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1CAN052201 10 CFR 50.55a(z)(2)

May 31, 2022

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Subject: Request for Relief Related to American Society of Mechanical Engineers (ASME) Code Case N-729-6 Augmented Examination Requirements
ANO1-ISI-035

Arkansas Nuclear One, Unit 1
NRC Docket No. 50-313
Renewed Facility Operating License No. DPR-51

Pursuant to 10 CFR 50.55a(z)(2), Entergy Operations, Inc. (Entergy) requests approval of the enclosed request for a one-time extension of the schedule for inservice examination of Control Rod Drive Mechanism (CRDM) Penetration No. 1 in the Arkansas Nuclear One, Unit 1 (ANO-1) reactor vessel closure head (RVCH). The augmented examination requirements of 10 CFR 50.55a(g)(6)(ii)(D) specify that periodic inservice volumetric or surface examinations be performed of RVCH penetrations in accordance with Code Case N-729-6. Examination of CRDM Penetration No. 1 in accordance with Code Case N-729-6 would present a hardship without a compensating increase in the level of quality and safety. The enclosure contains the affected components, applicable American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Case requirements, and the basis for request.

The requested alternative would permit extension of the schedule for the volumetric or surface examination of Penetration No. 1 until the time that the second B4.40 inservice examination is required for the other head penetrations. The examination of other head penetrations is within two inspection intervals (nominally 20 calendar years) after the spring 2021 refueling outage (1R29). This future inspection outage would be beyond the May 2034 expiration of the current ANO-1 renewed license.

While it will be shown in the enclosed request, the requested alternative volumetric re-examination period of about calendar 35.4 years is concluded to be sufficient to ensure structural and leak tight integrity of Penetration No. 1, Entergy requests approval of the requested alternative to the end of the current renewed ANO-1 Operating License (May 2034).

This letter contains no new regulatory commitments.

Approval of the proposed relief is requested prior to December 31, 2023, to provide time to plan for the 1R32 refueling outage scheduled to occur in fall 2025.

If there are any questions or if additional information is needed, please contact Riley Keele, Manager, Regulatory Assurance, at (479) 858-7826.

Respectfully,

Stephenie Pyle

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Stephenie Pyle

SLP/rwc

Enclosure: Request for Relief – ANO1-ISI-035

Attachment to Enclosure:

DEI Calculation C-4731-00-02, Rev. 0: “Axial Crack Growth Evaluation for CRDM Penetration Nozzle 1 in ANO Unit 1 Replacement RVCH”

cc: NRC Region IV Regional Administrator

NRC Senior Resident Inspector – Arkansas Nuclear One

NRC Project Manager – Arkansas Nuclear One

ENCLOSURE

1CAN052201

REQUEST FOR RELIEF
ANO1-ISI-035

Request for Relief – ANO1-ISI-035

Components / Numbers:	Reactor Vessel Closure Head (RVCH) Penetration Nozzle 0-1
Code Classes:	American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (Code), Class 1
References:	ASME Section XI 2007 Edition through 2008 Addenda. ASME Section XI, Division 1, Code Case N-729-6, Alternative Examination Requirements for PWR Reactor Vessel Upper Heads with Nozzles Having Pressure-Retaining Partial-Penetration Welds, Section XI, Division 1
Examination Category:	Table 1 of ASME Code Case N-729-6
Item Number(s)	B4.40
Description:	Nozzles and partial-penetration welds of primary water stress corrosion cracking (PWSCC)-resistant materials in head
Unit / Inspection Interval Applicability:	Arkansas Nuclear One, Unit 1 (ANO-1) / Fifth 10-Year Inservice Inspection (ISI) Interval (May 31, 2017, to May 30, 2027) and Sixth 10-Year Inservice Inspection (ISI) Interval (May 31, 2027, to May 20, 2034)

I. APPLICABLE REQUIREMENTS

The fifth 10-year ISI interval Code of Record for ANO-1 is the 2007 Edition through the 2008 Addenda of ASME Code, Section XI, *Rules for Inservice Inspection of Nuclear Power Plant Components.*

Examinations of the RVCH penetration nozzles are performed in accordance with ASME Code Case N-729-6, *Alternative Examination Requirements for PWR Reactor Vessel Upper Heads with Nozzles Having Pressure-Retaining Partial-Penetration Welds*, Section XI, Division 1 (Reference 1), as conditioned by 10 CFR 50.55a(g)(6)(ii)(D).

10 CFR 50.55a(g)(6)(ii)(D) requires, in part, that licensees of pressurized water reactors (PWRs) shall augment the inservice inspection program with ASME Code Case N-729-6 subject to the conditions specified in paragraphs (g)(6)(ii)(D)(2) through (8) of this section.

10 CFR 50.55a(g)(6)(ii)(D)(1) requires:

> (D) *Augmented ISI requirements: Reactor vessel head inspections— (1) Implementation*. Holders of operating licenses or combined licenses for pressurized-water reactors as of or after June 3, 2020, shall implement the requirements of ASME BPV Code Case N–729–6 instead of ASME BPV Code Case N–729–4, subject to the conditions specified in paragraphs (g)(6)(ii)(D)(2) through (8) of this section, by no later than one year after June 3, 2020. All previous NRC-approved alternatives from the requirements of paragraph (g)(6)(ii)(D) of this section remain valid.

Table 1 of Code Case N-729-6 requires a volumetric or surface examination per Item B4.40 with the following extent and frequency:

> All nozzles, not to exceed two inspection intervals (nominally 20 calendar years)

II. REQUEST FOR RELIEF

Entergy Operations, Inc. (Entergy) is requesting relief to defer the volumetric or surface examination of reactor vessel upper head penetration number 0-1 (Penetration No. 1) in the ANO-1 RVCH (one of the components covered by Item No. B4.40 of Table 1 of Code Case N-729-6) until the time that the second B4.40 inservice examination is required for the other head penetrations. Entergy performed a volumetric examination of the ANO-1 RVCH during the spring 2021 refueling outage (1R29) that satisfied the B4.40 inservice examination requirements for the other 68 penetrations in the RVCH. The applicable B4.40 examination frequency of once per two inspection intervals (nominally 20 years) requires that Penetration No. 1 be examined no later than the 1R32 refueling outage in fall 2025. Hence, relief is requested to defer the B4.40 inservice examination of Penetration No. 1 until two inspection intervals (nominally 20 calendar years) after the spring 2021 refueling outage (1R29). This future inspection outage would be beyond expiration of the current ANO-1 renewed license (May 20, 2034). While it will be shown below, the requested alternative volumetric re-examination period of about calendar 35.4 years is concluded to be sufficient to ensure structural and leak tight integrity of Penetration No. 1, Entergy requests approval of the requested alternative to the end of the current renewed ANO-1 Operating License (May 2034).

Entergy is requesting relief due to the hardship without a compensating increase in the level of quality and safety of removal and reinstallation of the post-accident reactor vessel water level (RADCAL) instrument installed on Penetration No. 1. Removal and subsequent reinstallation of the RADCAL instrument, entailing significant worker dose and considerable risks, would be necessary to obtain access to perform a volumetric or surface examination of Penetration No. 1 satisfying the requirements of N-729-6. Without removing the instrument, the tight gap between the RADCAL instrument guide assembly and the inside of Penetration No. 1 precludes ultrasonic testing (UT) or eddy current testing (ET) using a blade probe. Removal of the RADCAL instrument including its integral guide assembly would require unbolting the flanged joint connecting the instrument to the primary pressure boundary just above the RVCH. This bolted joint is intended to be a permanent mechanical connection. The risks of removal and reinstallation of the RADCAL instrument include unintended damage to the instrument and other

components and leakage of reactor coolant at the flanged joint, which would have the potential to cause corrosion of the upper RVCH surface.

The attached deterministic crack growth calculation specific to Penetration No. 1 demonstrates the acceptability of the proposed alternative to address the potential for leakage due to PWSCC affecting the Alloy 690 nozzle base metal material. The operating experience for the replacement nickel (Ni)-based alloys (Alloys 690, 52, and 152) used to fabricate the ANO-1 head is excellent, with no reports of PWSCC. The hardship affects only a single penetration out of the population of 69. Furthermore, defense in depth is maintained under the alternative through the performance of periodic bare metal visual examinations for evidence of head penetration leakage and through enhanced leakage detection capability.

In summary, removal of the RADCAL instrument to permit volumetric or surface examination of Penetration No. 1 would result in a hardship without a compensating increase in the level of quality and safety as specified in 10 CFR 50.55a(z)(2), and the proposed alternative would provide reasonable assurance of structural integrity of the control rod drive mechanism (CRDM) penetrations and RVCH.

III. BASIS FOR RELIEF

Background

The primary degradation mechanism addressed by 10 CFR 50.55a(g)(6)(ii)(D) and ASME Code Case N-729-6 is PWSCC. This degradation mechanism occurs when a susceptible material is exposed to the PWR reactor coolant environment, PWR operating temperature, and high tensile stresses. In the case of RVCH penetrations, the periodic examinations required by ASME Code Case N-729-6 as conditioned by the NRC are intended to ensure that potential PWSCC flaws will be detected before they challenge the structural or leak tight integrity of the RVCH within current nondestructive examination limitations.

Operating experience demonstrates that the susceptibility of Alloy 690 nozzles to PWSCC is very low. To date, there have been no reports of PWSCC affecting components fabricated using Alloy 690 wrought material or Alloys 52/152 weld material. This is in contrast with the operating experience for Alloy 600 and Alloys 82/182 material, including PWSCC observed to cause CRDM penetration leakage after as few as 5.5 effective full power years (EFPY) (Reference 2).

ANO-1 Replacement RVCH

During refueling outage 1R19 in the fall of 2005, Entergy replaced the original RVCH, which contained PWSCC-susceptible Alloy 600 nozzles and Alloy 82/182 weld metal, with a replacement RVCH containing CRDM nozzles fabricated using PWSCC-resistant material UNS N06690 (Alloy 690) and UNS N06052 and UNS W86152 (Alloy 52 and Alloy 152). Alloy 690 wrought material and the associated weld metals (Alloys 52 and 152 and their variants) are highly resistant to PWSCC due to a chromium content of approximately 30%.

The ANO-1 replacement RVCH contains 69 CRDM penetrations (designated 0-1 through 0-69), with the central penetration (Penetration 0-1) also functioning as the head vent. The RVCH

CRDM nozzle housings are fabricated from SB-167 UNS N06690, and the CRDM nozzle housing adapter flanges are fabricated from A182 F-304 stainless steel. Weld materials ERNiCrFe-7 (UNS N06052) and ENiCrFe-7 (UNS W86152) were used to attach the nozzles to the inside of the RVCH. The CRDM nozzle housing materials and applicable weld materials were procured and certified to ASME Section III, 1989 Edition, no Addenda, but have been reconciled to ASME Section III, 1998 Edition, with Addenda through 2000, to eliminate the requirement to use Code Cases, as would be required using the 1989 Edition.

The nozzle for Penetration No. 1 was fabricated using the same heat of Alloy 690 material used to fabricate 65 of the other 68 head penetrations (Reference 13). Therefore, the examinations already performed of all 68 penetrations other than Penetration No. 1 are directly relevant to the heat-specific material susceptibility of the nozzle for Penetration No. 1. The behavior for the Alloy 690 material heat used to fabricate Penetration No. 1 has been well sampled.

During the 1R29 refueling outage in spring 2021, 68 of 69 of the penetrations of the replacement RVCH were examined in accordance with the requirements of 10 CFR 50.55a(g)(6)(ii)(D) and ASME Code Case N-729-6. The other penetration (Penetration No. 1) is the subject of this relief request.

In 1R29 ANO was planning to perform an open housing inspection on the center nozzle. It was known that the center nozzle contained the RADCAL, but due to the proprietary nature of the configuration, it was not understood that certain portions of the RADCAL assembly were permanently installed and were not removed during normal refueling activities.

Prior to attempting to insert an inspection probe into the Penetration No. 1 housing, it was discovered that the CRDM adapter flange and withdrawal shroud remained in the nozzle housing. These components were not removed with the manometer tube and GT probe as was thought to be the case.

Entergy contacted Framatome to inquire about different probe options based upon Framatome Operating Experience with performing these inspections for other Babcock and Wilcox (B&W) design RVCH's. Entergy discovered through conversation with Framatome that the ANO-1 center nozzle was a different configuration than other B&W designs, and there were no probes in existence that would permit a UT inspection of the center nozzle.

No evidence of PWSCC was detected during the 1R29 examination, which included UT from the nozzle inside diameter (ID) of the 68 penetrations to detect PWSCC and UT leak path examinations of the 68 penetrations to detect evidence of leakage, as well as eddy current (ET) examinations of 35 of the 68 penetrations of the nozzle ID surfaces. All CRDM nozzle UT examinations covered the volume for greater than 2 inches above the highest point of the weld and the entire volume below the weld to the radiused bottom end of the CRDM nozzle.

<u>PWSCC Crack Growth Evaluation</u>

In support of this relief request, a deterministic PWSCC crack growth evaluation was performed to demonstrate the effectiveness of the proposed alternative to address the potential for PWSCC of the CRDM Penetration No. 1 nozzle base metal to lead to pressure boundary leakage. A main objective of the volumetric or surface examinations required under Items B4.20 and B4.40 of ASME Code Case N-729-6, Table 1 is to detect PWSCC degradation

affecting the nozzle base metal prior to through-wall leakage occurring. As documented in the attachment to this Enclosure, the crack growth evaluation is specific to Penetration No. 1 of the ANO-1 replacement head, and it applies the same type of deterministic fracture mechanics procedure that has commonly been applied for this purpose. Accordingly, growth of axial flaws originating both on the nozzle outside diameter (OD) at the toe of the weld and on the nozzle ID at the top of the weld was simulated. As the nominal geometry for the central CRDM penetration is axisymmetric, the crack growth analysis is applicable to axial flaws at any azimuthal position.

The initial flaw depth in each case was taken as 10% through the nominal nozzle thickness of 0.625 inch. This common assumption is based on the UT detectability limit for PWSCC flaws affecting RVCH penetrations. In this case, the initial flaw is assumed to be present at the time of head replacement, and thus the assumed initial depth of 10% through-wall is conservatively large with regard to the calculated time until leakage. NB-2550 of the construction code for the replacement RVCH (1989 edition of ASME Section III) requires that seamless pipe and tubing products (e.g., SB-167) larger than 2.5-inch OD be ultrasonically examined in two circumferential and two axial directions, with reference specimens having flaws no deeper than 5% of the wall thickness per NB-2552.3.

Growth of an axial flaw on the nozzle ID was simulated from 10% through the nozzle thickness until the flaw reaches the nozzle OD annulus and causes leakage. Growth of an axial flaw on the nozzle OD centered at the toe of the J-groove weld was simulated from 10% through the nozzle thickness until the upper tip of the flaw reaches the nozzle OD annulus above the weld, causing leakage. These postulated initial locations minimize the flaw growth distance that causes leakage and place the flaw in a region of elevated tensile hoop stress. Each flaw was assumed to have a semi-elliptical shape until penetrating through the nozzle thickness. A reasonably large total-length-to-depth (2c/a) aspect ratio of 6 was assumed for the initial flaw in each case. The aspect ratio was permitted to change with time as the crack growth rate was calculated separately for the surface and deepest points on the semi-elliptical crack front according to the stress intensity factors calculated for these two points. The stress intensity factor was determined using the standard influence coefficient approach for a cubic polynomial fit to the dependence of the total operating stress (reflecting weld residual stress and normal operating conditions of pressure and temperature) through the nozzle wall thickness. The growth calculation for the crack originating on the nozzle OD showed the crack penetrating to the nozzle ID surface prior to the upper flaw tip reaching the top of the weld. Hence, upon the semi-elliptical flaw penetrating to the ID, the flaw was conservatively modeled to instantaneously transition to an idealized slit through the nozzle thickness to determine the additional time until the upper tip reaches the top of the weld, resulting in leakage.

Because a recommended PWSCC crack growth rate equation specific to Alloy 690 is not available, the crack growth rate is calculated using the factor of improvement (FOI) approach. Adjusting the crack growth rate using the FOI is equivalent to calculating the time required for a crack in Alloy 600 to grow to a given size, and then multiplying by the FOI value to obtain the equivalent growth time for an Alloy 690 component. Consequently, growth was simulated for PWSCC using the standard PWSCC crack growth rate equation of MRP-55 (Reference 3), which has been included within Nonmandatory Appendix C of ASME Section XI versions that are incorporated by reference within 10 CFR 50.55a.

The stress profiles applied in the crack growth calculation were determined based on a weld residual stress analysis specifically produced for CRDM Penetration No. 1 of the ANO-1 replacement RVCH (Reference 4). This analysis applied the industry best practices including simulation of the effect of hydrostatic testing, and the resulting stresses included the effects of normal operating pressure and temperature. The welding was simulated using the best-estimate industry practices for bead size and weld pass location and grouping. Prior to the final operating condition, a repeating cycle of application and removal of operating conditions was simulated to shake down the material response and obtain elastic behavior.

For the ID axial flaw case, the most limiting hoop stress profile in the area near or above the top of the weld (i.e., 0.12 inch above the top of the weld) was conservatively applied to result in the shortest growth time to leakage. For the OD axial flaw case, the hoop stress profile at the bottom toe of the weld (i.e., the center point for the assumed initial flaw) was applied. This relatively high tensile total stress profile, which is the location with the greatest tensile OD hoop stress, was conservatively assumed to apply uniformly in the nozzle axial direction. The effect of normal operating pressure on the crack face was appropriately considered in the calculation of stress intensity factor by adding the internal reactor coolant system (RCS) pressure to the membrane stress. Each stress intensity factor applied in the crack growth calculations was conservatively constrained to be no less than 15 MPa√m (13.7 ksi√in) for the entire simulation, ensuring that the stress intensity factor threshold of the MRP-55 equation was not given inappropriate weight. The normal operating temperature applicable to the ANO-1 RVCH and penetrations of 613°F (Reference 5) was applied in the PWSCC crack growth rate equation. Finally, an availability factor was applied to base the predicted crack growth on operating time in terms of effective full power years (EFPY). The actual accumulated EFPY was applied for operation with the ANO-1 replacement RVCH through the most recent refueling outage 1R29 in May 2021, and an availability factor of 0.96 was conservatively applied for future operation.

As reported in the attachment, a FOI of at least 8.2 results in a crack growth time exceeding the proposed alternative period between examinations of 35.4 calendar years (32.7 EFPY). The limiting case is the time for an OD axial crack centered at the toe of the weld to grow from 10% through the nozzle wall until the upper tip of the flaw reaches the annulus at the nozzle OD, causing leakage. This required FOI of 8.2 is much less than the FOI of 38 that is recommended by EPRI MRP-386 (Reference 6) to apply for Alloy 690 material in reference to the PWSCC crack growth rate predicted by the MRP-55 equation for Alloy 600 material. In 2017, NRC (Reference 7) found that Entergy's use of an FOI value of 9.5 was justified and bounded by the relevant available data included in a report summarizing the laboratory crack growth rate data produced by PNNL and ANL (Reference 8). Based on an analysis applying the FOI value of 9.5, NRC approved a one-time extension of the examination frequency for all penetrations of the ANO-1 replacement RVCH to a total of 15.5 calendar years. (Subsequent to approval of this extension, the required frequency of 10 CFR 50.55a(g)(6)(ii)(D) was revised to a nominal 20 calendar years.) Applying the FOI of 9.5 results in a limiting crack growth time until leakage of about 40.9 calendar years (38.0 EFPY). In summary, the crack growth evaluation specific to ANO-1 Penetration No. 1 shows that the alternative nominal interval of about 28.4 calendar years for volumetric or surface examination of CRDM Penetration No. 1 provides reasonable assurance of leak tightness of the Alloy 690 base metal.

Plant Experience Confirming High PWSCC Resistance of Alloys 690, 52, and 152

As documented in MRP-375 (Reference 9), the high PWSCC resistance of Alloy 690 and corresponding weld metals Alloy 52 and Alloy 152 is confirmed by the lack of PWSCC indications reported in these materials, in over 33 consecutive years of service for thousands of Alloy 690 steam generator tubes, and over 31 consecutive years of service for thick-wall and thin-wall Alloy 690 applications. This operating experience includes service at pressurizer temperatures substantially higher than those on the RVCH and includes Alloy 690 wrought base metal and Alloy 52/152 weld metal. This experience includes inservice volumetric examinations performed in accordance with the applicable revision of ASME Code Case N-729 as conditioned by 10 CFR 50.55a(g)(6)(ii)(D) on 18 of the 43 replacement RVCHs using Alloy 690/52/152 materials that have operated in the U.S. PWR fleet.

Reasonable Assurance of RVCH Structural Integrity

The main potential concerns for structural integrity are circumferential PWSCC cracking within the nozzle above the top of the J-groove weld leading to nozzle ejection and boric acid corrosion of the low-alloy steel head material resulting from leakage caused by PWSCC. Axial cracking within the nozzle does not represent a credible rupture concern as the critical axial crack length is much longer than the region of high tensile weld residual stress that drives PWSCC growth (Appendix D.1.1 of Reference 10).

MRP-375 (Reference 9) documents the results for three sets of industry deterministic crack growth calculations evaluating the time for a through-wall circumferential crack to extend to encompass a large fraction of the nozzle cross section and produce a nozzle ejection. Each of these calculations conservatively assumes an initial idealized 30° through-wall circumferential flaw with equal angular extent on the nozzle ID and OD. Furthermore, a factor of 2 is applied to the crack growth rate given by the MRP-55 deterministic equation to account for the possibility of an environment more aggressive than normal primary water due to concentration of leaking coolant. The resulting growth times in Table 4-1 of MRP-375 were normalized to a head temperature of 613°F to cover the PWR fleet (including the ANO-1 replacement head, which has an assumed operating head temperature of 613°F) and applied to RVCHs with Alloy 690 nozzles using an assumed FOI of 20. With an assumed FOI of 20, the crack growth times vary from about 120 to 320 EFPY. Applying instead a FOI of 9.5 would result in a range between 57 and 152 EFPY. Application of these industry results is appropriate given the large margins in comparison to the alternative examination period. The alternative volumetric re-examination period of about calendar 35.4 years is concluded to be sufficient to ensure structural integrity of Penetration No. 1.

The deterministic axial crack growth analysis specific to the ANO-1 replacement RVCH presented above shows that leak tightness of the nozzle base metal is ensured under the proposed alternative. As leakage is a necessary precursor to boric acid corrosion of the low-alloy steel head material, the proposed alternative is effective to address the potential for boric acid corrosion. In summary, the proposed alternative will provide reasonable assurance of structural integrity of the CRDM penetrations and RVCH. As described below, defense in depth is provided by the required periodic visual examinations for evidence of leakage and by the enhanced leak rate monitoring program.

Maintenance of Defense in Depth

PWSCC is not a known active degradation mechanism for RVCHs with Alloy 690 penetrations. Conservatively assuming the presence of a hypothetical growing PWSCC flaw immediately upon head replacement, the crack growth evaluation specific to ANO-1 Penetration No. 1 described above shows that the alternative nominal interval of about 35.4 years for volumetric or surface examination of CRDM Penetration No. 1 provides reasonable assurance of leak tightness of the CRDM nozzle Alloy 690 base metal. Defense in depth, including addressing the potential for leakage resulting from PWSCC within the Alloy 52/152 weld metal, is provided by the required periodic visual examinations for evidence of leakage and by the enhanced online leakage detection capability.

Under the proposed alternative, the direct visual examination (VE) of the ANO-1 closure head required by ASME Code Case N-729-6, Table 1, Item No. B4.30 would still be performed every third refueling outage. This sensitive visual examination for evidence of pressure boundary leakage will provide defense in depth in the unlikely case that leakage was to occur due to base metal cracking. Similarly, the periodic VEs address the possibility that PWSCC in the Alloy 52/152 J-groove welds could produce leakage resulting in significant boric acid corrosion. Also, during all refueling outages, IWB-5220 system leakage tests including VT-2 visual examinations and boric acid corrosion control program walkdowns are performed on the RVCH.

In addition, ANO-1 has an enhanced leakage detection capability that monitors RCS leakage. Entergy trends daily RCS leak rate values in accordance with procedures consistent with the guidance of WCAP-16465-NP (Reference 11). These guidelines for enhanced leak rate monitoring would require a response in the case where the seven-day rolling average of daily RCS unidentified leak rates exceeded 0.1 gallons per minute (gpm), two consecutive days exceeded 0.15 gpm, or any day exceeds 0.3 gpm. If an unidentified RCS leak is greater than 1 gpm or if an identified RCS leak is greater than 10 gpm, the plant Technical Specification (TS) 3.4.13, RCS Operational Leakage, outlines the timely actions required to maintain safe operability for recovery, including a shutdown. These online detection methods ensure that head penetration leakage at levels as low as 0.1 gpm would be detected in a timely fashion. Moreover, a leak or increase in radiation levels within containment would be captured in the containment sump and detected by radiation monitoring during operation if a substantial leak were to develop.

Precedents

The plant-specific crack growth analysis performed in support of this relief request (attachment to this enclosure) applies the same type of deterministic fracture mechanics procedure that has commonly been applied in the industry for this and similar purposes. Similar crack growth analyses have often been applied by licensees to justify cases of limited coverage for UT at the bottom of CRDM nozzles. Such evaluations are applied in accordance with Appendix I of ASME Code Case N-729-6 (Reference 1). Similar crack growth calculations of hypothetical PWSCC flaws were applied as part of the basis for a recent relief request to delay volumetric or surface examination of the Byron Unit 2 RVCH for one cycle of operation. NRC (Reference 12) approved that proposed alternative in September 2020. As discussed above, in 2017, NRC (Reference 7) found that Entergy's use of an FOI value of 9.5 was justified and bounded by the relevant available laboratory crack growth rate data. In contrast, a FOI of only 8.2 applied to the

crack growth analysis specific to ANO-1 RVCH Penetration No. 1 shows a time to leakage exceeding the operating period under the proposed alternative.

Conclusion

In summary, the crack growth evaluation specific to ANO-1 RVCH Penetration No. 1 demonstrates the effectiveness of the proposed alternative examination frequency to prevent pressure boundary leakage due to conservatively postulated PWSCC affecting the nozzle base metal. The operating experience for the replacement Ni-based alloys (Alloys 690, 52, and 152) used to fabricate the ANO-1 head is excellent, with no reports of PWSCC. The hardship related to inspecting Penetration No. 1 affects only a single penetration out of the population of 69. Furthermore, defense in depth is maintained under the alternative through the performance of periodic bare metal visual examinations for evidence of head penetration leakage and through the enhanced online leakage detection capability.

Removal of the RADCAL instrument to permit volumetric or surface examination of Penetration No. 1 in accordance with 10 CFR 50.55a(g)(6)(ii)(D) and ASME Code Case N-729-6 would result in a hardship without a compensating increase in the level of quality and safety as specified in 10 CFR 50.55a(z)(2), and the proposed alternative would provide reasonable assurance of structural integrity of the CRDM penetrations and RVCH. Entergy requests approval of the proposed alternative to address this unique hardship.

While it has been shown above that the requested alternative volumetric re-examination period of about calendar 35.4 years is concluded to be sufficient to ensure structural and leak tight integrity of Penetration No. 1, Entergy requests approval of the requested alternative to the end of the current renewed ANO-1 Operating License (May 2034).

IV. BASIS FOR HARDSHIP

Gaining access for volumetric or surface examination of Penetration No. 1 represents a hardship or unusual difficulty without a compensating increase in the level of quality and safety based on the information provided in Section III above. CRDM Penetration No. 1 at the head center contains the post-accident reactor vessel water level (RADCAL) instrument. The adapter flange/closure extension guide assembly of the RADCAL instrument tightly fits inside Penetration No. 1 and is bolted directly to the Penetration No. 1 nozzle housing adapter flange. This assembly provides guidance and protection for the RADCAL gamma thermometer (RGT) manometer tubes, provides protection for the instrument leads, and forms a portion of the primary pressure boundary. Access to this bolted connection in the area just above the head is especially challenging as Penetration No. 1 is at the center of the 69 penetrations. This bolted joint is intended to be a permanent mechanical connection.

In order to obtain access to perform a volumetric or surface examination for this unique configuration satisfying the requirements of N-729-6, the RADCAL instrument would need to be removed and subsequently reinstalled, entailing significant worker dose and considerable risks. Without removing the instrument, the tight gap between the RADCAL instrument guide assembly and the inside of Penetration No. 1 precludes UT or ET using a blade probe. A probe would have to be manufactured for this specific design and application. Removal of the

RADCAL instrument including its integral guide assembly would require unbolting the flanged joint connecting the instrument to the primary pressure boundary just above the RVCH.

Removal and reinstallation of the RADCAL instrument would result in approximately 2.1 person-rem of worker dose, and additional personnel dose would be required to perform the volumetric or surface examination of this single penetration beyond that which would result if an examination of Penetration No. 1 were performed during the same refueling outage when the other 68 penetrations were examined. The risks of removal and reinstallation of the RADCAL instrument include unintended damage to the instrument and other components (for example due to galling) and leakage of reactor coolant at the mechanical seal of the flanged joint, which would have the potential to cause corrosion of the upper RVCH surface. Due to the uniqueness of the RADCAL instrument, spare parts would need to be fabricated due to none being in existence.

V. REFERENCES:

1. ASME Boiler and Pressure Vessel Code Case N-729-6, Alternative Examination Requirements for PWR Reactor Vessel Upper Heads With Nozzles Having Pressure-Retaining Partial-Penetration Welds, Section XI, Division 1, approval date March 3, 2016.
2. Letter from A. Boland (NRC) to B. Allen (FirstEnergy), “Davis-Besse Nuclear Power Station Special Inspection to Review Flaws in the Control Rod Drive Mechanism Reactor Vessel Closure Head Nozzle Penetrations 05000346/2010-008(DRS) and Exercise of Enforcement Discretion,” dated October 22, 2010. NRC ADAMS Accession No. ML102930380.
3. *Materials Reliability Program (MRP): Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Materials (MRP-55) Revision 1*, EPRI, Palo Alto, CA: 2002. 1006695. NRC ADAMS Accession No. ML023010510.
4. Dominion Engineering, Inc., “ANO Unit 1 CRDM Penetration Nozzle 1 Welding Residual Stress Analysis,” DEI Proprietary Calculation C-4731-00-01, Rev. 0, March 2022.
5. Letter from Entergy to U.S. NRC, Request for Alternative ANO1-ISI-024, “Request for Alternative from Volumetric/Surface Examination Frequency Requirements of ASME Code Case N-729-1,” dated April 28, 2014. NRC ADAMS Accession No. ML14118A477.
6. *Materials Reliability Program: Recommended Factors of Improvement for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) Growth Rates of Thick-Wall Alloy 690 Materials and Alloy 52, 152, and Variants Welds (MRP-386),* EPRI, Palo Alto, CA: 2017. 3002010756.
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13. Entergy Record / Document Number QC-00005037, AREVA Quality Assurance Data Package 23-5041654-02, Revision 2, June 2004.

ENCLOSURE, ATTACHMENT

1CAN052201

DEI Calculation C-4731-00-02, Rev. 0:

“Axial Crack Growth Evaluation for CRDM Penetration Nozzle 1 in ANO Unit 1 Replacement RVCH"

RECORD OF REVISIONS

Rev.	Description	Prepared by Date	Checked by Date	Reviewed by Date	Approved by Date
0	Original Issue	G H. Schmidt 04/25/22 G.H. Schmidt Engineer	04/25/2022 A.J. Simon Engineer	G.A. White 4/25/2022 G.A. White Principal Engineer	G.A. White 4/25/2022 G.A. White Principal Engineer

The last revision number to reflect any changes for each section of the calculation is shown in the Table of Contents. The last revision numbers to reflect any changes for tables and figures are shown in the List of Tables and the List of Figures. Changes made in the latest revision, except for Rev. 0 and revisions which change the calculation in its entirety, are indicated by a double line in the right hand margin as shown here.

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1 PURPOSE

The purpose of this calculation is to document the results of crack growth analyses of CRDM Penetration Number 1 of the replacement reactor vessel closure head (RVCH) in operation at Arkansas Nuclear One, Unit 1 (ANO-1). The analyses calculate the time for a postulated axial flaw in the nozzle tube base metal to grow from a conservatively large assumed initial size (i.e., 10% through the nozzle nominal wall thickness) until it causes leakage. As illustrated in Figure 1, in the case of a flaw located on the nozzle inner diameter (ID) surface, leakage is assumed to occur once the flaw penetrates to the nozzle outer diameter (OD) surface. In the case of a flaw located on the nozzle OD surface at the weld toe, leakage is calculated to occur when the flaw grows upward to the nozzle OD annulus above the weld. The ANO-1 RVCH is a replacement head fabricated using Alloy 690 nozzles attached to the inside of the head with Alloy 52/152 weld material, so a factor of improvement (FOI) is applied on the crack growth rate (CGR) equation for Alloy 600 to reflect the resistance of Alloy 690 to primary water stress corrosion cracking (PWSCC).

2 SUMMARY OF RESULTS

An axial crack growth evaluation was performed applying the specific geometry and loads applicable to ANO-1 CRDM Penetration Number 1, including the results of the plant-specific welding residual stress (WRS) analysis documented in DEI Calculation C-4731-00-01, Revision 0 [1]. The results of these crack growth calculations demonstrate reasonable assurance that leak tightness will be maintained for the nozzle base metal of this penetration beyond the time that the second inservice volumetric or surface examination is required for the other RVCH penetrations. The nominal timing of the next required volumetric or surface examination for the other 68 penetrations is May 11, 2041, which corresponds to 35.4 calendar years and 32.7 effective full power years (EFPY) of operation for the replacement head. This future inspection outage would be beyond the end of the current renewed operating license for ANO-1 (May 20, 2034). The results of the crack growth calculation are provided in Table 3.

The limiting case is for a flaw originating on the nozzle OD surface at the toe of the J-groove weld. A FOI of at least 8.2 results in a crack growth time exceeding 35.4 calendar years (32.7 EFPY). This required FOI of 8.2 is much less than the FOI of 38 that is recommended by EPRI MRP-386 [2] to apply for Alloy 690 material in reference to the PWSCC crack growth rate predicted by the MRP-55

[3] equation for Alloy 600 material. Applying the FOI value of 9.5 previously found by NRC [4] to be justified for application to the ANO-1 replacement RVCH results in a limiting crack growth time until leakage of about 40.9 calendar years (38.0 EFPY), substantially greater than 35.4 calendar years (32.7 EFPY).

3 INPUT REQUIREMENTS

The following inputs are used for the analysis supporting this calculation:

1. The nominal geometry of the replacement RVCH and CRDM penetrations is provided in References [5.a] and [6]. The relevant dimensions of the CRDM penetration #1 nozzle and J-groove weld are as follows:
   a. Nozzle:
   – CRDM Nozzle OD = 4.00 inches [5.a, D-4 and G-10] (nozzle OD ground to fit penetration hole)
   – CRDM Nozzle ID = 2.75 inches (middle value of tolerance band) [5.a, Zone E-4]
   – CRDM Nozzle thickness, $t = (4.00 – 2.75)/2 = 0.625$ inch
   – Incidence angle of CRDM Penetration #1 = 0°, being at dead center of head [5.a]
   b. J-groove Weld:
   – Weld height specific to CRDM penetration #1: 1.25 inches, which is determined as the sum of the following three vertical distances:
     i) As-built J-groove weld distance from butter to projection of head base metal to cladding interface = 0.7087 inches [5.b, Zone J-12]
     ii) Cladding thickness = 0.19 inch [5.a, Zone E-10]
     iii) Vertical height of fillet weld extending below projection of inside of cladding = 0.35 inch ($\sqrt{2}$ × minimum fillet weld throat of 0.25 inch [6])
2. The operating pressure for the ANO Unit 1 RVCH is 2185 psig [7, Table 3A-5].
3. The operating stress profiles (including welding residual stress) for the ANO-1 CRDM Penetration 1 are calculated by finite-element analysis (FEA) in DEI Calculation C-4731-00-01 R0 [1]. That analysis considers the local configuration of the J-groove weld attaching the CRDM Penetration No. 1 nozzle to the RVCH. Table 1 of C-4731-00-01 R0 [1] provides the total hoop stress during operation for the nodes in the Alloy 690 CRDM nozzle base material. Key nodal results from that table are repeated in Table 1 of this calculation.
4. The material of construction for the CRDM nozzles in the ANO-1 replacement RVCH is Alloy 690 (SB-167 N06690) [5.a, Item 11]. The J-groove weld for the CRDM penetrations is formed using Alloy 52 (ERNiCrFe-7) and/or Alloy 152 (ENiCrFe-7) material [6].

5. The PWSCC crack growth rate for Alloy 600 is per C-8511 from Nonmandatory Appendix C of ASME Section XI [8]. This equation is included in versions of ASME Section XI incorporated by reference within the NRC regulations (10 CFR 50.55a). This is identical to the PWSCC crack growth rate equation published in MRP-55 [3] for thick-wall wrought Alloy 600 material. The PWSCC crack growth rate for Alloy 600 is needed to calculate the crack growth rate applicable to the actual Alloy 690 nozzle material on the basis of the factor of improvement (FOI) approach.
6. The stress intensity factor (K_I) of hypothetical cracks in the CRDM nozzle are obtained using the influence coefficient method in the French RSE-M and RCC-MR code appendices for flaw analysis, as documented by Marie et al. [9]. This approach is applied using the appropriate tabular coefficients developed for cylindrical pipes:
   a. For the semielliptical flaw on the inside surface of the nozzle tube, the coefficients are per TUB-LDSI (Table 39) [9].
   b. For the semielliptical flaw on the outside surface of the nozzle tube, the coefficients are per TUB-LDSE (Table 44) [9].
   c. For the idealized flaw through the nozzle thickness assumed upon penetration of the outside surface flaw to the nozzle ID, the coefficients are per TUB-LTR (Table 35) [9].
7. Given the CRDM penetration geometry ([5.a] and [6]), as illustrated in Figure 1, pressure boundary leakage will occur if either of the following conditions develop:
   a. For an axial flaw growing from the nozzle inside surface at or above the weld, leakage would occur once the flaw depth reaches 100% of the nozzle wall thickness.
   b. For an axial flaw growing from the nozzle wetted outside surface at or below the weld toe, leakage would occur once the upper crack tip reaches the OD nozzle annulus (i.e., at the elevation of the J-groove weld root).
8. The ANO-1 replacement RVCH containing CRDM Penetration No. 1 entered service December 21, 2005 following refueling outage 1R19 [10]. The most recent ANO-1 refueling outage was 1R29, which completed when the plant restarted May 11, 2021 [11]. The accumulated effective full power years (EFPY) for ANO-1 from December 21, 2005 until the start of Cycle 30 was 36.253 – 22.734 = 13.519 EFPY [12].

4 ASSUMPTIONS

1. This calculation considers axial flaws in the CRDM nozzle tube (i.e., flaws that are detectable during periodic volumetric examinations before they grow to cause leakage). The limiting locations that are considered are a flaw centered on the nozzle outer surface at the bottom (toe) of the J-groove weld and a flaw on the nozzle inner surface near or above the top of weld elevation. Flaws at these two locations have the shortest distance to grow to cause leakage and are subject to highly tensile stress profiles. As shown in C-4731-00-01 [1], the axial stresses that would drive circumferential crack growth are much less tensile in magnitude than the corresponding hoop stresses. Hence, the axial flaw results bound the time for growth of circumferential flaws.

2. The ANO-1 RVCH operates at a head temperature of 613°F during normal steady-state operating conditions. This temperature value was applied in prior evaluations [13] of the ANO Unit 1 closure head nozzle penetrations submitted to the NRC that considered the ANO-1 reactor coolant system (RCS) temperature and effects of flow streaming.
3. The end condition for this crack growth evaluation is the occurrence of leakage (see Inputs 1 and 7).
4. In accordance with the common practice for calculating crack-tip stress intensity factors (e.g. per Nonmandatory Appendix A of ASME Section XI [14], or as documented in Marie et al. [9]), axial surface flaws evaluated in this crack growth calculation are modeled to have a semielliptical shape.
5. For the case analyzing the outside surface flaw, it is assumed that when the crack grows to 100% depth ($a = t$) and penetrates to the nozzle ID surface, the crack transitions immediately from semielliptical shape to an idealized uniform through-wall slit. The initial length of the idealized through-wall flaw is taken as the length (i.e., axial extent) of the semielliptical flaw when it penetrates to the nozzle ID. This is a conservative assumption that neglects the time over which the transition occurs.
6. An initial aspect ratio ($2c/a$) of 6 is conservatively applied, as longer flaws tend to have higher stress intensity factors at the crack tip on both the surface and the deepest points, and thus grow more rapidly. The aspect ratio evolves over time due to the differing growth rates calculated at the surface tip and deepest point of the crack.
7. An initial flaw depth of 10% through-wall ($a/t = 0.1$) is applied, which is the minimum flaw depth covered by the ultrasonic testing (UT) qualification requirements of ASME Code Case N-729-6 [15]. Paragraph NB-2550 [16] of the design code for the ANO-1 replacement RVCH (1989 edition of ASME BPVC Section III per [17]) requires that seamless pipe and tubing products (e.g., SB-167) larger than 2.5 inch OD be ultrasonically examined in two circumferential and two axial directions, with reference specimens having flaws no deeper than 5% of the wall thickness per NB-2552.3. Hence, it is conservative to postulate that a surface-connected planar flaw of 10% through-wall depth would be present at the start of head operation.
8. As stated in MRP-55 [3], the laboratory data used to develop the MRP-55 crack growth rate equation did not include stress intensity factor values below about 15 MPa√m (13.65 ksi√in). Hence, each stress intensity factor used for calculating the crack growth rate will be conservatively selected as the maximum of the value calculated by Equation [5-1] and 15 MPa√m (13.65 ksi√in), ensuring that the stress intensity factor threshold of the MRP-55 equation (K_{th}) is not given inappropriate weight.
9. Because a PWSCC crack growth rate equation for Alloy 690 is not available in ASME Section XI, the crack growth rate will be calculated using the factor of improvement (FOI) approach, which is discussed further in EPRI MRP-386 [2]. In this approach, the crack growth rate is calculated using the PWSCC crack growth rate equation for Alloy 600. This crack growth rate is then divided by a numeric factor (the FOI value) to account for the lower PWSCC crack growth rate of Alloy 690. This is equivalent to calculating the time required for a crack in Alloy 600 to

grow to a given size, and then multiplying by a numeric factor to obtain the equivalent growth time for an Alloy 690 component.

10. As the augmented examination requirements per ASME Code Case N-729-6 [15] were developed to address the potential for PWSCC degradation of the RVCH penetrations, this analysis considers crack growth due to PWSCC. Growth due to fatigue of the postulated flaws is not considered.

11. Consistent with the required inputs for the influence coefficient method approach [9], a third-order polynomial is used to fit the stress profile driving growth for the part-through-wall flaws.

12. The stress profiles are taken from the set of nodes at a single elevation in the FEA welding residual stress model [1] based on the postulated flaw locations (Assumption 1):

    a. The stress profile for the inside surface flaw is conservatively taken from the nodes at a nozzle elevation of 3.49 inch (i.e., one nodal row above the top of the weld), which is the limiting elevation in the region near or above the top of the weld that results in the fastest ID flaw growth beginning with $a/t = 0.1$ until penetration to the nozzle OD ($a = t$) and assumed leakage.

    b. The stress profile for the outside surface flaw is conservatively taken from the nodes at the elevation of the bottom (toe) of the weld, which is the elevation having the highest tensile through-wall average stress below the top of the weld and the highest tensile stress on the wetted surface of the nozzle OD.

    c. The uniform hoop stress applied for the idealized through-wall flaw is conservatively taken as the average at the elevation of the weld toe. This average is the largest for any elevation below the top of the weld.

13. Values for the influence coefficients are obtained by interpolating or extrapolating from tables in Marie et al. [9]. Coefficients are provided for $0.0625 \leq a/c \leq 1.0$ and $0 \leq a/t \leq 0.8$.

    a. For input parameters inside the domains provided inside those tables, influence coefficients are determined through log-linear interpolation on t/R_i and on a/c, and linear interpolation on a/t.

    b. The only time input parameters are required outside of the provided domains is for the crack growth beyond $a/t > 0.8$. Therefore, the influence coefficients are linearly extrapolated for the range $0.8 < a/t < 1.0$. Extrapolation of influence coefficients for $a/t > 0.8$ is necessary to calculate the time until leakage and common practice (e.g., [18]).

14. Time steps of 0.01 year (for the outside surface flaw) and 0.05 year (for the inside surface flaw) are applied for the crack growth calculations. These time steps are appropriately refined to yield converged results given the timescale over which a crack in Alloy 600 grows to the nozzle OD annulus and causes leakage.

15. The assumed future outage duration is 25 days [12]. For an 18-month fuel cycle, this corresponds to a plant capacity factor of 0.954 (= (365.25×1.5 – 25)/(365.25×1.5)). Conservatively, a capacity

factor characteristic of future operation of 0.96 is assumed, and thus the effective full power years (EFPY) corresponding to each future calendar year of operation is 0.96 EFPY.

5 ANALYSIS

This calculation document describes the stress intensity factor calculations (Section 5.1) and crack growth calculations (Section 5.2) performed specific to the nozzle of CRDM Penetration Number 1 of the replacement RVCH at ANO Unit 1. Deterministic crack growth calculations are used to determine the time required for a postulated axial flaw to grow from an initial depth of 10% through the nozzle thickness to leakage. Growth of an axial flaw on the nozzle ID is simulated until the flaw reaches the nozzle OD annulus and causes leakage. Growth of an axial flaw on the nozzle OD centered at the toe of the J-groove weld is simulated until the upper tip of the flaw reaches the nozzle OD annulus above the weld, causing leakage. These postulated initial locations minimize the flaw growth distance that causes leakage and place the flaw in a region of elevated tensile hoop stress. As described in Section 5.2.4, the result assuming crack growth behavior for Alloy 600 is converted to the predicted growth time for the actual Alloy 690 nozzle material, including in terms of calendar years.

5.1 Stress Intensity Factor Calculation

5.1.1 Loads and Stresses

Tensile stresses are one of the key factors influencing PWSCC. For the purposes of crack growth calculations, only stresses orthogonal to the plane of crack growth are considered (i.e., only stresses in the hoop direction drive axial crack growth). The stresses that drive PWSCC growth are the welding residual stresses and normal operating stresses that are present during steady-state operation.

As described in Input 3, welding residual stresses and normal operating stresses were calculated using finite-element analyses that are documented in DEI Calculation C-4731-00-01 [1]. That analysis considers the local configuration of the J-groove weld attaching the CRDM Penetration No. 1 nozzle to the RVCH. Table 1 of C-4731-00-01 documents the full set of nodal results for the total hoop stress during operation (including WRS) in the Alloy 690 nozzle tube. Key nodal results from that table relevant to this crack growth calculation are repeated in Table 1 of this calculation. The two hoop stress profiles that are selected for the crack growth analyses are plotted in Figure 2 as a function of

relative distance through the nozzle tube. Figure 2 shows cubic fits to the nodal stresses, with the fitted coefficients documented in Table 2.

The stress profile for the inside surface flaw is taken from the nodes at a nozzle elevation of 3.49 inch (i.e., one nodal row above the top of the weld), which is the limiting elevation in the region near or above the top of the weld that results in the fastest ID flaw growth beginning with $a/t = 0.1$ until penetration to the nozzle OD ($a = t$) and assumed leakage. The stress profile for the outside surface flaw is taken at the bottom toe of the weld (i.e., the center point for the assumed initial flaw). This relatively high tensile total stress profile, which is the location with the greatest tensile OD hoop stress, is conservatively assumed to apply uniformly in the nozzle axial direction.

A membrane stress equal in value to the operating pressure, P, is also included in the crack growth analysis to properly account for the additional stress resulting from application of the internal pressure, P, to the crack face. The superposition principle of linear elastic fracture mechanics (LEFM) allows treatment of the crack face pressure as a remote membrane stress loading.

5.1.2 Influence Coefficient Method

Given the total hoop stress profiles defined in Section 5.1.1, along with the assumed initial depth and aspect ratio of the crack (Assumptions 6 and 7), stress intensity factors are calculated using the influence coefficient method. Figure 2 shows the cubic fit (3rd order polynomial) to the hoop stress distribution for use with the influence coefficient method (Assumption 11), and Table 2 lists the coefficients resulting from the polynomial fit.

For axial semielliptical part-through-wall cracks, the general form of the mode I stress intensity factor calculation by way of the influence coefficient method is provided by Marie et al. [9] for a cylindrical pipe geometry:

$$K_{\mathrm{I}} = \sqrt{\pi a} \sum_{j=0}^{3} i_j \left(\frac{t}{R_i}, \frac{a}{c}, \frac{a}{t} \right) \sigma_j \left(\frac{a}{t} \right)^j \qquad [5\text{-}1]$$

where:

K_{I} = mode I stress intensity factor (ksi√in)

i_j = coefficient of influence of order j (function of geometry of crack and nozzle)

a = crack depth (in.)

c = crack half-length (in.)

t = CRDM nozzle thickness (in.)

R_i = CRDM nozzle inner radius (in.)

σ_j = coefficient of order j of polynomial fit stress profile as function of x/t (ksi)[1]

x = distance along the stress profile from the flawed surface (in.)

Different tabular values for i_j per the tables listed in Input 6 are applied when calculating K_I for the surface tip ($K_{I,0}$) and the deepest tip ($K_{I,90}$) of the flaw [9]. Values from tables of influence coefficients are interpolated in t/R_i, a/c, and a/t to obtain values of i_j specific to the crack geometry at a given timestep. This is accomplished by performing interpolation of the influence coefficients (Assumption 13):

1. Log-linear interpolation in t/R_i (i.e. linear interpolation of values on the scale $\ln(t/R_i)$)
2. Log-linear interpolation in a/c
3. Linear interpolation in a/t
   a. If $a/t > 0.8$, linearly extrapolate up to $a/t = 1.0$ (Assumption 13.b).

For axial through-wall cracks loaded by a remote membrane stress, the general form of the mode I stress intensity factor calculation by way of the influence coefficient method is provided by Marie et al. [9] for a cylindrical pipe geometry:

$$K_I = \sigma_m F_m \sqrt{\pi c} \qquad [5\text{-}2]$$

where:

K_I = mode I stress intensity factor (ksi√in)

c = crack half-length (in.)

σ_m = remote membrane stress (ksi) (per Assumption 12.c)

F_m = influence coefficient for membrane stress (function of geometry parameter λ)

[1] The σ_0 is the sum of the 0th order polynomial coefficient and the internal pressure to account for the influence of crack face pressure on the stress intensity factor.

λ = $c/\sqrt{R_m t}$

R_m = mean nozzle radius (in.)

Interpolation is applied to obtain F_m as a function of the current value of λ.

5.2 Crack Growth Calculation

5.2.1 Approach

As discussed in Assumptions 9 and 10, the crack growth analysis applies the PWSCC crack growth rate for Alloy 600 and then converts to an Alloy 690 crack growth rate using the factor of improvement approach.

Accordingly, the standard PWSCC crack growth rate equation described in ASME Section XI Nonmandatory Appendix C [8] for Alloy 600 is applied:

$$\frac{da}{dt} = \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right]\varphi(K_{\text{I},90} - K_{th})^{\eta} \qquad [5\text{-}3]$$

$$\frac{dc}{dt} = \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right]\varphi(K_{\text{I},0} - K_{th})^{\eta} \qquad [5\text{-}4]$$

where

da/dt = crack growth rate at the deepest point of the crack (in/hr)

dc/dt = crack growth rate at the surface point of the crack (in/hr)

Q_g = thermal activation energy for crack growth = 31.0 kcal/mol [8]

R = universal gas constant = 1.103×10^{-3} kcal/(mol-°R)

T = absolute operating temperature at crack location = 1072.67°R (Assumption 2)

T_{ref} = absolute temperature (617°F) used to normalize crack growth data = 1076.67°R [8]

φ = crack growth rate coefficient for Alloy 600 = 4.21×10^{-7} (in/hr)(ksi√in)$^{-\eta}$ [8]

$K_{\text{I},90}$ = stress intensity factor at the deepest point of the crack, calculated per Section 5.1 (ksi√in)

$K_{I,0}$ = stress intensity factor at the surface point of the crack, calculated per Section 5.1 (ksi√in)

K_{th} = threshold stress intensity factor for stress corrosion cracking = 8.19 ksi√in [8]

η = crack growth rate exponent = 1.16 [8]

The stress intensity factor K_I used for calculating the crack growth rate was conservatively constrained to be no less than 15 MPa√m (13.65 ksi√in) as discussed in Assumption 8.

To model growth of the cracks over time, the crack growth rate is calculated and integrated using a fully explicit forward-difference approximation to determine the new crack depth and length using time steps of 0.01 year for the outside surface flaw and 0.05 year for the inside surface flaw (Assumption 14). Using this approach, the times required for the flaw growth to reach the end condition of leakage (Input 7) are calculated.

Initial conditions applied assume an initial crack depth of 10% through-wall (Assumption 7), along with an initial aspect ratio ($2c/a$) of 6 (Assumption 6). As discussed in Section 5.1.1, appropriately conservative hoop stress profiles are applied in the evaluation for each assumed flaw location (Assumption 12; Figure 2).

5.2.2 Results for Alloy 600 PWSCC Crack Growth Rate Equation

The times required for a flaw with an initial depth of 10% through the nozzle thickness to grow to a size causing leakage in Alloy 600 are reported in Table 3. Initial axial flaws located on both the ID and OD wetted nozzle surfaces were evaluated to determine the limiting case for the time until pressure boundary leakage occurs. The ID flaw case is for a flaw located near or above the top of the weld, where leakage would occur immediately or shortly after the flaw penetrates to the nozzle OD surface. The OD flaw case is for an initial flaw centered at the weld bottom (i.e., weld toe location), with leakage resulting when the half-length (c) of the flaw reaches the value of the weld height along the nozzle OD. As the central nozzle has an axisymmetric geometry, these flaws represent the case of any azimuthal position around the nozzle circumference.

Figure 3 and Figure 4 show the stress intensity factor as a function of time for both inside and outside flaws, respectively, at the deepest point and the surface point of the crack. Figure 5 and Figure 6 show the growth in time, respectively, of crack depth and crack length, while Figure 7 and Figure 8 show the crack aspect ratio evolution as a function, respectively, of crack depth and crack length.

These results are used in Section 5.2.4 to obtain results for the actual Alloy 690 material.

5.2.3 Total EFPY during Head Operating Period

The evaluation period for Penetration No. 1 of the ANO-1 replacement RVCH is from startup following head replacement on December 21, 2005, until the time that the second inservice volumetric or surface examination is required for the other RVCH penetrations. Entergy performed a volumetric examination of the ANO-1 RVCH during the spring 2021 refueling outage (1R29) that satisfied the inservice examination requirements for the other 68 penetrations in the RVCH. Per Input 8, the ANO-1 replacement head has accumulated 13.52 EFPY prior to the restart from outage 1R29 on May 11, 2021. Hence, the nominal timing of the next required volumetric or surface examination for the other 68 penetrations per the applicable examination frequency of once per two inspection intervals (nominally 20 years) [15] is May 11, 2041. This future inspection outage would be beyond expiration of the current ANO-1 renewed license (May 20, 2034 [19]). The period including May 11, 2021 until May 11, 2041 is 7,306 days. Consequently, conservatively applying a capacity factor of 0.96 for future operation (Assumption 15), the total EFPY during the evaluation period is:

$$13.52\ \text{EFPY} + 0.96\ {}^{\text{EFPY}}/_{\text{year}} * \frac{7306\ \text{days}}{365.25\ {}^{\text{days}}/_{\text{year}}} = 32.7\ \text{EFPY} \qquad [5\text{-}5]$$

Thus, the evaluation period of 35.4 calendar years (December 21, 2005 through May 11, 2041) corresponds to 32.7 EFPY.

5.2.4 Results for Alloy 690 Based on Factor of Improvement

The factor of improvement approach (Assumption 9) is used to apply the crack growth results of Section 5.2.2 to the actual Alloy 690 material of Penetration No. 1. As the same FOI applies to each point in time, the time until leakage for the actual Alloy 690 material is simply the growth time for Alloy 600 multiplied by the assumed FOI.

As shown in Table 3, the limiting time for a postulated flaw to grow to cause leakage in Alloy 600 material is 4.00 EFPY. The limiting case is the time for an OD axial crack centered at the toe of the weld to grow from 10% through the nozzle wall until the upper tip of the flaw reaches the annulus at

the nozzle OD. In this case, an FOI of 8.2 corresponds to the evaluation period of 32.7 EFPY. This required FOI is much less than the FOI of 38 that is recommended by EPRI MRP-386 [2] to apply for Alloy 690 material in reference to the PWSCC crack growth rate predicted by the MRP-55 [3] equation for Alloy 600 thick-wall wrought material. Additionally, NRC found in 2017 [4] that Entergy's use of an FOI value of 9.5 was justified and bounded by the relevant available data included in a report summarizing the laboratory PWSCC crack growth rate data produced by PNNL and ANL [20]. On this basis, NRC approved a one-time extension of the examination frequency for all penetrations of the ANO-1 replacement RVCH to a total of 15.5 calendar years. When applied to this calculation, the FOI value of 9.5 results in a limiting crack growth time until leakage of about 40.9 calendar years (38.0 EFPY).

5.3 Software Usage

The following software, controlled in accordance with DEI's quality assurance program for nuclear safety-related work [21], was used in preparing this calculation.

The stress intensity factor and crack growth calculations used in this work were performed using Excel for Office 365 as a one-time-use spreadsheet on a Dell Precision 5550 with an Intel(R) Core(TM) i7-10850H processor and running Windows 10 Pro 21H2 (Build 19044.1348).

The results from this one-time-use spreadsheet were checked and reviewed in accordance with DEI's Nuclear Quality Assurance program ([21], [22]). As discussed in M-4731-00-01 R0 [23], an alternate calculation implementing the same methodology was used to validate the results. This alternate calculation was prepared independently of the original calculation to be checked. Native electronic files for the spreadsheet calculation and the alternate calculation are included in data disk D-4731-00-01 R0 [24], the contents of which are listed for convenience in Appendix A.

6 REFERENCES

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   b. Entergy Drawing M1B-444, Sheet 1, Revision 0, November 2010

6. Entergy M1B-414, Sheet 1, Revision 0, October 2010. Transmitted in IC-4731-00-03, Email from Dale Stringer, Entergy, to Glenn White, DEI, "RE: Inputs for ANO-1 CRDM Penetration No. 1," October 18, 2021.

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14. ASME Boiler and Pressure Vessel Code, Section XI, Nonmandatory Appendix A, "Analytical Evaluation of Flaws," 2017 Edition.

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Table 1. Hoop Stress in CRDM Penetration #1 at Key Elevations (Repeated from C-4731-00-01 R0 [1])

Elevation (in.)	Distance Through Wall – all stresses in psi								
	ID	12.5%	25%	37.5%	50%	62.5%	75%	87.5%	OD
2.12	26993	25442	24008	23100	24719	30191	39447	48685	56298
3.37	29872	27827	27521	27818	28630	30561	33959	38716	46829
3.49	28028	27762	29947	31012	31300	32278	33837	36691	43556

Note: Elevation is relative to the nozzle bottom (0 inch), with the weld bottom (toe) at 2.12 inch, and weld top (root) at 3.37 inch. The stress profile for the inside surface flaw is taken from the nodes at a nozzle elevation of 3.49 inch (i.e., one nodal row above the top of the weld), which is the limiting elevation in the region near or above the top of the weld that results in the fastest ID flaw growth beginning with $a/t = 0.1$ until penetration to the nozzle OD ($a = t$) and assumed leakage. These stresses do not include the crack face pressure.

Table 2. Cubic Stress Profile Fit to Hoop Stress in CRDM Penetration #1

Stress Profile	Profile Axial Location	Elevation (in.)	Coefficients of Polynomial Fit of Stress Profile in terms of x/t (psi), where x is the distance from flawed surface				Average (psi)
			σ_3	σ_2	σ_1	σ_0	
Outside	Weld Bottom (Toe)	2.12	7308	54359	-91176	57490	31848
Inside	One Nodal Row Above Top of Weld	3.49	40048	-43219	18858	27326	N/A

Note: These stresses do not include the effect of crack face pressure.

Table 3. Crack Growth Results

Crack Location	Final Flaw	Growth Time in Alloy 600 (EFPY)	Growth Time in Alloy 690 (EFPY)		FOI for Alloy 690 Growth in 32.7 EFPY
			FOI = 9.5	FOI = 38	
Inside surface	100% depth (leakage)	7.77	73.8	295	4.2
Outside surface	Half-length equal to weld height (leakage)	4.00	38.0	152	8.2

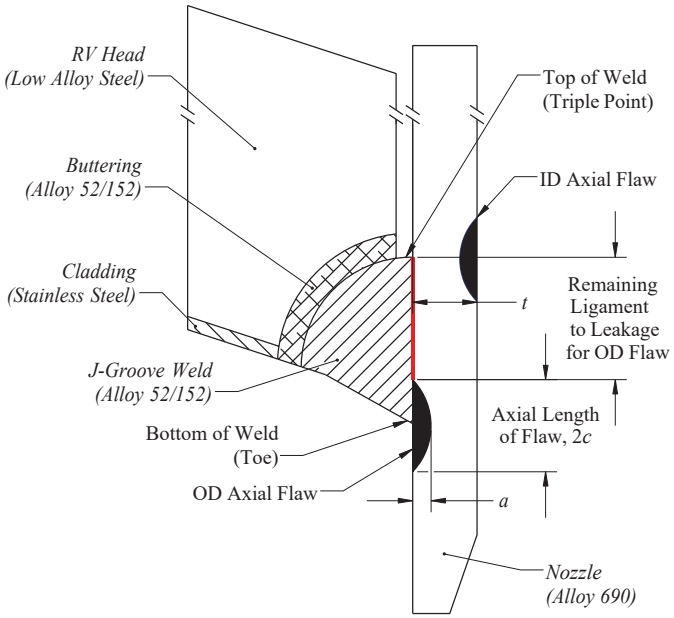

Figure 1. Hypothetical Flaw Growth Geometry Definition

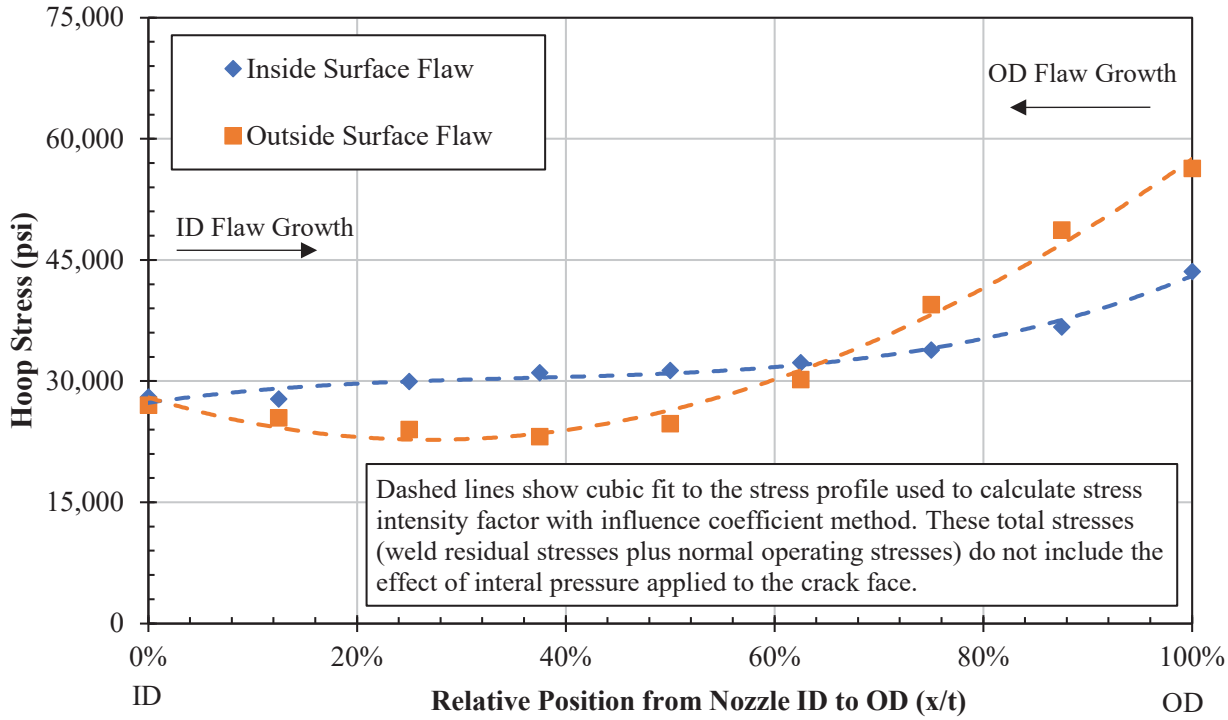

Figure 2. Total Stress Profiles Applied in Crack Growth Evaluation Cases

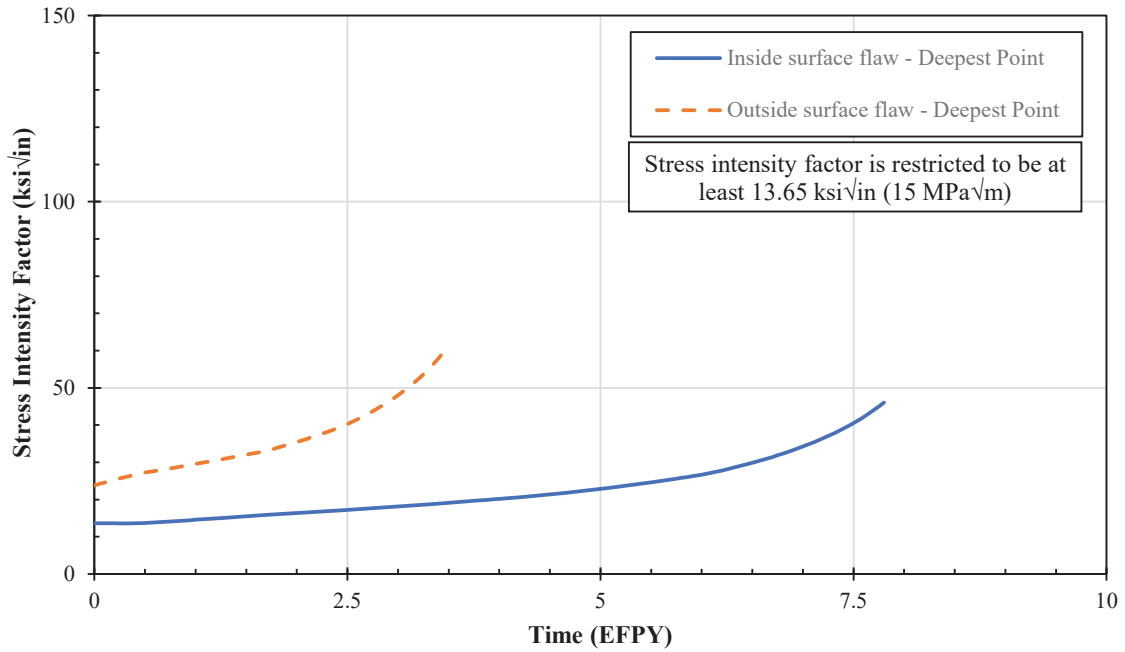

Figure 3. Stress Intensity Factors Calculated for Flaw Deepest Point vs. Time

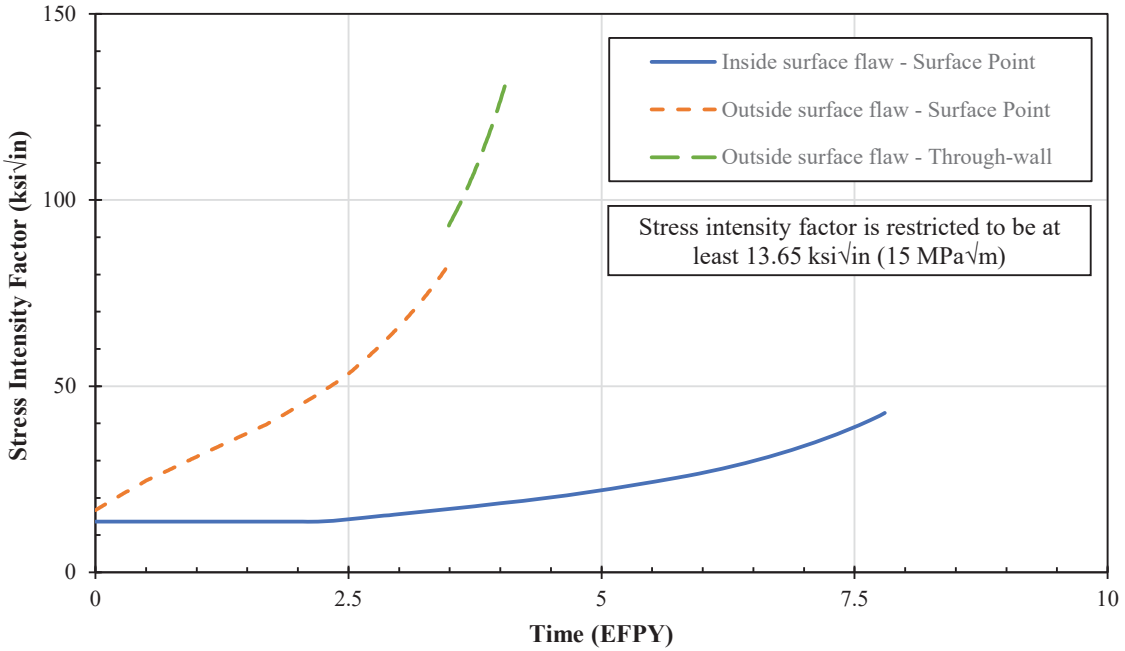

Figure 4. Stress Intensity Factors Calculated for Flaw Surface Point vs. Time

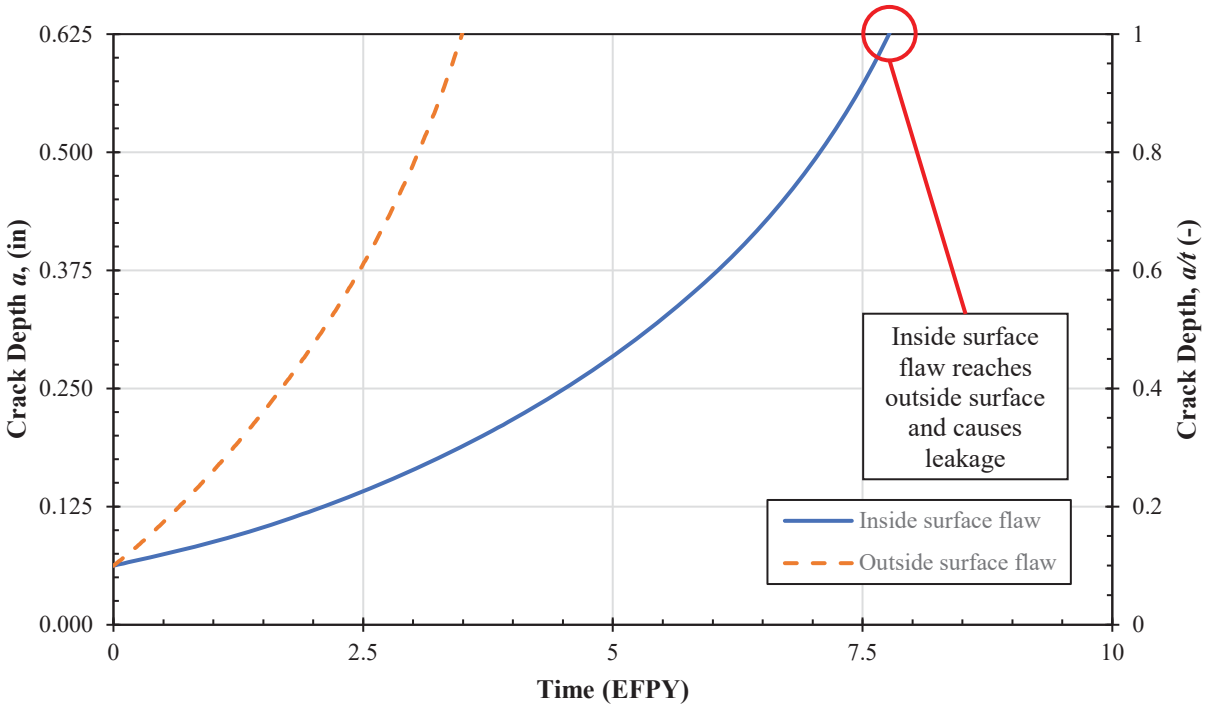

Figure 5. Crack Depth Growth

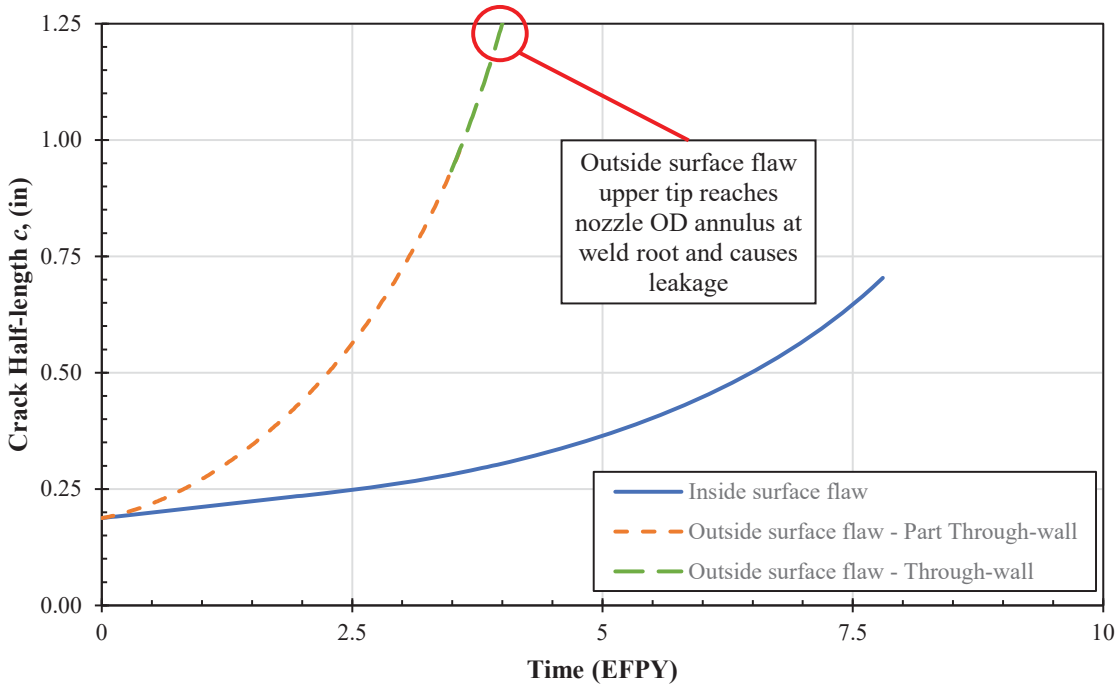

Figure 6. Crack Length Growth

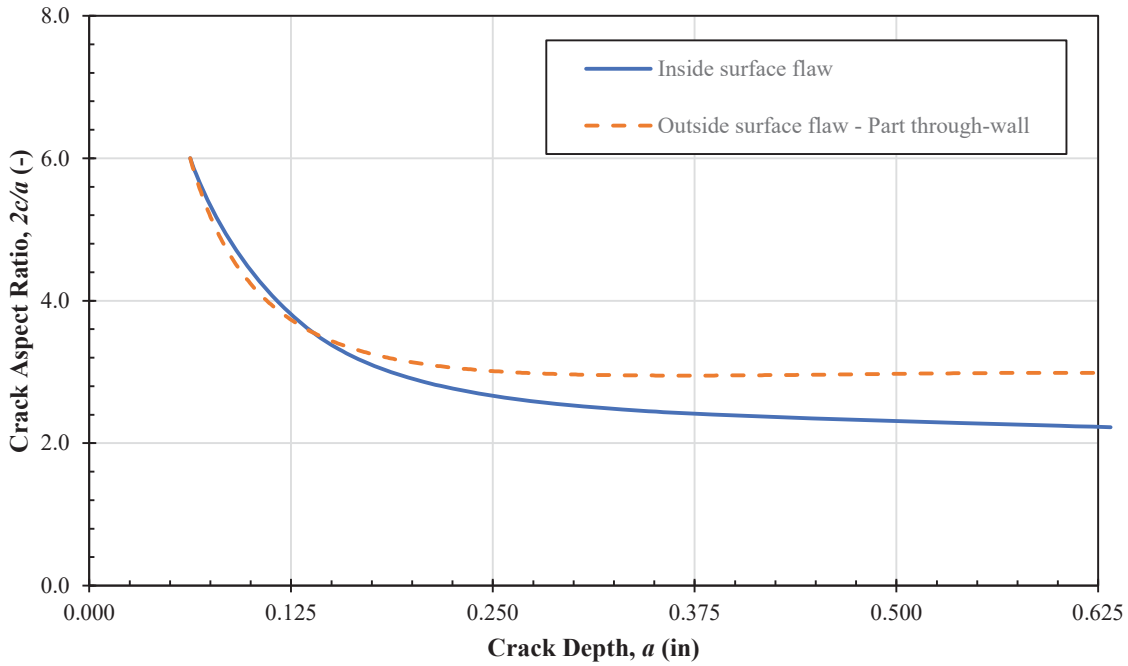

Figure 7. Crack Aspect Ratio Evolution as Function of Crack Depth

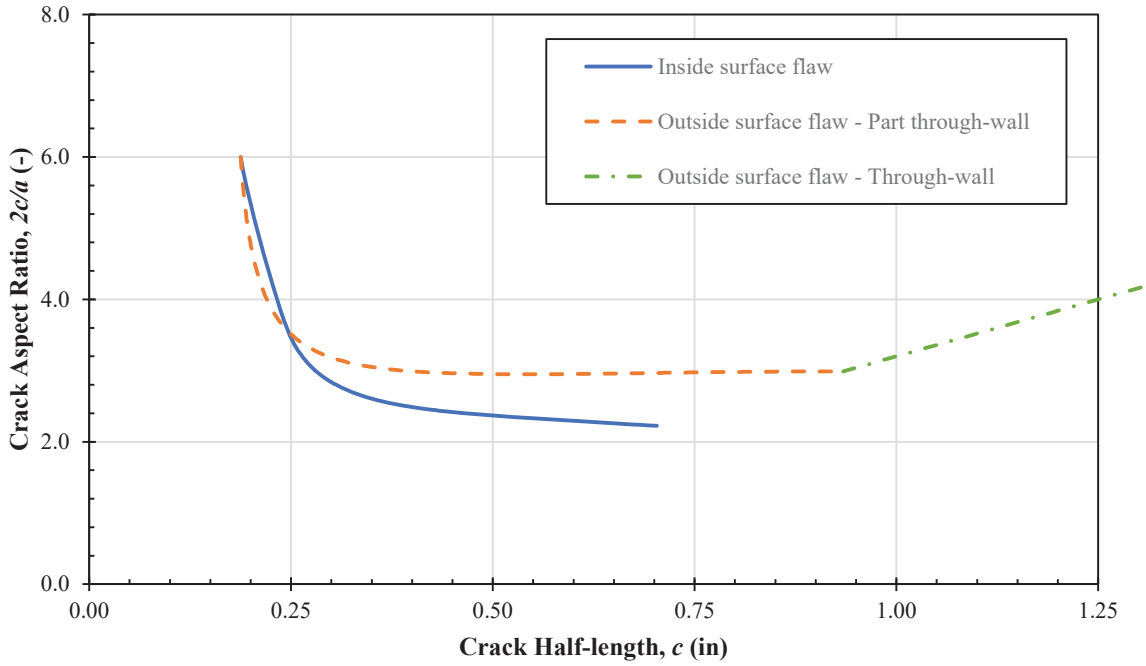

Figure 8. Crack Aspect Ratio Evolution as Function of Crack Length

A CONTENTS OF D-4731-00-01 [24]

Directory	Filename	Description
Check Files/	Figures.xlsx	Recreation of figures in this calculation
Check Files/Coefficient Tables/	AxialGsCEA_OD.txt	Influence coefficients for OD axial flaws
Check Files/Coefficient Tables/	AxialGsCEA.txt	Influence coefficients for ID axial flaws
Check Files/Input Files – 4731/	4731 ANO1 CRDM 1.csv	Inputs for both ID and OD cases
Check Files/Out/4731 ANO1 CRDM 1 2022-03-09 (1806) /	ID (3.49) - OUT.png	Plots of crack size, crack shape, and stress intensity factors for ID case
Check Files/Out/4731 ANO1 CRDM 1 2022-03-09 (1806) /	ID (3.49) - OUT.txt	Detailed results for ID case
Check Files/Out/4731 ANO1 CRDM 1 2022-03-09 (1806) /	OD - OUT.png	Plots of crack size, crack shape, and stress intensity factors for OD case
Check Files/Out/4731 ANO1 CRDM 1 2022-03-09 (1806) /	OD - OUT.txt	Detailed results for OD case
Check Files/Out/4731 ANO1 CRDM 1 2022-03-09 (1806) /	Results_Summary.txt	Summary of results for both ID and OD cases
Check Files/src/	calc_K_infl.py	Python code for calculation of stress intensity factors
Check Files/src/	crdm_growth_extrap.py	Python code for simulating crack growth
Check Files/src/	utilities.py	Python code containing utility functions
/	C-4731-00-02 R0 Crack Growth Calculation.xlsx	One Time Use Spreadsheeet