing No. 185286-E, Revision 1, "Control Rod Mech. Housing" (Byron Unit 2).

3A. Babcock and Wilcox Drawing No. 185314-E, Revision 0, "Closure Head Sub-Assembly Sheet #1" (Braidwood Unit 1).

3B. Babcock and Wilcox Drawing No. 185313-E, Revision 0, "Closure Head Assembly" (Braidwood Unit 1).

3C. Babcock and Wilcox Drawing No. 185317-E, Revision 0, "Control Rod Mech. Housing" (Braidwood Unit 1).

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APPENDIX A

CRDM HOOP STRESS DISTRIBUTIONS BELOW THE WELD

In this section, the CRDM hoop stress distributions below the weld are plotted for the 0° (center penetration), 25.4°, 42.8°, 43.8°, and 47.0° penetration rows on both the downhill and uphill sides. The information presented in this Appendix can be used to determine the extent of inspection coverage needed in order to meet the NRC Order EA-03-009 requirements or facilitate the submittal of relaxation requests in the event that the NRC order requirements cannot be met.

Figure A-1
Hoop Stress Distribution Downhill and Uphill Side
(0° CRDM Penetration Nozzle)

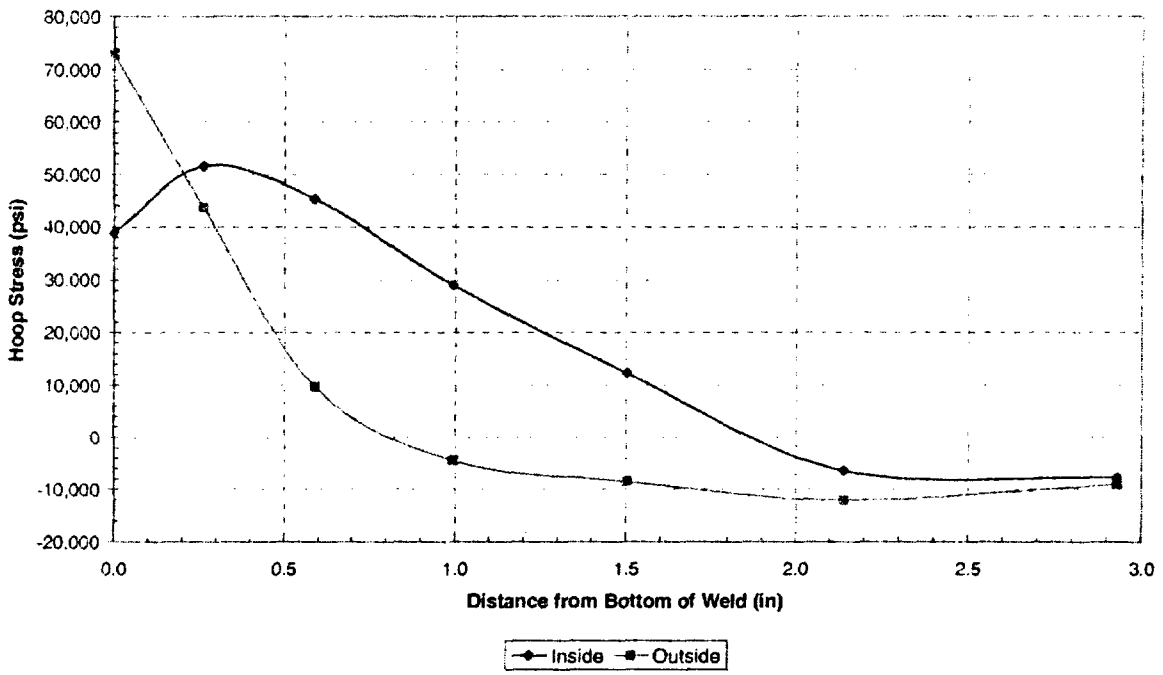

Figure A-2
Hoop Stress Distribution Downhill Side
(25.4° CRDM Penetration Nozzle)

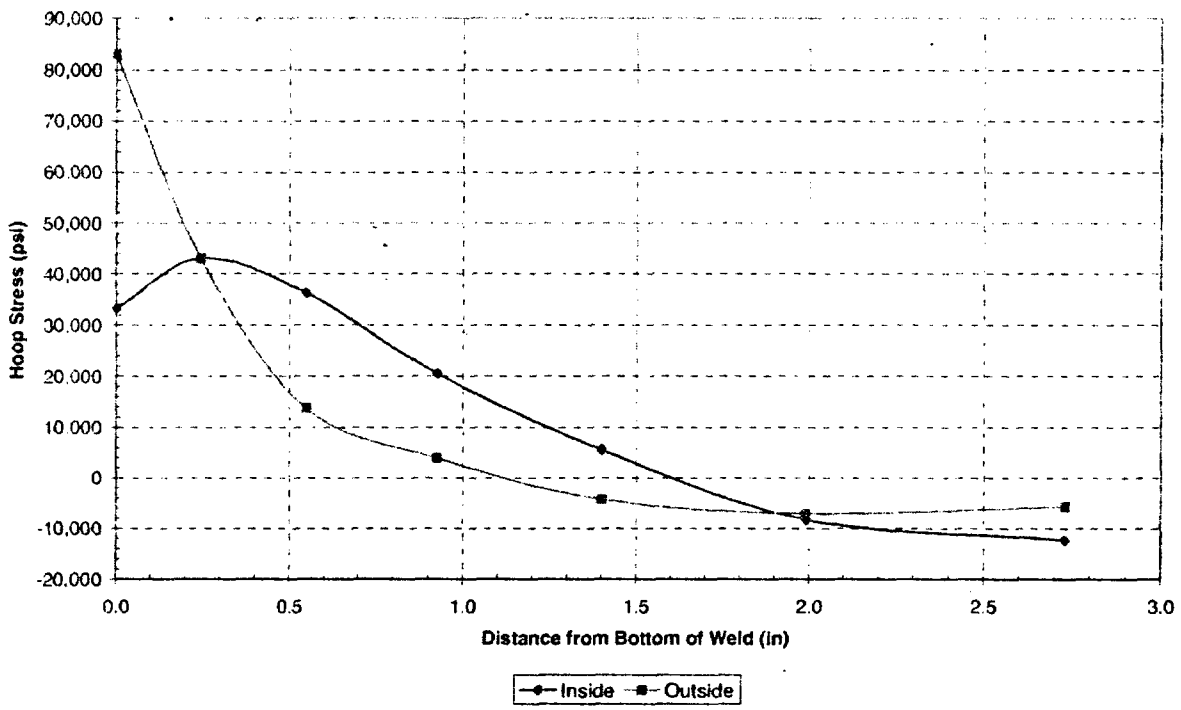

Figure A-3
Hoop Stress Distribution Uphill Side
(25.4° CRDM Penetration Nozzle)

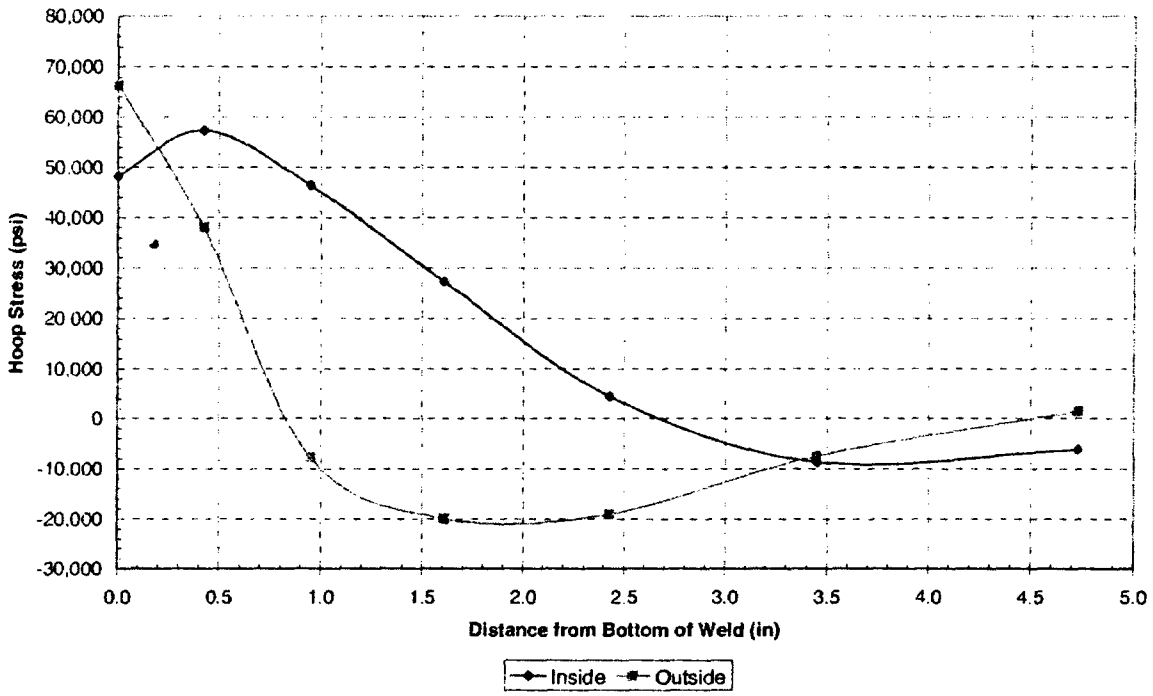

Figure A-4
Hoop Stress Distribution Downhill Side
(42.8° CRDM Penetration Nozzle)

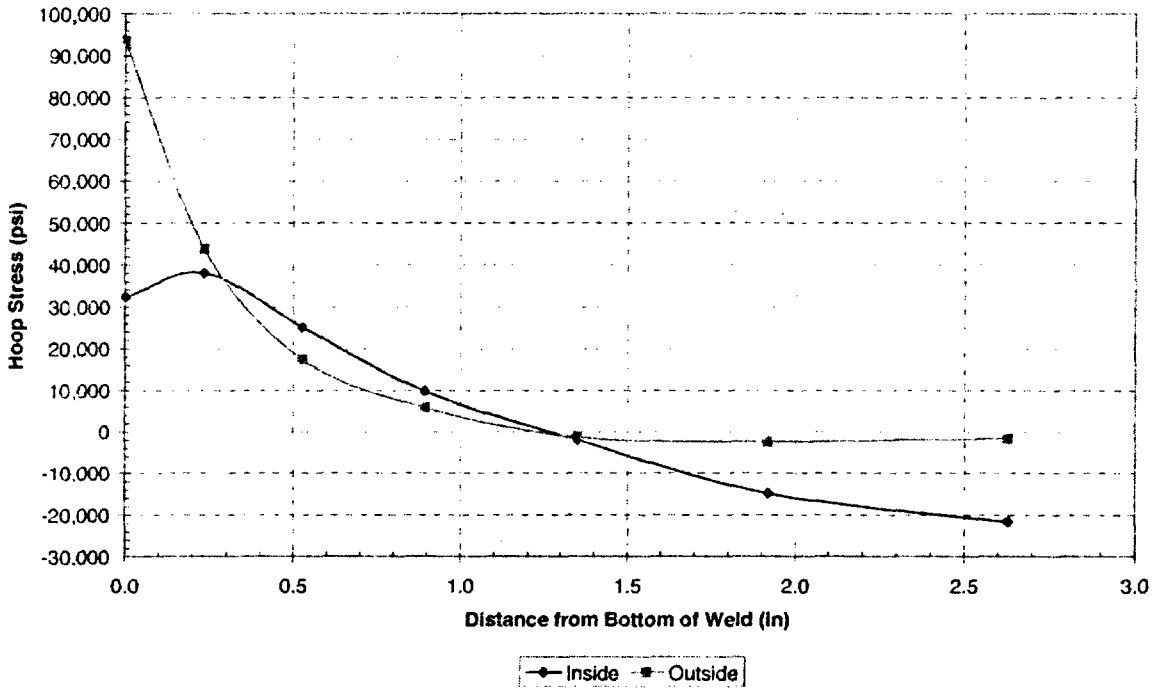

Figure A-5
Hoop Stress Distribution Uphill Side
(42.8° CRDM Penetration Nozzle)

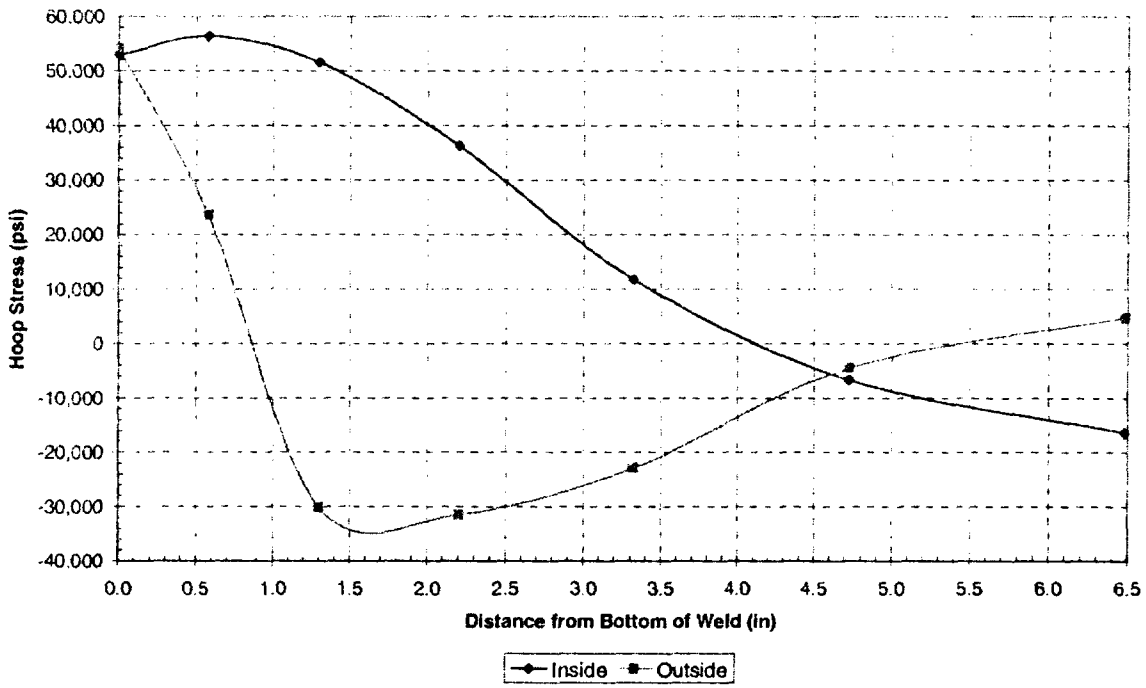

Figure A-6
Hoop Stress Distribution Downhill Side
(43.8° CRDM Penetration Nozzle)

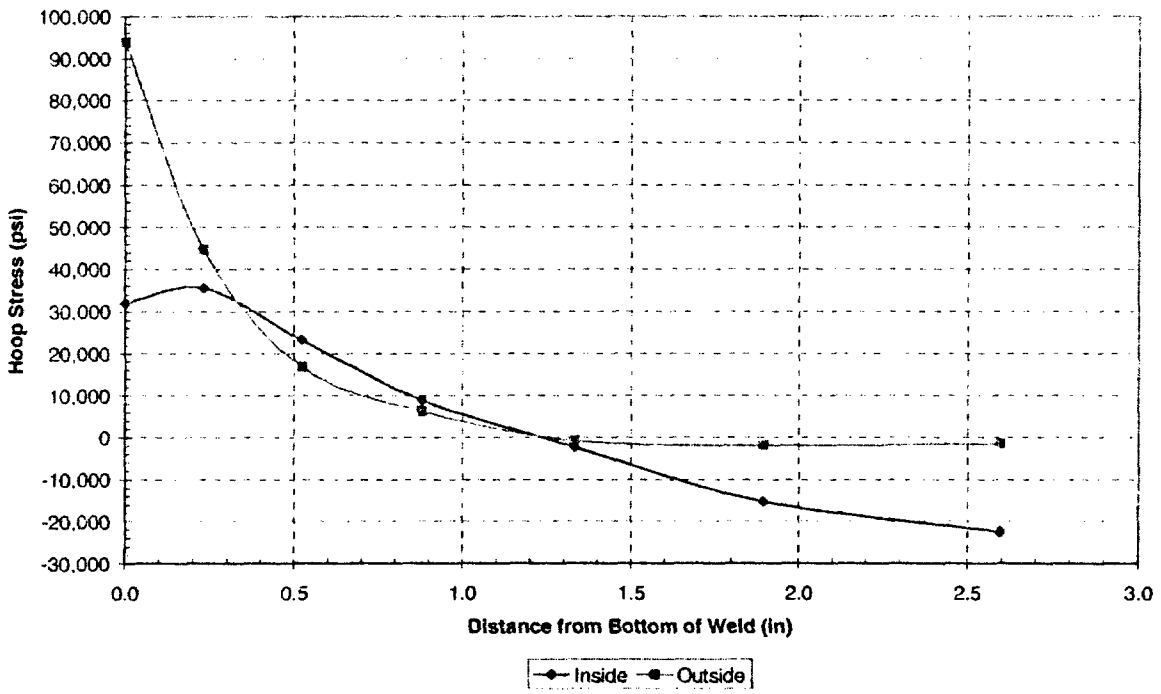

Figure A-7
Hoop Stress Distribution Uphill Side
(43.8° CRDM Penetration Nozzle)

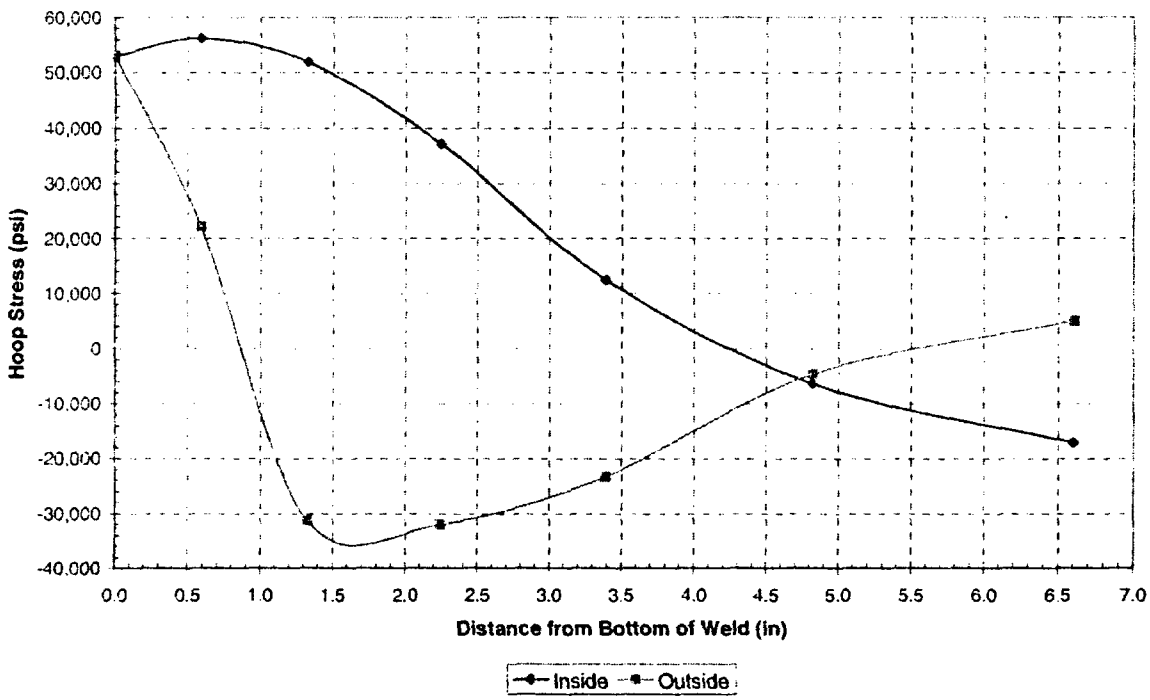

Figure A-8
Hoop Stress Distribution Downhill Side
(47.0° CRDM Penetration Nozzle)

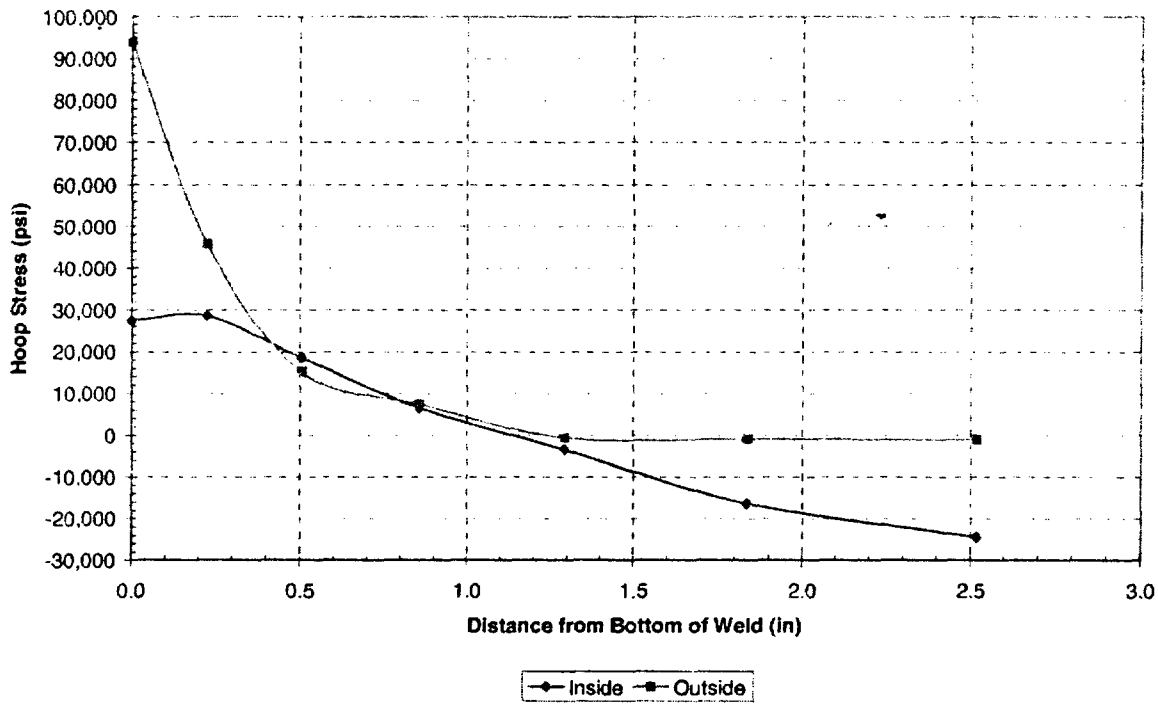
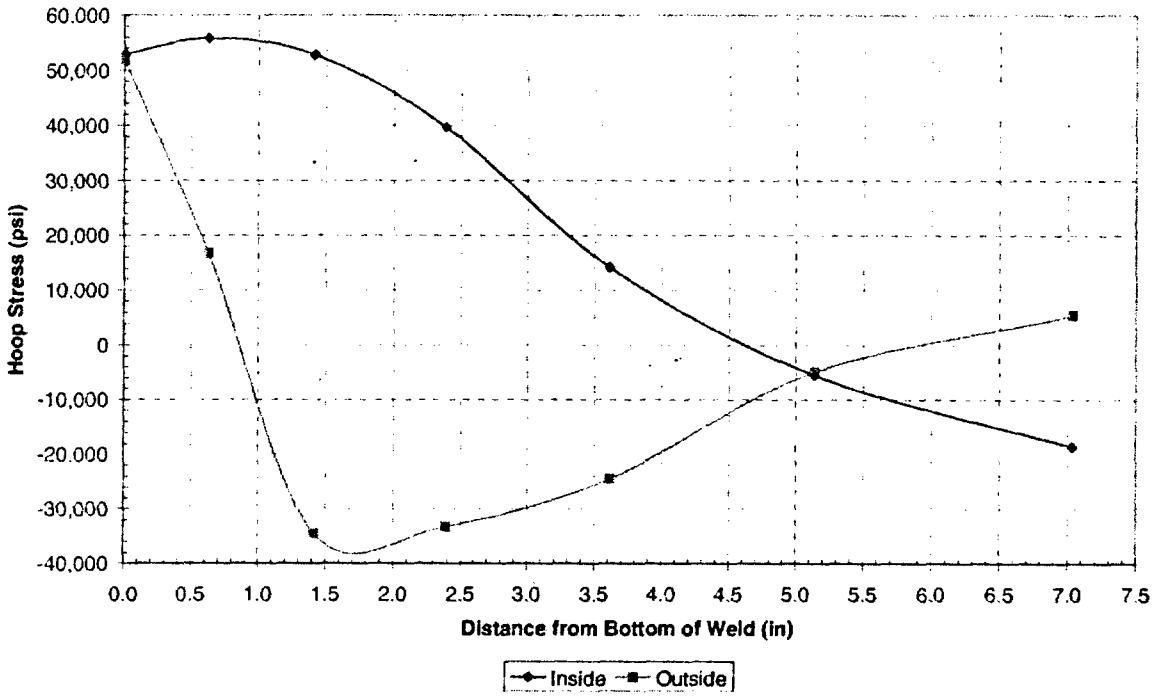
Figure A-9
Hoop Stress Distribution Uphill Side
(47.0° CRDM Penetration Nozzle)