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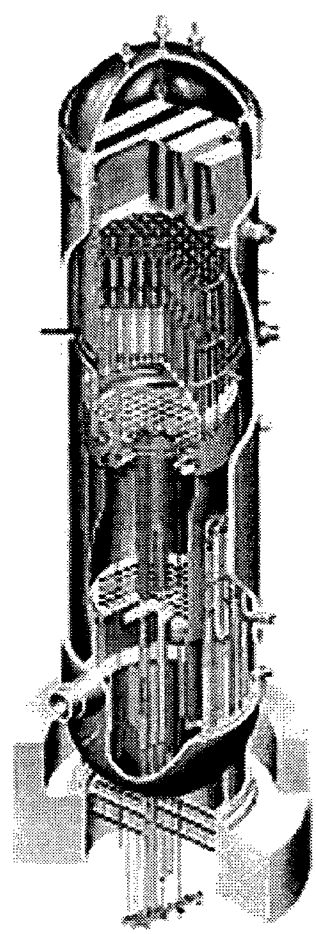
BWRVIP-203NP: BWR Vessel and Internals Project

RPV Axial Weld Inspection Coverage Evaluation



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RPV Axial Weld Inspection Coverage Evaluation

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REPORT SUMMARY

This Boiling Water Reactor (BWR) Vessel and Internals project evaluates reactor pressure vessel (RPV) axial weld inspection coverage.

Background

An evaluation of inspection requirements BWR reactor pressure vessel RPV beltline shell welds was performed and documented in BWRVIP-05. It was shown in BWRVIP-05 that the probability of failure from circumferential welds is orders of magnitude lower than that for RPV beltline axial welds. BWRVIP-05 concluded that the amount of inservice inspections could be reduced while still meeting Nuclear Regulatory Commission (NRC) safety margin requirements. Based on the NRC safety evaluation report, a permanent relief of beltline circumferential shell welds inspections was permitted.

Since the acceptance of BWRVIP-05, many inspections of axial welds in RPV beltlines have been performed. Field experience shows that in many cases it is not possible to attain the required inspection coverage of these welds specified by the Code of Federal Regulations, 10CFR50, and Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (Section XI). Generally, the inability to attain necessary inspection coverage is caused by obstructions such as permanent insulation on the exterior of the RPV and hardware internal to the reactor such as guide rods, core shroud repairs, and welded attachments.

Objectives

To determine the allowable reduction in inspection coverage of RPV shell axial welds as a function of the adjusted reference temperature (ART).

Approach

The project team followed a similar approach employed in BWRVIP-05 and BWRVIP-108. A test matrix was developed consisting of a wide range of ARTs to account for 60 years of operation. Monte Carlo simulations were performed to determine the failure probability of axial welds. Calculations were performed for 90%, 70%, 50%, and 20% inspection coverage and ARTs ranging from -66°F (-54°C) to 267°F (131°C). Results were used to assess permissible inspection coverage as a function of ART.

Results

Allowable inspection coverage was determined based on ART for two different wall thicknesses—5.897 inches (150 mm) and 5.375 inches (137 mm)—various inspection coverages, and crack growth up to 60 years of operation. In general, a reduction in inspection coverage requires a lower ART at the end of the operating interval corresponding to the time of the next

inspection. Conversely, as inspection coverage increases, the ART requirement is less stringent, that is, higher ARTs are permissible.

A single diagram is provided in the report to determine acceptable inspection coverage considering 30, 40, 50, and 60 years of crack growth. The appropriate wall thickness curve is selected along with the actual inspection coverage that can be obtained. If ART lies below the curve, inspection coverage is adequate to satisfy the acceptance criteria.

EPRI Perspective

The BWR Vessel and Internals Project (BWRVIP) successfully completed a project to eliminate the requirement for inspection of RPV circumferential welds (TR-105697, September 1995). However, it is necessary to periodically inspect RPV axial welds. Field experience shows that in many cases, it is not possible to attain the required 90% inspection coverage of RPV axial welds stipulated in 10CFR50, and the ASME Section XI Code cannot be achieved. Results of this current project can be used to determine the acceptability of a specific inspection coverage for these welds.

Keywords

Boiling water reactor
Reactor pressure vessel
Axial welds
Inspection coverage
Probabilistic fracture mechanics

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1
INTRODUCTION

1.1 Background

An evaluation of the inspection requirements for Boiling Water Reactor (BWR) reactor pressure vessel (RPV) beltline shell welds was performed and documented in BWRVIP-05 [1]. It was shown in BWRVIP-05 that the probability of failure from the circumferential welds is orders of magnitude lower than that for the RPV beltline axial welds. It was concluded that the amount of inservice inspections could be reduced while still meeting NRC safety margin requirements. Based on the NRC safety evaluation report [2], a permanent relief of inspection of the beltline circumferential shell welds was permitted provided that it can be demonstrated that the vessel is bounded by the limiting plant transient used in the BWRVIP-05 evaluations.

Since the acceptance of BWRVIP-05, based on the Section XI of the ASME Boiler and Pressure Vessel Code (Section XI) requirements of inspecting essentially 100% of the axial welds, many inspections have been performed of the axial beltline welds. Field experience shows that in many cases, it is not possible to attain 100% inspection of the axial welds. Generally, the inability to attain 100% is caused by obstructions such as permanent insulation on the exterior of the RPV and hardware internal to the reactor such as guide rods, core shroud repairs and welded attachments.

1.2 Purpose

This evaluation determines the allowable inspection coverage of the RPV shell axial welds as a function of the adjusted reference temperature (ART). The approach employs methods similar to those published in BWRVIP-05 and BWRVIP-108 [3]. This evaluation incorporates updated inputs to the probabilistic fracture mechanics analysis based on Reference 4.

For this evaluation, results are obtained for 30, 40, 50 and 60 calendar years. Any flaws are considered up to 60 years and the periodic 10 year inspections are simulated which may identify the flaws. Unidentified flaws can continue to grow during future operation. Predicted failures are a result of crack growth and/or reduction of fracture toughness (which is a function of ART).

Conservative assumptions are used in this analysis to determine the acceptable inspection coverage of a RPV axial weld at a specified ART. The results in this report should not be used to establish the failure probability of an RPV axial weld when the inspection coverage capability is equal to or greater than 90% to justify reduced inspection for an upcoming inspection. These results, because they are based on very conservative assumptions, are not applicable to determining the probability of failure for cases where the inspection capability can meet the essentially 100% inspection requirement.

Inspection coverage requirements are determined for an upcoming inspection by using the ART at the end of the interval following the inspection. This will assure that safety margins are met through the interval following the inspection.

1.3 Implementation Guidelines

These results can be used as a technical basis to support an owner in preparing a relief request to show the acceptability of a specific inspection coverage for BWR RPV shell axial welds (within or outside the beltline) when the required inspection coverage stipulated in 10CFR50 and the ASME Section XI Code cannot be achieved. If the results of this report are implemented it will be in accordance with the terms agreed to by the owner and NRC as part of the relief request. Therefore the classifications defined in Nuclear Energy Institute (NEI) 03-08, Guideline for the Management of Materials Issues, are not applicable.

2
PROBABILISTIC FRACTURE MECHANICS ANALYSIS

2.1 Methodology

This evaluation was performed using a methodology similar to that described in References 1 and 3. Various changes to the input values are discussed in this report. A Monte Carlo simulation was performed to determine the failure probability of the RPV axial welds using a project-specific version of the program VIPER Version 1.2, called VIPERXP Version 2.0 [5], developed by Structural Integrity Associates (SI). The software, VIPER, was originally developed to evaluate the failure probability of BWR RPV shell welds. Results were used to justify eliminating the circumferential welds from the Section XI inspection program.

2.2 Weld Chemistry and Fluence

The weld chemistry and fluence at the reactor pressure vessel quarter thickness depth (¼T) for the BWR vessel weld materials were obtained from Reference 6, shown in Table 2-1. The maximum and minimum weld chemistry and fluence at the inner surface from the BWR fleet are presented in Table 2-2. The maximum and minimum Cu weight (wt.%) contents are 0.34 and 0.019, respectively. The maximum and minimum Ni wt.% contents are 1.1 and 0.043, respectively. The maximum and minimum inside surface fluence is 7.96×10^{18} n/cm^2 and 0.23×10^{18} n/cm^2, respectively. This information was used to determine a range of adjusted reference temperature (ART) values, calculated using Regulatory Guide 1.99, Revision 2 [7], as input to the probabilistic model. This is presented in Section 2.10.

2.3 Flaw Density and Flaw Size Distribution

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Equation 2-1

Figure 2-1 shows the PVRUF flaw size distribution.

Table 2-1
Limiting BWR Vessel Weld Materials

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Table 2-2
Data Summary from BWRVIP-86A

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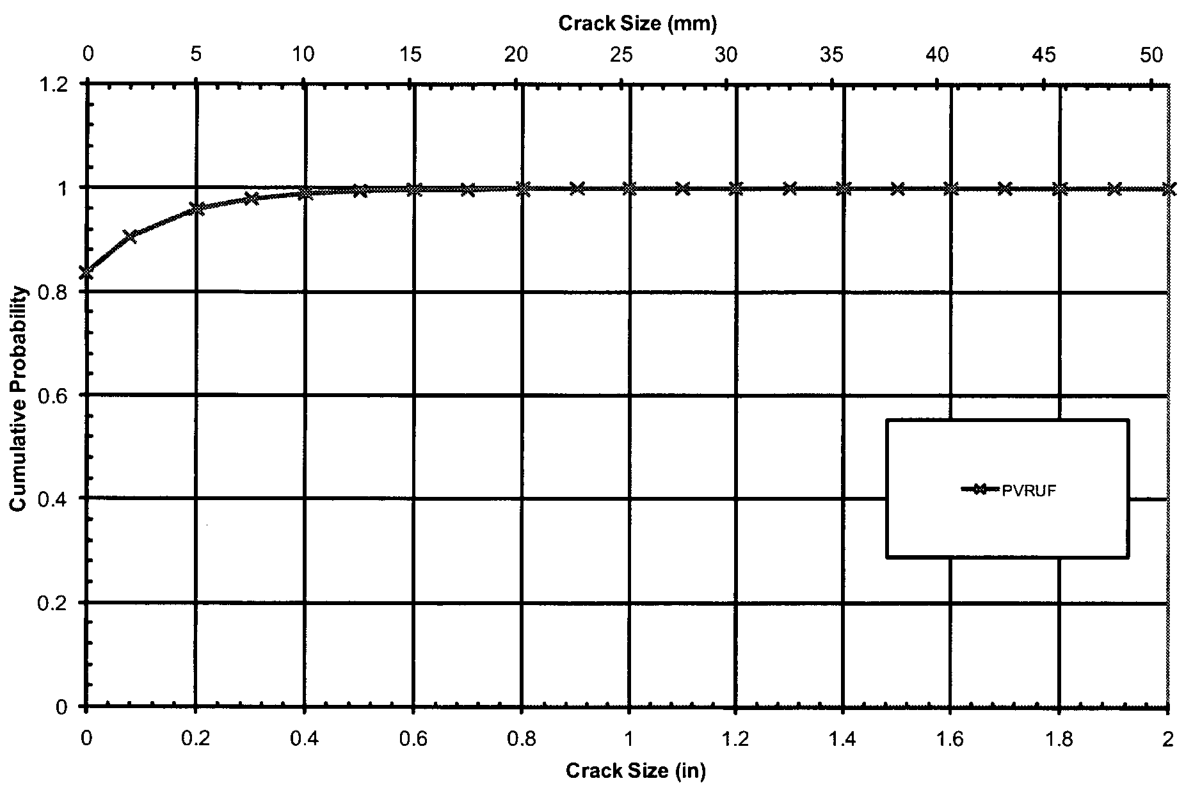

Figure 2-1
PVRUF Flaw Size Distribution

2.4 Stress Corrosion Initiation and Crack Growth Rate

The cladding stress corrosion crack initiation curve was obtained from Reference 1 and presented in Figure 2-2. The open squares correspond to field stress corrosion cracking (SCC) data for stainless steel weld metal and cast stainless steel. The data are relatively sparse. More data are available for wrought, sensitized stainless steel in the BWR environment, as indicated by the solid diamonds in Figure 2-2. A best fit curve was developed for the cast stainless steel and stainless steel weld metal and represented by the following equation:

Equation 2-2

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Figure 2-2
Cladding Stress Corrosion Initiation

Stress corrosion crack growth rates of low alloy steel (LAS) in the BWR environment were obtained from BWRVIP-60-A [9]. There are two crack growth disposition curves for LAS in normal water chemistry (NWC) or hydrogen water chemistry (HWC) with conductivity ≤ 0.3 μS/cm and are given below:

Equation 2-3

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Equation 2-4

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2.5 Probability of Detection Curve

Reference 2 states that the probability of detection (PoD) was obtained from the Program for Inspection of Steel Components (PISC II) study. This PoD curve was obtained from Reference 10 (Page 11, Figure 2.8). This PoD curve is originated from Reference 11 where Becker documented the findings of the U. S. Performance Demonstration Initiative (PDI) which has manufactured 20 RPV mockups that contain in excess of 300 flaws. It shows the probability of detection as a function of crack depth considering pooled data from both manual and automated inspection processes. The curve is based on results of the candidates that passed plus the failed candidates. The inclusion of the candidates that passed plus the failed candidates is taken to provide a lower bound estimate of expected inspection performance.

The PISC II PoD curve was curve-fit to the following form for use in the probabilistic fracture mechanics evaluation:

$$PoD = \frac{m}{1 + b * \exp(-cx)}$$

Equation 2-5

where x = crack size (in)
m = 0.999937
b = 1.214018
c = 15.00636

The comparison of PISC with other PoD curves from Reference 1 is shown in Figure 2-3. These are Full-V ultrasonic angle beam (FULLV), multi-mode ultrasonic (SLIC), eddy current (EDDY) and a combination of the three techniques assuming complete independency (COMBINED). The PoD curve COMBINED was used in BWRVIP-05 evaluation [1].

It is shown that the PISC PoD curve has a better detection probability for small flaws (a < ~ 0.06 inch) but a lower detection probability for flaws between ~0.06 inch (1.5mm) and 0.5 inch (12.7mm). For larger flaws (i.e. > 0.5 inch (12.7mm)), the PoD is about the same between PISC and COMBINED.

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Figure 2-3
Comparison of PoD Curves

2.6 Flaw Aspect Ratio

In Appendix G, Article 2000 of the ASME Boiler and Pressure Vessel Code, Sections III [12] and XI [16], the maximum postulated defect with a ¼T depth and a flaw length/depth (l/a) aspect ratio) of 6 to 1 is used in the criteria for protection against failure. In Reference 10, an aspect ratio of 6 to 1 was used to determine the recommended screening limits for Pressurized Thermal Shock (PTS).

Also in Regulatory Guide 1.161 [13], it is stated that, for Levels A and B conditions, a semi-elliptical surface flaw with a flaw depth/wall thickness ratio (a/t) = 0.25 and with a l/a of 6 to 1 can be postulated. For Levels C and D conditions, a postulated surface flaw with depth up to one-tenth the base metal wall thickness, plus the clad thickness, but with the total depth not to exceed 1.0 inch (2.54 cm) and with an l/a of 6 to 1 is used. This postulated flaw shape is also restated in Reference 14.

In this evaluation, a flaw aspect ratio of l/a = 6 is used in the axial weld evaluation.

Table 2-3
Design Information for BWR Reactor Vessels

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2.7 Reactor Pressure Vessel Wall Thickness

The reactor pressure vessel (RPV) wall thicknesses for the BWR fleet were obtained from Reference 9, shown in Table 2-3. The maximum wall thickness is 7.125 inches (181 mm) and the minimum wall thickness is 4.47 inches (113.5 mm). The maximum vessel inner diameter is 254 inches (6.45 m) and the minimum vessel inner diameter is 185 inches (4.7 m).

The average wall thickness of the BWR fleet is 5.897 inches (150 mm). There is one vessel each at 4.47 inches (113.5 mm), 5.063 inches (128.6 mm) and 5.29 inches (134.4 mm). All other vessels are at 5.375 inches (137 mm) or thicker.

2.8 Comparison of Input with BWRVIP-05

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Figure 2-4
Comparison of Stress Corrosion Initiation Time

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Figure 2-5
Comparison of Stress Corrosion Crack Growth Rate

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Figure 2-6
Distribution of Test Case ART

2.9 Low Temperature Overpressurization Event.

The LTOP event is defined by a temperature of 88°F (31°C) and a pressure of 1150 psig (7.93 MPa) [1, 2]. The probability of event occurrence is 1×10^{-3} per year [1, 2].

Other Inputs

- The normal operating pressure and temperature are 1050 psi (7.24 MPa) and 550°F (288°C), respectively.
- The inspection interval is assumed at the end of every tenth year.
- The hoop stress due to pressure is calculated using the thin wall cylinder equation.
- Calculations are presented for a plant operating term of 30, 40, 50 and 60 years (crack growth), with 80% availability (32 and 48 effective full power years, respectively).

Table 2-4
Comparison of Input Data

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Table 2-4 (continued)
Comparison of Input Data

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2.10 Calculations

2.10.1 Test Matrix for Adjusted Reference Temperature

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The effect of vessel base metal wall thickness on the probability of failure (PoF) of the RPV was evaluated. Two base metal wall thicknesses were used. The thicknesses used were 5.897 inches (150 mm), the average wall thickness of the BWR fleet, and 5.375 inches (137 mm), the fourth thinnest wall thickness, as shown in Table 2-3.

Also four inspection coverages were used in the evaluation. They are "essentially 100%" (assumed 90%), 70%, 50% and 20%.

Table 2-5
Test Matrix

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2.10.2 Modification of VIPER

The software [5] was modified to accommodate the input for the new stress corrosion crack growth rate, PISC PoD curve for inspection, and an elliptical axial flaw with aspect ratio of l/a = 6.

The new version of software was used and is identified as VIPERXP, Version 2.0 [5].

2.10.3 Monte Carlo Simulation

The probabilities of failure for the BWR axial welds are evaluated using probabilistic fracture mechanics (PFM). A Monte Carlo method was used with the random variables identified in Table 2-4. For each case in the test matrix, 10,000 simulations were used.

3
RESULTS

3.1 Average Wall Thickness of 5.897 inches (150 mm)

Figure 3-1 presents the conditional probability of failure (CPoF) results for the 90%, 70%, 50% and 20% inspection coverage cases with the average reactor vessel wall thickness of 5.897 inches (150 mm), a flaw aspect ratio of l/a = 6 and an operating term of 40 years for crack growth.

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**Figure 3-1
Conditional PoF versus ART, for Different Inspection Coverage, 5.897 inches (150 mm) Wall Thickness with Flaw Aspect Ratio of 6, 40 Years of Crack Growth**

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Figure 3-2
Increases in CPoF from 90% inspection, 5.897 inches (150 mm) Wall Thickness with Flaw Aspect Ratio of 6, 40 Years of Crack Growth

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**Figure 3-3
Conditional CPoF versus ART, for Different Inspection Coverage, 5.897 inches (150 mm) Wall Thickness with Flaw Aspect Ratio of 6, 60 Years of Crack Growth**

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Figure 3-4
Increases in CPoF from 90% inspection, 5.897 inches (150 mm) Wall Thickness with Flaw Aspect Ratio of 6, 60 Years of Crack Growth

3.2 Wall Thickness of 5.375 inches (137 mm)

Figure 3-5 presents the conditional probability of failure for 90%, 70%, 50% and 20% inspection coverage with the reactor vessel wall thickness of 5.375 inches (137 mm), a flaw aspect ratio of l/a = 6 and a plant operating term of 40 years for crack growth.

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Figure 3-6 presents the increases in CPoF on a per year basis from 90% inspection coverage to a lower inspection coverage for a plant operating term of 40 years for crack growth. Similar to the results for the average reactor vessel wall thickness, the significant changes in CPoF occur in the same temperature range.

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**Figure 3-5
Conditional PoF versus ART, for Different Inspection Coverage, 5.375 inches (137 mm) Wall Thickness with Flaw Aspect Ratio of 6, 40 Years of Crack Growth**

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Figure 3-6
Increases in CPoF from 90% inspection, 5.375 inches (137 mm) Wall Thickness with Flaw Aspect Ratio of 6, 40 Years of Crack Growth

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Figure 3-7
Conditional PoF versus ART, for Different Inspection Coverage, 5.375 inches (137 mm) Wall Thickness with Flaw Aspect Ratio of 6, 60 Years of Crack Growth

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Figure 3-8
Increases in CPoF from 90% inspection, 5.375 inches (137 mm) Wall Thickness with Flaw Aspect Ratio of 6, 60 Years of Crack Growth

3.3 Inspection Coverage Summary

For the situation when "essentially 100%" inspection of the RPV axial welds cannot be achieved during the inservice inspection of RPV axial welds, Figure 3-9 can be used to determine the allowable inspection coverage (less than 90%) based on the ART for two different wall thicknesses (5.897 inches (150 mm) and 5.375 inches (137 mm)

The allowable inspection coverage is based on the difference in the probability of failure between the actual inspection coverage and the required 'essentially 100%' inspection. Inspection coverage is considered acceptable if the difference in probability of failure is smaller than the acceptance criteria stated in Regulatory Guide 1.174 criteria [15].

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In general, smaller inspection coverage requires a lower ART at the time of inspection. A thinner wall thickness requires a lower ART for the same inspection coverage. Also, longer plant operating terms requires a lower ART for the same inspection coverage. As the inspection coverage increases, the ART requirement is less stringent (i.e. can have a higher ART).

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**Figure 3-9
Inspection Coverage as a Function of ART at Inspection Interval for 30 Years, 40 Years, 50 Years and 60 Years of Crack Growth**

3.3.1 Required Inspection Coverage

The results of these calculations discussed in Section 3.3 can be used to determine the acceptability of a specific inspection coverage for RPV axial welds when the "essentially 100%" coverage cannot be achieved.

Given the inspection coverage capability, wall thickness, operating term for crack growth (defined by number of years until the end of the next interval) and ART (at the end of the next interval), Figure 3-9 may be used to determine acceptability. The acceptable inspection coverage, for the upcoming inspection, is determined using the ART at the end of the next inspection interval since this will demonstrate acceptance per the criteria of Regulatory Guide 1.174 [15] through the next operating interval. The appropriate wall thickness curve is selected along with the actual inspection coverage that can be obtained. If the ART falls above the appropriate curve, the inspection coverage is not adequate. If the ART falls below the curve, the inspection coverage is sufficient.

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