Attachment 2

10 CFR 50.55a RELIEF REQUESTS

Report 3002003099, "Materials Reliability Program: Reevaluation of Technical Basis for Inspection of Alloy 600 PWR Reactor Vessel Top Head Nozzles (MRP-395)"

ELECTRIC POWER RESEARCH INSTITUTE

Materials Reliability Program: Reevaluation of Technical Basis for Inspection of Alloy 600 PWR Reactor Vessel Top Head Nozzles (MRP-395)

2014 TECHNICAL REPORT

Materials Reliability Program: Reevaluation of Technical Basis for Inspection of Alloy 600 PWR Reactor Vessel Top Head Nozzles (MRP-395)

3002003099

Final Report, September 2014

EPRI Project Manager

C. Harrington

All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

YES NO

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REPORT SUMMARY

This report documents reevaluation of the technical basis for inspection requirements for pressurized water reactor (PWR) vessel top heads with Alloy 600 nozzles and Alloy 82/182 attachment welds to address the potential for primary water stress corrosion cracking (PWSCC). It includes a technical basis for a volumetric or surface reexamination interval of two fuel cycles for heads with previously detected PWSCC that operate at reactor cold-leg temperature.

Background

Overall plant experience for Alloy 600 reactor vessel top head nozzles in U.S. PWRs shows that the currently required inspection intervals have successfully managed the PWSCC concern. No through-wall cracking has been observed in the U.S. after performance of the first in-service volumetric or surface examination of all control rod drive mechanism (CRDM) or control element drive mechanism (CEDM) nozzles in a given head. The current inspection intervals have facilitated identification of any PWSCC in relatively early stages. PWSCC has now been reported in five heads with Alloy 600 nozzles operating at reactor cold-leg temperature (T_{cold}) in U.S. PWRs. The Materials Reliability Program (MRP) applied the experience gained over the last ten years to perform a detailed reevaluation of the technical basis for the inspection requirements.

Objectives

To update the technical basis for the American Society of Mechanical Engineers (ASME) Code Case N-729-1 inspection requirements for reactor vessel top heads, including those operating at reactor cold-leg temperature (T_{cold}), to include operating experience gained since the original 2004 technical basis work.

Approach

The project team applied deterministic and probabilistic calculations to assess the effect of the latest inspection experience, including indications detected in heads operating at T_{cold}, on the Weibull crack initiation parameters applied in the original MRP-105 (EPRI 1007834) technical basis document. The specific concern addressed is the extent to which the probability of crack initiation implied by the recent cold head experience is greater than that assumed in the 2004 MRP-105 evaluation.

The probabilistic calculations are based on a Monte Carlo simulation model of the PWSCC process, including PWSCC initiation, crack growth, and flaw detection via ultrasonic testing. The current probabilistic model is similar in form to the original MRP-105 model, but includes refinements in several areas such as modeling of part-depth crack growth. The outputs of the probabilistic model are leakage frequency and nozzle ejection frequency.

Results

The deterministic calculations demonstrate that the interval for volumetric or surface examination is sufficient to detect any PWSCC before it could develop into a safety-significant circumferential flaw that approaches the large size necessary to produce a nozzle ejection. They also demonstrate that any base metal PWSCC would likely be detected prior to the occurrence of a through-wall penetration. On the basis of plant experience and the deterministic and probabilistic analyses, the current inspection requirements of ASME Code Case N-729-1 as conditioned by 10 CFR 50.55a(g)(6)(ii)(D) are still sufficient to address the PWSCC concern. In particular, the reexamination interval limit of Re-Inspection Year (RIY) = 2.25 for periodic volumetric or surface examination remains valid for all heads without previously detected PWSCC, including heads that operate at T_{cold}. In addition, a volumetric or surface reexamination interval of two fuel cycles for heads with previously detected PWSCC that operate at T_{cold} would provide a sufficient level of conservatism, as was previously concluded in MPR-117 (EPRI 1007830). The current requirement for a volumetric or surface reexamination interval of every fuel cycle for a head with previously detected PWSCC regardless of head operating temperature is overly conservative for heads operating at T_{cold}. On the basis of previous assessments, plant experience, and the latest analyses, the project team concluded that the requirements of Code Case N-729-1 for periodic visual examinations of the upper head surface are still a suitably conservative approach for addressing the potential for boric acid corrosion associated with leakage due to PWSCC.

Applications, Value, and Use

This technical basis report is applicable to PWR reactor vessel top heads with Alloy 600 partial-penetration welded nozzles and Alloy 82/182 J-groove attachment welds. As of July 2014, there are 25 such original heads still in operation in the U.S. This technical basis document confirms the adequacy of current inspection requirements for Alloy 600 reactor vessel top head penetration nozzles in U.S. PWRs, including for heads operating at T_{cold}. The document also provides a technical basis for requesting from the U.S. Nuclear Regulatory Commission (NRC) an alternative volumetric or surface reexamination interval of two 18-month fuel cycles for heads with previously detected PWSCC and that operate at T_{cold}. The report includes specific recommended changes to the latest version of ASME Code Case N-729 to implement this alternative. NRC acceptance of such a revised code case would be required before the case could be applied without necessitating a licensee to request relief. Alternatively, the NRC could directly modify the regulation mandating Code Case N-729-1 to change the applicable condition.

Keywords
Alloy 600
Alloy 82
Alloy 182
Primary water stress corrosion cracking (PWSCC)
PWR reactor vessel head
Reactor pressure vessel head penetration nozzles (RPVHPNs)

ABSTRACT

Overall plant experience for Alloy 600 reactor vessel top head nozzles in U.S. pressurized water reactors (PWRs) shows that the currently required inspection intervals have been very successful in managing the primary water stress corrosion cracking (PWSCC) concern. No through-wall cracking has been observed in the U.S. after the first in-service volumetric or surface examination was performed of all control rod drive mechanism (CRDM) or control element drive mechanism (CEDM) nozzles in a given head. The current inspection intervals have facilitated identification of any PWSCC in relatively early stages. PWSCC has now been reported in five heads with Alloy 600 nozzles operating at reactor cold-leg temperature (T_{cold}) in U.S. PWRs. Therefore, the Materials Reliability Program (MRP) applied the experience gained over the last ten years to perform a detailed reevaluation of the technical basis for the inspection requirements. This report evaluates the adequacy of the current inspection requirements, including the frequency of periodic volumetric or surface examinations for heads operating at T_{cold}. It also evaluates whether an interval of two 18-month fuel cycles is justified for heads operating at T_{cold} in which PWSCC has been detected previously. This technical basis report is applicable to PWR reactor vessel top heads with Alloy 600 partial-penetration welded nozzles and Alloy 82/182 J-groove attachment welds. As of July 2014, there are 25 such original heads still in operation in the U.S.

The project team applied deterministic and probabilistic calculations to assess the effect of the latest inspection experience on the Weibull crack initiation parameters applied in the original MRP-105 (EPRI 1007834) technical basis document. The deterministic calculations demonstrate that the interval for volumetric or surface examination is sufficient to detect any PWSCC before it could develop into a safety-significant circumferential flaw that approaches the large size necessary to produce a nozzle ejection. They also demonstrate that any base metal PWSCC would likely be detected prior to a through-wall penetration occurring. The probabilistic calculations, which are used to predict leakage and nozzle ejection frequencies, are based on a Monte Carlo simulation model of the PWSCC process, including PWSCC initiation, crack growth, and flaw detection via ultrasonic testing.

This technical basis document confirms the adequacy of current inspection requirements for Alloy 600 reactor vessel top head penetration nozzles in U.S. PWRs, including those operating at T_{cold}. The document also provides a technical basis for requesting from the U.S. Nuclear Regulatory Commission (NRC) an alternative interval for volumetric or surface examination of two 18-month fuel cycles for heads with previously detected PWSCC and that operate at T_{cold}. The report includes specific recommended changes to the latest version of American Society of Mechanical Engineers (ASME) Code Case N-729 to implement this alternative. NRC acceptance of such a revised code case would be required before the case could be applied without necessitating a licensee to request relief. Alternatively, the NRC could directly modify the regulation mandating Code Case N-729-1 to change the applicable condition.

ACRONYMS

AEF	Average Ejection Frequency
ALF	Average Leakage Frequency
ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
B&WTP	Babcock & Wilcox Tubular Products
BMV	Bare Metal Visual
CBI	Chicago Bridge & Iron
CCDP	Conditional Core Damage Probability
CDF	Cumulative Distribution Function
CEDM	Control Element Drive Mechanism
CFR	Code of Federal Regulations
CGR	Crack Growth Rate
CRDM	Control Rod Drive Mechanism
EDY	Effective Degradation Year
EFPY	Effective Full Power Year
EPRI	Electric Power Research Institute
ET	Eddy Current Testing
FEA	Finite Element Analysis
ID	Inside Diameter
IEF	Incremental Ejection Frequency
ILF	Incremental Leakage Frequency
LER	Licensee Event Report
MC	Monte Carlo
MRP	[EPRI] Materials Reliability Program
NDE	Non-Destructive Examination
NRC	U.S. Nuclear Regulatory Commission

NSC	Net Section Collapse
OD	Outside Diameter
PFM	Probabilistic Fracture Mechanics
POD	Probability of Detection
PT	[Liquid] Penetrant Testing
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
RFO	Refueling Outage
RIY	Re-Inspection Year [per ASME Code Case N-729-1]
RPV	Reactor Pressure Vessel
RPVH	Reactor Pressure Vessel Head
RPVHPN	Reactor Pressure Vessel Head Penetration Nozzle
SCC	Stress Corrosion Cracking
TW	Through-Wall
UT	Ultrasonic Testing
VE	per ASME Code Case N-729-1, direct examination of the bare-metal surface of the entire outer surface of the head, including essentially 100% of the intersection of each nozzle with the head and additional requirements
VT-2	per ASME Code Case N-729-1, IWA-2212 VT-2 visual examination of the head performed under the insulation through multiple access points, permitted with the reactor vessel depressurized

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INTRODUCTION

1.1 Background

1.1.1 Plant Experience

Overall plant experience for Alloy 600 reactor vessel top head nozzles in U.S. PWRs shows that the currently required inspection intervals have been very successful in managing the PWSCC concern. No through-wall cracking has been observed in the U.S. after the first in-service volumetric or surface examination was performed of all CRDM or CEDM nozzles in a given head. The current inspection intervals have facilitated identification of any PWSCC in its relatively early stages. PWSCC has now been reported in five heads with Alloy 600 nozzles operating at reactor cold-leg temperature (T_{cold}) in U.S. PWRs. Given this experience, as documented in this report, the MRP has performed a detailed reevaluation of the technical basis for the inspection requirements to apply the experience gained over the last 10 years.

1.1.2 Current Inspection Requirements

The NRC regulation 10 CFR 50.55a(g)(6)(ii)(D) requires that all U.S. PWRs augment their inservice inspection programs with ASME Code Case N-729-1 [1],[1] subject to several conditions identified in this regulation. This code case defines inspection intervals for visual examinations and for volumetric or surface examinations for all reactor vessel top head nozzles attached to the head with partial-penetration (i.e., J-groove) welds.

For heads with Alloy 600 nozzles, the inspection interval for volumetric or surface examination (between examinations of all nozzles) is based on the RIY (Re-Inspection Year) parameter, which is a measure of operating time normalized to a head temperature of 600°F using the consensus temperature dependence of the primary water stress corrosion cracking (PWSCC) crack growth rate. The required interval is every eight (8) calendar years or before RIY = 2.25, whichever is less. For top heads that operate at reactor cold-leg temperature (T_{cold}), commonly referred to as "cold heads," this generally equates to an interval of four or five 18-month fuel cycles. More frequent volumetric or surface examinations may be required if PWSCC has previously been detected in the subject head. The NRC conditions on Code Case N-729-1 [1] limit the interval for volumetric or surface examination to one fuel cycle in such cases.

For heads with Alloy 600 nozzles, the visual inspection interval for successive direct examinations of the bare-metal surface is every refueling outage. This interval is extended to every third refueling outage or five (5) calendar years, whichever is less, for heads with less than eight (8) cumulative effective degradation years (EDYs) of operating time and for which

[1] Although ASME Code Case N-729-4 [2] has been approved by the Standards Committee, ASME Code Case N-729-1 [1] is the version currently mandated in 10 CFR 50.55a(g)(6)(ii)(D).

PWSCC has not been detected requiring repair.[2] Like the RIY parameter, the EDY parameter is a measure of operating time normalized to a head temperature of 600°F. However, the EDY parameter is calculated using the best-estimate temperature dependence of the PWSCC crack initiation time instead of the PWSCC crack growth rate. Thus, the EDY parameter is associated with the cumulative operating time to first cracking in a head, while the RIY parameter is associated with the operating time available between inspections for propagation of existing cracks.

1.1.3 Original Technical Basis for Inspection Requirements

The original technical basis for the top head inspection requirements defined in ASME Code Case N-729-1 [1] is documented in Section 3 of MRP-117 [3].[3] The technical basis is supported by the MRP-110 [4] top-level safety assessment report, and the lower-level safety assessments that it references including the MRP-105 [6] probabilistic assessment.

The probabilistic fracture mechanics (PFM) analyses of MRP-105 [6] using a Monte Carlo simulation algorithm were performed to determine a probability of failure versus time for PWR vessel top heads for a set of input parameters, including operating temperature, inspection types (visual or volumetric NDE), and inspection intervals. Input into this algorithm included an experience-based time-to-leakage correlation based on a Weibull model of plant inspections, fracture mechanics analyses of various nozzle configurations containing axial and circumferential cracks, and the MRP-developed statistical crack growth rate model for Alloy 600 (MRP-55 [7]). The parameters used in the analysis were calibrated using the set of reported circumferential cracks located in the nozzle wall above or near the top of the J-groove weld in U.S. plants. The analyses concentrated on U.S. plant experience because of significant nozzle design and materials differences for the heads in U.S. plants versus heads in some other countries. Analysis results were in agreement with experience to that time (2004), including distinctly lower cracking and leakage likelihoods associated with cold heads.

Since the time of the MRP-105 [6] analysis, indications of PWSCC have been identified in Alloy 600 CRDM nozzles in five domestic PWR cold heads. Since the technical basis was developed in part based upon plant experience with PWSCC, and since the PWSCC experience has recently extended to cold heads in the U.S. fleet, it is appropriate to assess the implications of this new experience on the technical basis.

1.2 Objective

The objective of this report is to update the technical basis for the ASME Code Case N-729-1 [1] inspection requirements for reactor vessel top heads, including those operating at reactor cold-leg

[2] In addition, an IWA-2212 VT-2 visual examination (per Section XI of the ASME Boiler & Pressure Vessel Code) of the head must be performed under the insulation through multiple access points during refueling outages that the bare metal visual examination is not performed.

[3] The inspection requirements for top head nozzles developed on the basis of the MRP-110 [4] safety assessment were published by EPRI/MRP in MRP-117 [3]. These requirements were intended to supersede the inspection requirements of NRC Order EA-03-009 [5], but instead MRP-110 and MRP-117 formed the technical basis for the inspection requirements of ASME Code Case N-729-1 [1], which replaced the NRC order as the current mandatory inspection requirements document (subject to certain NRC conditions as listed in 10 CFR 50.55a(g)(6)(ii)(D)).

temperature (T_{cold}), to include operating experience since the original 2004 technical basis work. The report evaluates the adequacy of the current inspection requirements, including the frequency of periodic volumetric or surface examinations for heads operating at T_{cold}, considering the recent cases of PWSCC reported at T_{cold}.

In addition, this report evaluates whether an interval of two 18-month fuel cycles is justified for heads operating at T_{cold} for which PWSCC has been previously detected. The original technical basis for the N-729-1 inspection requirements [3] concluded that a ceiling of two cycles was a conservative approach. The NRC conditions imposed on Code Case N-729-1 in 10 CFR 50.55a(g)(6)(ii)(D) modified the interval to be single fuel cycle in all cases if PWSCC has been previously detected.

1.3 Scope

This technical basis report is applicable to PWR reactor vessel top heads with Alloy 600 partial-penetration welded nozzles and Alloy 82/182 J-groove attachment welds. As of July 2014, there are 25 such original heads still in operation in the U.S. Twenty of the 25 operate at the reactor cold-leg temperature (T_{cold}) and are informally known as cold heads, and the other five heads operate at temperatures significantly above T_{cold} (i.e., non-cold heads). Plans have been publicly announced for replacement of two of the 25 heads with heads having PWSCC-resistant materials (one cold and one non-cold head).

1.4 Approach

Deterministic and probabilistic calculations are applied to assess the effect of the latest inspection experience, including indications detected in cold heads, on the Weibull crack initiation parameters applied in the original MRP-105 [6] technical basis document. The specific concern addressed is the extent to which the probability of crack initiation implied by the recent cold head experience is greater than that assumed in the MRP-105 [6] evaluation in 2004.

The deterministic calculations demonstrate that the interval for volumetric or surface examination is sufficient to detect any PWSCC before it could develop into a safety-significant circumferential flaw that approaches the large size necessary to produce a nozzle ejection. The deterministic calculations also demonstrate that any base metal PWSCC would likely be detected prior to a through-wall penetration occurring.

The probabilistic calculations are based on a Monte Carlo simulation model of the PWSCC process, including PWSCC initiation, PWSCC crack growth, and flaw detection via ultrasonic testing. The basic structure of the probabilistic model is derived from the model applied in MRP-335 Rev. 1 [8] to evaluate mitigation of PWSCC on CRDM nozzles by peening. The same basic model was also previously applied in MRP-375 [9] to evaluate the appropriate reexamination interval for top heads with Alloy 690 penetration nozzles. The current probabilistic model is similar in form to the original MRP-105 [6] model, but includes refinements in several areas such as with regard to modeling of part-depth crack growth. The outputs of the probabilistic model are leakage frequency (i.e., frequency of through-wall cracking) and nozzle ejection frequency. Using inputs including the recent industry experience, the probabilistic results show:

- An acceptably low risk of nozzle ejection (below 5E-5 ejections per year per reactor vessel head, averaged across the operating lifetime) when using a UT inspection interval in accordance with the RIY = 2.25 requirement of ASME Code Case N-729-1 [1]. This low risk of nozzle ejection is demonstrated even though the frequency of UT examination remains in accordance with the RIY = 2.25 requirement for heads with detected PWSCC, instead of the increased frequencies specified by ASME Code Case N-729-1 and as conditioned by 10 CFR 50.55a(g)(6)(ii)(D).
- Suitably low average penetration leakage frequencies due to cracks initiating in the nozzle tube base metal material, below 0.05 new leaking penetrations per year for all the cases evaluated.

1.5 Report Structure

This technical basis report is organized as follows:

1. INTRODUCTION (SECTION 1)

   Section 1 introduces the need for a reevaluation of the technical basis for the re-examination interval for PWR reactor vessel top heads with Alloy 600 nozzles. Included are the objective of this report, an outline of the approach used, and a description of how this report is organized.

2. PWSCC EXPERIENCE FOR ALLOY 600 TOP HEAD NOZZLES (SECTION 2)

   Section 2 presents an overview of the updated Weibull initiation model. Also included are comparisons of ranges of relative crack growth rates inferred from the inspection results against the crack growth rate inputs to the probabilistic analyses and an overall assessment of the effectiveness of the current inspection requirements in detecting any PWSCC in a timely fashion.

3. DETERMINISTIC CRACK GROWTH ANALYSIS (SECTION 3)

   Section 3 is provided as a precursor to probabilistic evaluation presented in Section 4 and to illustrate directly the continued conservatism of the N-729-1 inspection intervals for top heads with Alloy 600 nozzles operating at T_{cold}. This chapter includes an explanation of the evaluation approach, a presentation of key results, and a statement of the conclusions drawn from these results.

4. PROBABILISTIC MONTE CARLO SIMULATION ANALYSIS (SECTION 4)

   Section 4 provides an overview of the probabilistic evaluations of the effect of inspection intervals on risks related to PWSCC degradation of heads with Alloy 600 nozzles using inputs reflecting industry experience. This overview includes an explanation of the evaluation approach, a presentation of key results, and a statement of the conclusions drawn from these results.

5. ASSESSMENT OF CONCERN FOR BORIC ACID CORROSION (SECTION 5)

   Section 5 assesses the concern for boric acid corrosion of the low-alloy steel head material due to primary coolant leakage at a through-wall PWSCC flaw. It is concluded that the current requirements for periodic visual examinations for evidence of pressure boundary leakage (per ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D)) remain valid to address the concern.

6. CONCLUSIONS (SECTION 6)

   Section 6 presents the conclusions of this technical basis report. It is concluded on the basis of plant experience and the deterministic and probabilistic analyses that the current inspection requirements of ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D) are still sufficient to address the PWSCC concern. In particular, the Re-Inspection Year (RIY) = 2.25 interval for periodic volumetric or surface examination remains valid for all heads without previously detected PWSCC, including heads that operate at reactor cold-leg temperature (T_{cold}).

   In addition, a volumetric or surface reexamination interval of two fuel cycles for heads with previously detected PWSCC that operate at T_{cold} would provide a sufficient level of conservatism. The current requirement for a volumetric or surface reexamination interval of every fuel cycle for a head with previously detected PWSCC regardless of head operating temperature is overly conservative for the case of heads operating at T_{cold}. The detailed probabilistic analyses presented in this study support use of the RIY = 2.25 interval (i.e., an interval of four or five 18-month cycles for heads operating at T_{cold}) regardless of whether PWSCC has been previously detected. Reducing the interval to two 18-month cycles in the case of previously detected PWSCC in a head operating at T_{cold} represents a substantial conservatism.

7. REFERENCES (SECTION 7)

   Section 7 provides a comprehensive list of references cited in this report.

A. UPDATE OF WEIBULL STATISTICAL ASSESSMENT OF U.S. ALLOY 600 CRDM/CEDM NOZZLE INSPECTION EXPERIENCE (APPENDIX A)

   Appendix A describes the detailed results of a 2014 update to the Weibull statistical analysis originally performed as part of the original MRP-105 [6] technical basis. The Weibull assessment indicates the likelihood of crack initiation occurring as a function of operating time and head operating temperature.

2 PWSCC EXPERIENCE FOR ALLOY 600 TOP HEAD NOZZLES

2.1 Updated Industry Weibull

In support of this assessment, as documented in Appendix A, the MRP Weibull statistical assessment of U.S. top head inspection experience was revised to reflect experience through fall 2013, including the four cases of apparent PWSCC detected at cold head plants in 2011 [10], 2012 ([11], [12]), and 2013 [13]. Weibull fits to the latest set of compiled plant experience are applied in Section 4 to develop crack initiation inputs for the probabilistic modeling.

Two different Weibull fits to the U.S. plant experience for Alloy 600 top heads were developed in Appendix A:

- Table 2-1 summarizes the fit parameters for the various cases investigated.
- Figure 2-1 shows the Weibull fit applied in the MRP-105 [6] study based on plant experience prior to its publishing in 2004. Also shown are the Weibull lines for the bounding values of characteristic time assumed in MRP-105. For each Monte Carlo trial in the MRP-105 probabilistic assessment, a Weibull distribution is applied lying between the bounding lines shown in this figure. In particular these inputs are applied in MRP-105 for the four case studies defined in its Table 8-9, including Case IV for an example cold head. The Weibull slope parameter, which describes the degree of scatter in the time to cracking, applied in these case studies of MRP-105 is 3. At the time MRP-105 was completed in 2004, it was judged that there were insufficient data to determine a best-fit slope value using the top head plant experience available at that time. Instead the typical slope value of 3 for Alloy 600 steam generator tube PWSCC was selected.
- The Weibull fit to top head experience from the 2014 update (Appendix A) for all nozzle materials is shown in Figure 2-2. Like Figure 2-1, this plot reflects the operating time until detectable PWSCC is produced in at least one of the nozzles in a head. Both part-depth cracks and through-wall (i.e., leaking) cracks are included in the basis for this Weibull fit. However, a best-fit slope is fitted to the top head data to model the scatter among different heads. It was judged that with the additional data since 2004, especially the PWSCC experience for the cold heads, it was appropriate to use a fitted slope rather than a standard value of 3. Assuming normally distributed data scatter, the 5% and 95% confidence bounds were calculated on the basis of θ values 1.65 standard deviations from the mean θ for the fit to the linearized Weibull equation.

  The fitted slope of 1.38 results in a somewhat higher probability of cracking for relatively small cumulative EDY values as discussed below. The slope of 1.38 represents a greater relative degree in scatter in time to crack initiation than the previously assumed slope of 3, and is a consequence of the range of nozzle material processing practices and head fabrication practices applied across the U.S. fleet.

- As discussed in Appendix A, nozzles fabricated using Alloy 600 material supplied by B&W Tubular Products (B&WTP) have shown the highest relative incidence of PWSCC. The Weibull fit to top head experience from the 2014 update for only this subset of plants is shown in Figure 2-3. As with Figure 2-2, this plot is based on data for both part-depth cracks and through-wall (i.e., leaking) cracks, and shows a best-fit slope is fitted to the top head data to model the scatter among different heads. The slope of 1.17 indicates a relatively wide range of PWSCC susceptibility for the heads with nozzles fabricated using material supplied by B&WTP. This variation in susceptibility likely reflects the substantial differences in the susceptibility of different material heats supplied by B&WTP.

Figure 2-4 shows how the Weibull fits developed for the cracking data per the 2014 analysis compare to the Weibull fit developed in 2004 for application to the MRP-105 [6] case studies. In Figure 2-4, it is seen that:

- *All nozzle materials*. For cumulative EDY values greater than ~11 the new fit predicts a reduced mean probability of cracking compared to that predicted by the MRP-105 fit, but for cumulative EDY values less than ~11 the opposite is the case.

  It is instructive to consider Figure 2-4 in terms of the current cumulative EDY values for each of the 25 Alloy 600 heads in service in the U.S.:

  – It is estimated that the 20 operating cold heads currently (January 2014) have a range of cumulative EDY values between 2.5 and 4.5, with a median of 3.8. For this range of EDY values, the 2014 Weibull fit results in a probability of crack initiation that is between 4 and 10 times higher than the corresponding probability for the 2004 Weibull fit, with a median ratio of 5. The estimated range of EDY values at the end of a 60-year operating period for each of the cold heads is between 5 and 11.

  – All five of the Alloy 600 non-cold heads still operating are estimated to currently have significantly more than EDY = 11.

- *B&WTP nozzle materials*. For cumulative EDY values greater than ~19 the new fit predicts a reduced mean probability of cracking compared to that predicted by the MRP-105 fit, but for cumulative EDY values less than ~19 the opposite is the case.

  The fit to data for only nozzles with B&WTP materials predicts a higher probability of cracking than the fit to data for all nozzle materials for the entire range of the distribution.

Table 2-1
Summary of Weibull Distribution Fit Parameters

Weibull Fit Case			No. Heads in Weibull Fit (with volumetric or bare metal visual exam)	No. Heads with Cracks or Leaks	Weibull Slope β		Weibull Characteristic Time Θ
Analysis Date	Failure Considered to be Crack or Leak	Material Types Considered			Description	Value	
MRP-105 (Spring 2003)[1]	Cracks (incl. leaks)	All	30	14	Assumed	3	15.2
2014[1,2]	Cracks (incl. leaks)	All	63	23	Fit	1.38	23.0
2014[1,2]	Cracks (incl. leaks)	B&WTP	16	14	Fit	1.17	11.0

Notes:
(1) It is assumed for these cases that the head temperature for each head is as reported in MRP-48, with the exception that for the 2014 cases the temperature for both the Plant BL/V original and first replacement heads were revised to reflect plant input. See Appendix A for details of the compiled data on a coded plant basis.
(2) It is assumed for these cases that the head temperature for each B&W plant head is 8°F higher than the hot leg temperature.

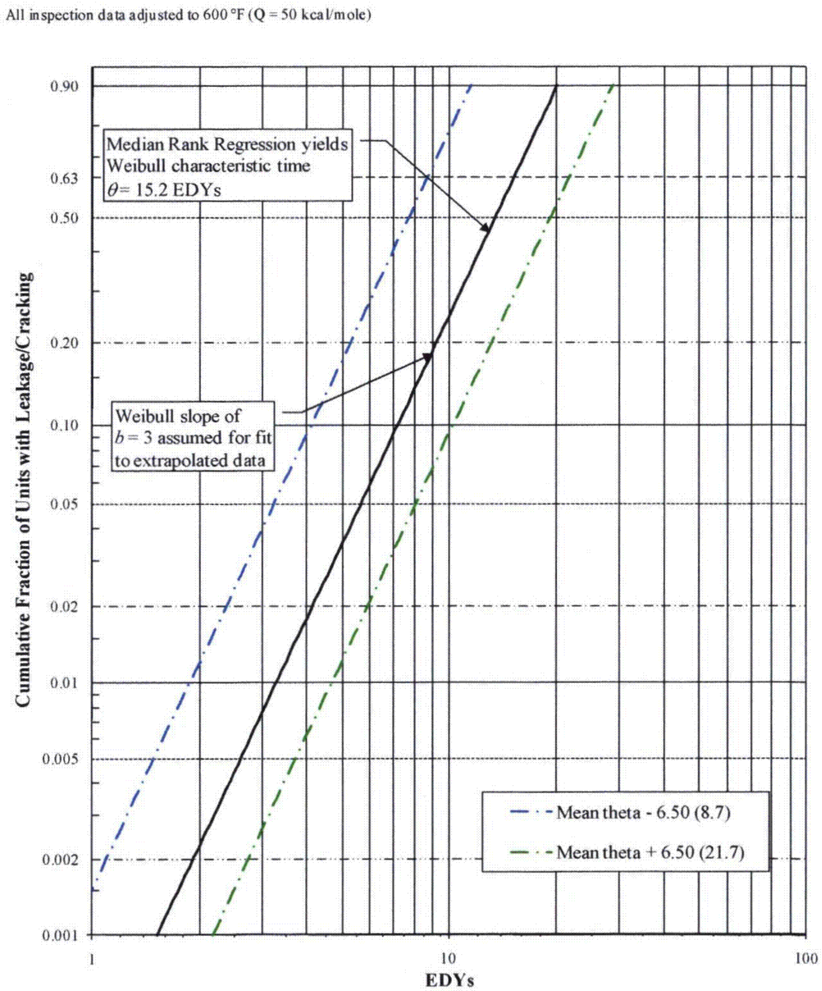

Figure 2-1
MRP-105 Case Study IV Assumed Fit with Uncertainty Bounds

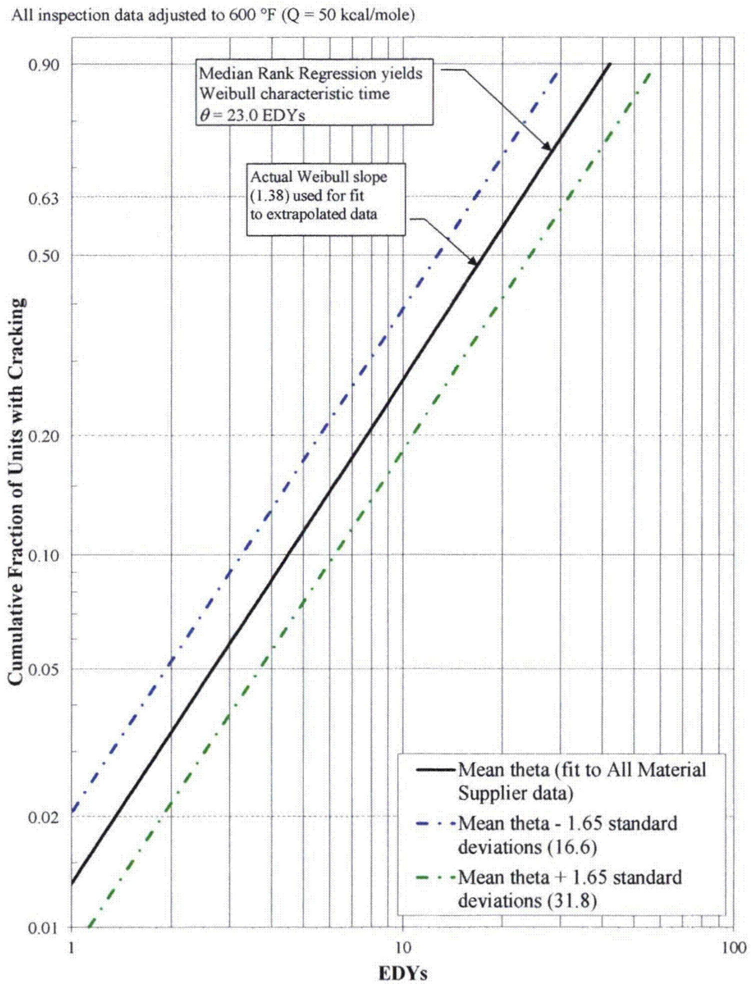

Figure 2-2
2014 Update NDE Best-Estimate Fit with Uncertainty Bounds – All Materials, New Temperatures (+8°F for all B&W Heads)

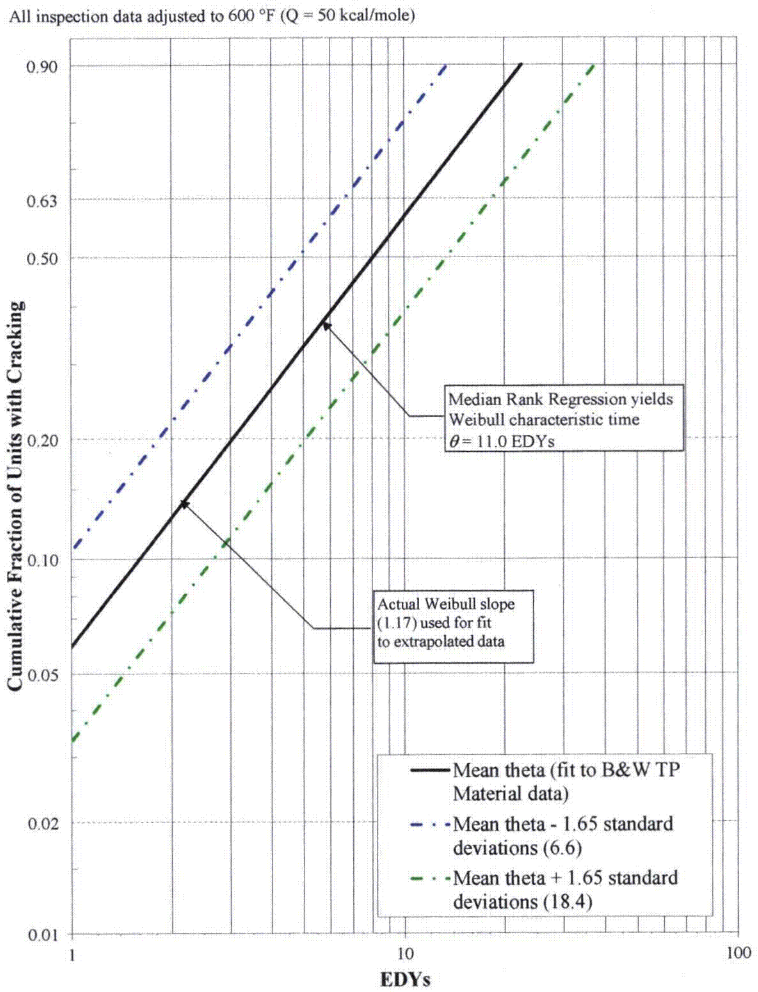

Figure 2-3
2014 Update NDE Best-Estimate Fit with Uncertainty Bounds – B&WTP Materials, New Temperatures (+8°F for all B&W Heads)

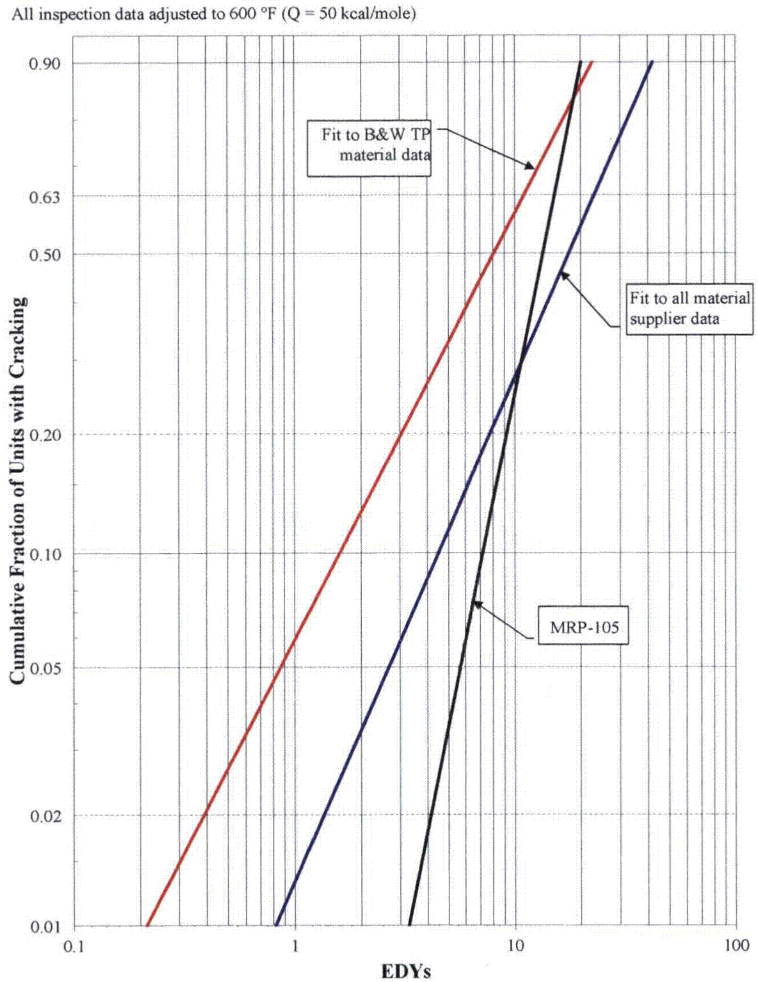

Figure 2-4
Comparison of MRP-105 Case Study IV Fit with 2014 Update NDE Fits

2.2 Implied Crack Growth Rates

Laboratory testing is the principal technique applied to determine relative crack growth rates for Alloy 600 wrought material and Alloy 82/182 weld metal material. The relative crack growth rate corresponds to the resistance of the material to PWSCC crack extension, and is calculated as the observed crack growth rate normalized for the effects of temperature and crack-tip stress intensity factor. Laboratory testing has the advantage of using simplified specimen geometries and loading that facilitate accurate calculation of crack-tip loading conditions, i.e., stress intensity factor. Using an extensive set of worldwide laboratory test data, the MRP-55 [7] crack growth rate study developed a log-normal distribution that describes the variability in crack growth rate due to the variability in material PWSCC resistance for Alloy 600 wrought material.

However, plant experience is a source of data that can in some cases be used to make estimates of the relative crack growth rate for comparison with statistical assessments of the laboratory crack growth rate data. As discussed below, the plant PWSCC experience for reactor vessel top head nozzles was assessed for cases in which meaningful crack growth rate information could be developed. In some cases, ranges of relative crack growth rates could be inferred from the inspection results for comparison with the material variability in crack growth rate exhibited by the MRP-55 [7] database of laboratory data. The MRP-55 [7] distribution of material variability in crack growth rate was applied in the original MRP-105 [6] technical basis calculations, as well as in the current probabilistic calculations documented in Section 4.

2.2.1 Cold Head Experience

There have been a few cases of apparent PWSCC detected in cold top heads in the U.S., all in CRDM nozzles fabricated from B&W Tubular Products (B&WTP) material:

- *2007 Cold Head Experience.* The first case of apparent PWSCC detected at a cold head was for the first in-service volumetric or surface examination at this plant in 2007 ([14], [15]) and was associated with a weld fabrication flaw. As such, this case was not a good candidate for assessment per the techniques described in the next bullet.
- *2011 Cold Head Experience.* The second cold head case was for the second in-service volumetric or surface examination at another plant in 2011 ([10], [16]). After an inspection interval of four cycles or approximately 6 calendar years, indications of PWSCC were detected in four CRDM nozzles, which were subsequently repaired during the same outage. Given the head temperature of 557°F [17] applicable to the period between the two examinations performed, the RIY value for this interval is estimated to be 1.86.

  Crack growth calculations were performed specific to each of the five indications in the four nozzles that were reported as service-related in 2011. All five indications were reported to be connected to the nozzle tube OD, with four being primarily axial in orientation and one primarily circumferential. In each crack growth calculation, the flaw was modeled as growing with a constant length-to-depth aspect ratio based on the flaw length and depth reported for the 2011 examination. Based on a comparison of the ultrasonic examination data collected in 2005 and 2011, flaw growth increments in the depth direction in the range from 0.083 to 0.097 inch were reported for each of the five indications [16]. In the crack growth calculation, a uniform hoop stress of variable magnitude is assumed to drive the crack growth, with the stress intensity factor solution by Marie et al. [18] applied for the case of an axial or circumferential semi-elliptical flaw on the outside surface of a pipe, as applicable.

Multiple cases were considered in the crack growth calculations to determine combinations of the driving stress value and relative crack growth rate (i.e., percentile of the MRP-55 uncertainty distribution) that result in the reported extension in crack depth for each reported flaw. Driving stresses in the range from 18 to 42 ksi were found to result in the observed extensions in crack depth if a crack growth rate percentile in the range from the 75th to 95th percentile is assumed. This stress range is consistent with the hoop stress results published for the nozzle tube wall below the weld by two organizations ([19], [20]) using FEA weld residual stress analysis techniques applied to example CRDM nozzle cases. Furthermore, this range of crack growth rate percentiles is consistent with the assumptions of the MRP-105 [6] and Section 4 probabilistic models. The MRP-105 model samples crack growth rate values according to a log-triangular distribution that reaches about the 99th percentile of the MRP-55 log-normal distribution. In addition, the MRP-105 model applies a "local crack growth rate variability" term that can result in crack growth rates up to about 5 times higher than the value sampled from the log-triangular distribution describing the relative crack growth rate (i.e., the power-law constant in MRP-105). Moreover the case studies of MRP-105 assume that the relative crack growth rate (i.e., power-law constant) is perfectly negatively correlated with the sampled time to crack initiation. Thus, there is a large bias in which the flaws that are simulated to initiate at relatively small EDY values are assumed to have high relative crack growth rates. Similarly, the refined probabilistic simulation model presented in Section 4 applies a truncated log-normal distribution similar to the log-triangular distribution applied in MRP-105. The probabilistic model in Section 4 includes sampling of relative crack growth rate values greater than the maximum relative crack growth rate reported for any laboratory data point, for both the case of Alloy 600 base metal per MRP-55 [7] and Alloy 182 weld metal per MRP-115 [21]. In addition, similar to the case for the MRP-105 probabilistic model, a probabilistic sensitivity case is presented in Section 4 for which the sampled time to crack initiation is negatively correlated with the sampled crack growth rate (Sensitivity Case M4 discussed in Section 4.3.2).

Hence, it is concluded that the extensions in crack depth reported for this cold head experience are consistent with the probabilistic crack growth rate inputs developed on the basis of the MRP-55 [7] assessment of laboratory crack growth rate data and used in both the MRP-105 [6] and Section 4 probabilistic assessments.

- *First 2012 Cold Head Experience.* The third cold head case was for the second in-service examination at a plant in 2012 [11]. After an inspection interval of four cycles or approximately 6 calendar years, one indication of PWSCC was detected in a single CRDM nozzle, which was subsequently repaired during the same outage. Given the head temperature of 556°F [22] applicable to the period between the two examinations performed, the RIY value for this interval is estimated to be 1.79.

  A crack growth calculation was performed for the indication that was reported as service-related in 2012. The indication was reported to be connected to the nozzle tube OD and primarily axial in orientation. As in the analysis of the 2011 cold head experience, the flaw was modeled as growing with a constant length-to-depth aspect ratio based on the flaw length and depth reported for the 2012 examination and a uniform hoop stress is assumed to drive crack growth. The flaw size during the prior examination is assumed to correspond to the typical limit of flaw detectability (15%). Driving stresses in the range from 29 to 48 ksi were found to result in the assumed extensions in crack depth if a crack growth rate percentile in the range from the 75th to 95th percentile is assumed and is consistent with the residual stress results mentioned in the 2011 experience. For assumed stresses of 25 and 60 ksi, the crack growth rate percentiles are the 98th and 62nd, respectively.

- *Second 2012 Cold Head Experience.* The fourth cold head case was for the second in-service examination at another plant in 2012 [12]. After an inspection interval of four cycles or approximately 6 calendar years, ten indications of PWSCC were detected in four CRDM nozzles, which were subsequently repaired during the same outage. Given the head temperature of 557°F [22] applicable to the period between the two examinations performed, the RIY value for this interval is estimated to be 1.90.

  A crack growth calculation was performed for the indication that had the largest reported depth in 2012. The indication was reported to be connected to the nozzle tube OD and primarily axial in orientation. As in the prior cold head analyses, the flaw was modeled as growing with a constant length-to-depth aspect ratio based on the flaw length and depth reported for the 2012 examination and a uniform hoop stress is assumed to drive crack growth. The flaw size during the prior examination is assumed to correspond to the typical limit of flaw detectability (15%). Driving stresses in the range from 41 to 72 ksi were found to result in the observed extensions in crack depth if a crack growth rate percentile in the range from the 75th to 95th percentile is assumed and is consistent with the residual stress results mentioned in the 2011 experience. For assumed stresses of 50 and 80 ksi, the crack growth rate percentiles are the 90th and 70th, respectively.

- *2012/2013 Cold Head Experience.* Five nozzles were detected with PWSCC indications at another plant during the second in-service examination in 2012 [23]. After another cycle of operation (1.38 EFPYs), one indication of PWSCC was detected in another CRDM nozzle, which was subsequently repaired during the same outage [13]. The nominal head temperature for this cycle was 557°F [24].

  A crack growth calculation was performed for the indication that was reported as service-related in 2013 after one cycle of operation from the previous inspection. The indication was reported to be primarily axial in orientation and to have a depth of 21% of the wall thickness from the nozzle OD [13], or about 0.13 inch. As in the prior cold head analyses, the flaw was modeled as growing with a constant length-to-depth aspect ratio based on the flaw length and depth reported for the 2013 examination and a uniform hoop stress is assumed to drive crack growth. The flaw size during the prior examination was taken as 0.057 inches, which is slightly below the typical range for flaw detectability.

  Considering the reported yield strength and incidence angle for the affected nozzle (#37), a total operating hoop stress (including weld residual stress) of about 70 ksi is estimated at the crack location for this CBI design head. This relatively high stress reflects an unusually large weld cross section at the downhill position for this head design. The crack location is an especially high hoop stress location.

  With the 70 ksi stress, an 89th percentile crack growth rate was calculated per the MRP-55 distribution for Alloy 600. This is above the 75th percentile that defines the deterministic CGR equation in MRP-55 and Appendices C and O of Section XI, but below the 95th percentile that was reported by ANL for CRDM nozzle material also supplied by B&WTP

for another plant [25]. If the flaw had been left in service for an additional fuel cycle (i.e., an interval of two cycles between inspections), the crack growth calculation predicts that the flaw would have been found extending to a depth of 45% of the wall thickness from the OD.

In summary, the amount of crack growth observed in this case was within the range expected and consistent with the distribution of crack growth rate variability assumed in probabilistic modeling.

- *2014 Cold Head Experience.* Five nozzles with detected PWSCC indications were repaired at a plant during the third in-service examination in 2014 ([26] and [27]). The second in-service examination at this plant was performed about 1.3 EFPY prior, in 2012. Given the head temperature of 557°F [22], the RIY value for this interval is estimated to be 0.43.

  A crack growth calculation was performed for the indication which grew the deepest from the provided depth in 2012. The indication was reported to be connected to the nozzle tube OD and primarily axial in orientation. As in the prior cold head analyses, the flaw was modeled as growing with a constant length-to-depth aspect ratio as reported in the 2014 examination, and a uniform hoop stress is assumed to drive crack growth. Based on a comparison of the ultrasonic examination data collected in 2012 and 2014, a flaw growth increment in the depth direction of 0.06 inch appears most likely. For assumed driving stresses of 50 and 80 ksi, the apparent crack growth rate percentiles of material variability are the 97^{th} and 87^{th}, respectively. As discussed above, residual stresses of this magnitude are consistent with the elevated hoop stresses in the region of the J-groove weld toe on the downhill side of the penetration. If this flaw were permitted to grow for an additional cycle prior to inspection (i.e., for a two-cycle interval instead of a single-cycle interval), the crack growth calculation predicts that the final flaw would be modestly larger than that detected in 2014. The final flaw would extend about 43% through the wall thickness from the nozzle OD, and the axial length would extend up through a relatively small fraction of the weld height such that the flaw would be far from causing leakage through the nozzle tube to the nozzle annulus.

  A second crack growth calculation was performed for the indication that had the largest reported depth in 2014. The indication was reported to be connected to the nozzle tube OD and primarily axial in orientation. The flaw was modeled as growing with a constant length-to-depth aspect ratio as reported in the 2014 examination, and a uniform hoop stress is assumed to drive crack growth. Based on a comparison of the ultrasonic examination data collected in 2006 and 2014, a flaw growth increment in the depth direction of 0.16 inch appears most likely. The estimate 6.6 EFPYs between the 2006 and 2014 examinations corresponds to RIY = 2.2. Driving stresses in the range from 26 to 43 ksi were found to result in the observed extensions in crack depth if a crack growth rate percentile in the range from the 75^{th} to 95^{th} percentile is assumed and is consistent with the residual stress results mentioned above in the 2011 experience for another cold head. For assumed stresses of 30 and 60 ksi, the crack growth rate percentiles are the 91^{th} and 57^{th}, respectively. If the flaw had been left in service for an additional cycle (i.e., for a two-cycle interval instead of a single-cycle interval), the crack growth calculation predicts that the flaw would have been found with a modestly greater depth of 58%. As the detected flaw in 2014 was indicated to have only extended a small distance into the weld, a significant distance would remain between the upper crack tip and the nozzle annulus above the triple point and no leak would have resulted.

The apparent amount of crack growth observed in these cases was within the range expected and consistent with the modeling performed later in this report. Based on the estimated stress levels, some of the reported flaws grew at growth rates corresponding to the upper portion of the MRP-55 [7] distribution of material variability for Alloy 600. As discussed in Section 4.3.2.1, the probabilistic modeling addresses the possibility of heads with nozzle material with relatively high susceptibility to PWSCC growth through negative correlation of the crack growth rate heat/weld factor and the time to crack initiation.

2.2.2 Non-Cold Head Experience

Through a detailed review of the non-cold head experience to date, five cases were identified as candidates for providing meaningful information on relative crack growth rates. Generally, meaningful crack growth rate information cannot be derived from cases in which the flaw was detected during the first NDE of the affected nozzle because of the lack of constraint on the crack initiation time. The five cases are discussed in the following:

- *1994-96 Non-Cold Head Experience.* In 1994, indications of PWSCC were detected on the inside surface of CRDM Nozzle #75 at this plant. These indications were re-examined in 1996, when the nozzle was weld repaired. The results of a crack growth rate assessment were presented in MRP-55 [7]. As shown in Figure 5-2 of MRP-55, the crack growth rates implied by the extension in length and depth of the deepest crack in this nozzle are significantly below that predicted by the MRP-55 equation, which corresponds to the 75th percentile of the crack growth rate uncertainty distribution per MRP-55.
- *2002-03 Non-Cold Head Experience.* In 2002, PWSCC was detected in three CRDM nozzles at a second non-cold head plant [28]. During the subsequent refueling outage in 2003, PWSCC was detected in an additional 11 nozzles [29]. Detailed data were not collected for this case, which reflects examinations performed prior to improvements made in CRDM nozzle inspection technology. Thus this effort to deduce relative crack growth rates from plant data concentrated on more recent cases.
- *2005 Non-Cold Head Experience.* In 2005, three CRDM nozzles were identified with possible indications of PWSCC at a third non-cold head plant [30]. These nozzles were previously examined in 2003 without PWSCC being reported. However, the flaws detected in 2005 were relatively shallow, with the maximum depth being 0.143 inch, or 22% through-wall per the nozzle tube wall thickness [22]. This maximum flaw depth is slightly greater than the typical flaw depth detectability limit of 10-15% through-wall expected for CRDM nozzle tubes examined by ultrasonic testing. Thus this experience is consistent with the crack growth rate assumptions of the probabilistic models of MRP-105 [6] and Section 4.
- *2009 Non-Cold Head Experience.* In fall 2009, a total of two indications reported to be service-related were detected in two CRDM nozzles at another non-cold head plant ([31], [32]). Each of the two indications detected in 2009 was circumferential in orientation and located on the nozzle tube OD below the weld. The RIY increment for each fuel cycle for this head is estimated to be 1.42 based on the head temperature of 601.3°F [33].

  In the same manner as for the cold head experience, a simplified crack growth calculation was performed for each of these two flaws. In this case the stress intensity factor solution per Marie et al. [18] was applied for the case of a circumferential semi-elliptical flaw on the outside surface of a pipe. In each crack growth calculation, the flaw was modeled as growing with a constant length-to-depth aspect ratio based on the flaw length and depth reported for the 2009 examination. Based on a comparison of the ultrasonic examination data collected in 2009 and during the previous two refueling outages, flaw growth increments in the depth direction of 0.053 and 0.093 inch were reported for the two indications [32]. The 0.093-inch increment corresponded to one cycle of growth, and the 0.053-inch increment corresponded to two cycles of growth.

Again, multiple cases were considered in the crack growth calculations to determine combinations of the driving stress value and relative crack growth rate (i.e., percentile of the MRP-55 uncertainty distribution) that result in the reported extension in crack depth for each reported flaw. For the flaw that showed an increment of 0.093 inch, a driving stress in the range from 32 to 52 ksi was found to result in the observed extension in crack depth if a crack growth rate percentile in the range from the 75th to 95th percentile is assumed. For the flaw that showed an increment of 0.053 inch, a driving stress in the range from 16 to 20 ksi was found to result in the observed extension in crack depth if a crack growth rate percentile in the range from the 75th to 95th percentile is assumed.

These stress ranges are consistent with the hoop stress results published for the nozzle tube wall below the weld by two organizations ([19], [20]) using FEA weld residual stress analysis techniques applied to example CRDM nozzle cases. Furthermore, the assumed range of crack growth rate percentiles is consistent with the assumptions of the MRP-105 and Section 4 probabilistic models. Hence, it is concluded that the extensions in crack depth reported for this case are consistent with the probabilistic crack growth rate inputs developed on the basis of the MRP-55 [7] assessment of laboratory crack growth rate data and used in the MRP-105 [6] and Section 4 probabilistic assessments.

- *2010 Non-Cold Head Experience.* As described in Appendix A, in 2010 after about 6 calendar years of operation, PWSCC including indications of pressure boundary leakage was detected in a first replacement head having Alloy 600 CRDM nozzles [34]. As part of its response, the utility sponsored detailed crack growth calculations including FEA stress calculations specific to the replacement head. The results of this work are discussed in the NRC Special Inspection report [35]. Considering that less than the 6 calendar years of operation were available for crack growth, the detailed calculations indicated that the flaw growth was consistent with relative growth rates in the range between the 75th and 95th percentiles of the MRP-55 uncertainty distribution.

  It is also noted that under sponsorship of NRC, ANL has performed laboratory PWSCC crack growth rate testing of Alloy 600 CRDM nozzle tube material removed from the original head at this plant at the time it was retired ([25], [36]). The ANL study concluded that the crack growth rates approximately corresponded to the 95th percentile of the MRP-55 uncertainty distribution. The nozzle material for the original and first replacement heads at this plant, as well as for the 2011 cold head experience cited above, was produced by the same material supplier. Material produced by this supplier also tended to show relatively high crack growth rates in the data compiled in the MRP-55 [7] study in comparison to other suppliers for heads installed in U.S. plants. As discussed above, the MRP-105 [6] and Section 4 probabilistic assessments includes cases with significant bias in which the nozzles that are predicted to crack at relatively small EDY values are assumed to have high relative crack growth rates.

2.2.3 Effect on Technical Basis

Plant inspection experience for both cold heads and heads operating at temperatures significantly above T_{cold} (i.e., non-cold heads) was assessed with regard to implied relative crack growth rates. The first case of apparent PWSCC detected at a cold head was for the first in-service volumetric or surface examination and was associated with a weld fabrication flaw. As such this case was not a good candidate for assessment. The crack growth rates implied by the ultrasonic examination data for the other cold head cases are consistent with the probabilistic crack growth rate inputs developed on the basis of the MRP-55 [7] assessment of laboratory crack growth rate data and used in the original MRP-105 [6] probabilistic assessment, as well as the current probabilistic assessment documented in Section 4. Furthermore, the cases in which relative crack growth rates could reasonably be inferred for non-cold heads were also consistent with the crack growth rate inputs of the probabilistic assessments. Hence, the crack growth rate assumptions of the technical basis for the N-729-1 [1] inspection requirements remain valid in light of the CRDM nozzle inspection experience.

2.3 Effectiveness of Current Inspection Requirements

As part of the top head safety assessment published in 2004 [4], a detailed assessment was made of top head plant inspection experience to that point in time, including tabulation of the numbers of nozzles affected by part-depth PWSCC and through-wall PWSCC (i.e., leakage). This plant experience assessment has been periodically updated by the MRP, and the latest such assessment is presented in Appendix A.

Over the period from 2002 to early 2008, a baseline volumetric or surface examination of all original heads with Alloy 600 nozzles was performed (with the exception of a small number of heads that were replaced prior to a baseline examination being required per the NRC Order [5] applicable at that time). The baseline examinations for cold heads were performed over the period from 2005 to early 2008. All Alloy 600 heads still in service are now in a program of periodic repeat volumetric or surface examinations, with the first repeat examinations in cold heads generally starting in 2011.

The findings of the top head examinations performed to date support the adequacy of the current inspection requirements, including the RIY = 2.25 interval for periodic volumetric or surface examinations:

- Since 2004, no circumferential PWSCC indications located near or above the top of the weld have been detected. These are the types of flaws that could produce a nozzle ejection were they to grow to a very large size.
- Since examinations capable of detecting flaws connected to the OD surface of the nozzle tube were first applied in the early 2000's, there have been no reports of top head nozzle leakage (i.e., through-wall cracking) occurring after the time that the first in-service volumetric or surface examination was performed of all CRDM or CEDM nozzles in a given head. The only incidence of nozzle leakage ([34], [35]) since 2004 was detected in 2010 during the first in-service inspection (after about 6 calendar years of operation) performed of a replacement Alloy 600 head from a cancelled plant. Thus, this initial examination experience is not directly relevant to the adequacy of the re-inspection interval requirement. No discernible corrosion was detected of the low-alloy steel head material during the bare-

metal visual examinations of this replacement Alloy 600 head. It is noted that in late 2011 this first replacement head was replaced with a head having PWSCC-resistant nozzles.

- The volumetric or surface examinations performed on cold heads and the repeat volumetric or surface examinations performed on non-cold heads have been effective in detecting the PWSCC degradation reported in its relatively early stages, with modest numbers of nozzles affected by part-depth cracking, often located below the weld, where the nozzle tube is inside (not directly a part of) the pressure boundary.
- Five of the 20 operating cold heads with Alloy 600 nozzles have shown indications of PWSCC. This cracking was part-depth, and for one of these five heads was associated with a weld fabrication defect. Hence, plant experience continues to show a very low probability of nozzle leakage for the cold heads given the examinations being performed.

It is emphasized that the lower incidence and extent of PWSCC in the cold heads is consistent with the relatively large sensitivity of the probability of PWSCC crack initiation to operating temperature ([4], [6]). Moreover, there is widespread acceptance among PWSCC researchers ([7], [21]) that changes in temperature at the crack location have a consistent and well characterized effect on the PWSCC crack growth rate, with a consensus value for the thermal activation energy describing this temperature dependence of 31 kcal/mole (130 kJ/mole). Thus, there is a relatively large benefit of operating near the cold leg temperature in reducing the PWSCC crack growth rate in comparison to heads operating at higher temperatures. The expected reduction factor for the PWSCC crack growth rate is between 4.0 and 2.8 for the range of cold leg temperatures at U.S. PWRs of about 547°F to 561°F versus a temperature of 600°F. These reduction factors result in substantially longer times for through-wall cracking to be produced, for circumferential flaws located above the weld to grow to a significant size, and for leaking cracks to grow larger and produce the leak rate magnitudes necessary for significant volumes of material loss to be produced via boric acid corrosion.

3 DETERMINISTIC CRACK GROWTH ANALYSIS

3.1 Approach

Deterministic crack growth evaluation can be applied to assess PWSCC risks for specific components and operating conditions. In general, such deterministic evaluation quantifies the time between a certain initial condition—a known or hypothetical flaw size—to some adverse condition—through-wall growth, a prescribed stability margin, etc.—under a set of assumptions. This time may inform options for inspection intervals, mitigation, and repair. Often, deterministic evaluations rely on conservative assumptions to allow margin for error.

A deterministic crack growth evaluation is provided in this section (as a precursor to probabilistic evaluation presented in Section 4) to illustrate directly the continued conservatism of the N-729-1 inspection intervals for top heads with Alloy 600 nozzles operating at T_{cold}. The evaluation also demonstrates the effectiveness of performing volumetric examinations every other refueling outage at T_{cold} plants that have previously experienced PWSCC. The deterministic evaluations rely on conservative crack growth rate predictions and the assumption of an existing flaw (which are replaced with best-estimate crack growth rates and a PWSCC initiation model for the probabilistic evaluation). The deterministic evaluations are therefore considered to provide a reasonable *lower bound* on the average time to adverse conditions, from which a *conservative* inspection interval may be recommended.

This evaluation draws upon existing crack growth calculations for Alloy 600/82/182 RPVHPNs. The following list describes each cited crack growth calculation and states key underlying conservatisms:

- **General:** The following conservatisms apply to all crack growth calculations presented in this section:
  - All calculations use a 75^{th} percentile crack growth rate curve derived from Alloy 600 data, as in MRP-55 [7].
  - For estimating crack stress intensity factors, all calculations assume residual stresses that are bounding of those predicted in the vicinity of the location of interest. There is no credit taken for a drop in residual stress as flaws grow in length away from stress concentrations.
  - Time to leakage evaluations for surface cracks start from a 10% TW (e.g., ~1 mm) crack. There is some likelihood of detecting cracks with UT or eddy current examination techniques before they reach this size.
  - Growth results for through-wall circumferential cracks along the J-groove weld are reported from 30° to 300°. Leakage is expected to manifest through cracks less than 30°

around the circumference, such that there is some likelihood of visually detecting cracks before they reach this size.

- Calculations are usually performed for uphill and downhill RPVHPN locations. Time for growth results are reported in this evaluation for the more conservative location in all cases.

- **MRP-105 Deterministic Calculations:** Section 6 of MRP-105 [6] provides deterministic crack growth analyses for the time to grow from 30° to 300° for through-wall circumferential flaws along the top edge of J-groove welds. Several conservatisms are applied including the use of stress intensity factors that bound those predicted across all penetration angles, for a given crack length, and a factor of two applied to all crack growth rates to account for environmental uncertainties.

  MRP-105 studies four distinct RPVHPN geometries, each the outermost penetration associated with one of four distinct reactor top head designs.

- **Examination Frequency Relief Request:** AM-2007-011 (Section 5.2 of Attachment 3 of the 10 CFR 50.55a Alternate Examination Frequency Relief Request for Byron 2) [37] provides time to leakage calculations for nozzle OD axial flaws, ID axial flaws, and OD circumferential flaws. Several conservatisms are applied including the assumption of constant aspect ratios for ID axial and OD circumferential flaws, i.e., growth is driven by crack depth growth calculations at the point of maximum residual stress, and the assumption that OD circumferential flaws are exposed to the reactor water environment.

  AM-2007-011 studies cracks present in nozzles with different penetration angles, each with different predicted residual stress fields. Results for time to leakage for the 42.8° penetration are reported in Table 3-1. These results are similar to or lower than those for other penetration angles investigated in the report.

- **Technical Basis for CRDM Inspection Interval:** Appendix B of R-3515-00-1-NP [38] provides calculations for the time to leakage for nozzle ID and OD axial flaws and the time to grow from 30° to 300° for through-wall circumferential flaws along the top edge of J-groove welds.

  R-3515-00-1 studies cracks present in nozzles with different penetration angles, each with different predicted residual stress fields. Results for growth times for the 27.1° penetration are reported in Table 3-1. These results are similar to or lower than those for other penetration angles investigated in the report.

- **Deterministic Calculations of this Report:** The deterministic calculations of this report are based on those described in Section 5-2 of MRP-335 [8]. This includes deterministic evaluation for the time to leakage for nozzle ID and OD axial flaws and the time to grow from 30° to 300° for through-wall circumferential flaws along the top edge of J-groove welds. Several conservatisms are applied including the use of stress intensity factors that bound those predicted across all penetration angles, for a given circumferential crack length; a zero stress intensity factor threshold for growth; and a factor of two applied to all circumferential crack growth rates to account for environmental uncertainties.

The assumed residual stress profile at each location is derived as an average of residual stress results across various different penetration angles. The average penetration angle in the underlying data set is roughly 20°.

Existing crack growth calculations for Alloy 600/82/182 RPVHPNs are selected and adjusted to be representative of RPVHPNs operating near the cold leg temperature.

- First, to allow consistent interpretation of the results, the initial and end conditions for each crack type are made uniform. Surface flaw results are estimated from an initial condition of 10% through-wall[4]. The end condition for ID axial and OD circumferential flaws is through-wall growth; the end condition for OD axial flaws is growth to the top (or heel) of the J-groove weld. Through-wall circumferential crack results are estimated from an initial condition of 30° around the nozzle to an end condition of 300° around the nozzle (suggestive of net section collapse risk).
- Then, to further allow consistent interpretation, all results are adjusted[5] to an operating temperature of 555°F, 563°F, and 605°F using the Arrhenius relationship with an activation energy of 130 kJ/mol. For Alloy 600 top heads, 555°F is the upper operating temperature limit for a volumetric inspection interval of five 18-month refueling cycles, 563°F is the upper limit for an interval of four 18-month cycles, and 605°F provides a comparison with a typical hot head (inspected every 24-month cycle).

3.2 Results

Results of deterministic evaluation are summarized in Table 3-1. As detailed in the previous subsection, these calculations compound various conservatisms and should thus be interpreted as reasonable lower bounds on the average time to adverse conditions on reactor vessel top heads, i.e., these times are not considered best estimates.

Table 3-1 shows the results of the deterministic evaluations adjusted to three possible operating temperatures. The conservative time between detectable flaw size (assumed to be 10% through-wall) and leakage varies between 8.4 and 17 EFPY at 555°F, between 6.7 and 14 EFPY at 563°F, and 2.3 and 4.7 EFPY at 605°F. The conservative time between detectable flaw size and leakage varies between RIY = 2.6 and 5.3 via the N-729-1 definition. This is consistent with the N-729-1 requirement of volumetric examination before RIY = 2.25. That is, even in the case of conservatively rapid flaw growth, a volumetric examination should occur and provide a high likelihood of detection prior to through-wall penetration.

The conservative time between evident leakage (assumed to result from a through-wall 30° circumferential flaw) and risk of net section collapse (assumed to result from a through-wall 300° circumferential flaw) varies between RIY = 8.3 and 22. Adjusted to specific temperatures, the time between leakage and risk of ejection varies between 27 and 72 EFPY at 555°F, 22 and 58 EFPY at 563°F, and 7.4 and 20 EFPY at 605°F. These results demonstrate that considerable time is anticipated for growth between evident leakage and risk of net section collapse.

[4] Most reports assumed an initial depth somewhat less than 10% through-wall; however, time to leakage from 10% through-wall could generally be estimated with depth versus time plots.

[5] In place of being able to reproduce results at different temperatures, adjustments to growth predictions are made simply by scaling time spans linearly by the appropriate Arrhenius factor. This is believed to be a reasonable approximation for the purposes of this deterministic evaluation.

Table 3-1
Summary of Deterministic Crack Growth Calculations

Crack Type	Case Name and Table Reference Number	Flaw Orientation and Location	Penetration Angle (°)	Initial Flaw Size	Initial Aspect Ratio	End Condition	Operating Temperature (°F)	Time for Growth from Initial to End Conditions (EFPY)	Time for Growth Adjusted to 555°F (EFPY)	Time for Growth Adjusted to 563°F (EFPY)	Time for Growth Adjusted to 605°F (EFPY)
Surface Crack	Examination Frequency Relief Request [1]	OD Circumferential Crack (Downhill)	42.8	~10%TW	6	100%TW	558	8.2	8.9	7.2	2.4
		ID Axial Crack (Uphill)	42.8	~10%TW	6	100%TW	558	7.7	8.4	6.7	2.3
		OD Axial Crack (Uphill)	42.8	~10%TW	2	to top of weld	558	9.4	10	8.2	2.8
	Inspection Interval Technical Basis [2]	ID Axial Crack (Downhill)	27.1	~10%TW	6	100%TW	599.7	2.8	9.0	7.3	2.5
		OD Axial Crack (Downhill)	27.1	~10%TW	2	to top of weld	599.7	5.1	16	13	4.5
	Deterministic Calculation of this Report	ID Axial Crack (Downhill)	~20	~10%TW	4.5	100%TW	600	5.3	17	14	4.7
		OD Axial Crack (Downhill)	~20	~10%TW	4.5	to top of weld	600	4.1	13	11	3.6
	Conservative Time Between Detectable Flaw and Leakage (Median of Cases)								**10**	**8.2**	**2.8**
Through-Wall Circumferential Crack	MRP-105 Deterministic Calculations [3]	Circumferential Crack along the J-groove Weld (Downhill)	38	30°	N/A	300°	600	22	72	58	20
			43.5	30°	N/A	300°	600	11	35	28	9.5
			48.8	30°	N/A	300°	600	9.3	30	24	8.2
			49.7	30°	N/A	300°	600	19	61	49	17
	Inspection Interval Technical Basis [2]		27.1	30°	N/A	300°	599.7	8.4	27	22	7.4
	Deterministic Calculation of this Report		~20	30°	N/A	300°	600	14	44	35	12
	Conservative Time Between Leakage and Stability Risks (Median of Cases)								**39**	**32**	**11**

[1] *Byron Unit 2 - Technical Basis for Reactor Pressure Vessel Head Inspection Relaxation*, AM-2007-011 Revision 1, Exelon Nuclear, 2007.
[2] *Technical Basis for RPV Head CRDM Nozzle Inspection Interval - H. B. Robinson Steam Electric Plant, Unit No. 2*, R-3515-001-NP, Dominion Engineering, Inc., 2003.
[3] *Materials Reliability Program: Probabilistic Fracture Mechanics Analysis of PWR Reactor Vessel Top Head Nozzle Cracking (MRP 105)*, EPRI, Palo Alto, CA: 2004. 1007834.

3.3 Conclusions

The following conclusions are drawn from the results of the deterministic evaluation:

- The current N-729-1 volumetric examination interval (i.e., RIY = 2.25) for RPVH without previous PWSCC detection is adequate to provide sufficient opportunity for flaw detection prior to significant leakage or ejection risk.
- The examination interval for RPVH operating at cold leg temperatures with previously detected PWSCC may be extended from the currently required interval of each RFO to every other RFO without introducing significant added risk of leakage or ejection. For example, all calculations assume the existence of a roughly 10%TW surface crack, among other conservatisms, and nevertheless predict times to leakage between 7 and 17 EFPY at cold head temperatures.
- The N-729-1 examination interval of each RFO for non-cold Alloy 600 heads with previously detected PWSCC is considered effective for limiting risks of leakage and ejection while not being overly conservative. This conclusion holds for operating temperatures bounding for the active fleet of Alloy 600 top heads.[6]

The purpose of the probabilistic analysis discussed in the next section is to quantify the risk of leakage and ejection more precisely through comprehensive simulation of the PWSCC degradation process, including the introduction of a PWSCC initiation model.

[6] According to the head temperatures in MRP-48 [21], the 605°F hot head temperature evaluated in this section is bounding for all currently operating Alloy 600 RPVHs. Of the five non-cold Alloy 600 heads that remain in service, the hottest is at 595°F and has announced head replacement in 2017 [39] while the next highest operating head temperature is 594.8°F [21].

4
PROBABILISTIC MONTE CARLO SIMULATION ANALYSIS

The probabilistic evaluation presented in this section replaces many of the conservatisms of the deterministic evaluation with best estimates, incorporating uncertainty to reflect lack of knowledge about and physical variability in the RPVH PWSCC degradation process. Probabilistic predictions are in the form of event frequencies and probabilities. Based upon these predictions, RPVH examination intervals are recommended to achieve acceptable levels of leakage and ejection risk, both relative to risks predicted with currently accepted examination intervals and with respect to absolute core damage frequency limits.

4.1 Approach and Modeling

This subsection provides an overview of the probabilistic model used to evaluate the technical basis for the current N-729-1 inspection interval for heads operating at T_{cold}. This model is derived from the model applied in MRP-335 Rev. 1 [8] to evaluate mitigation of PWSCC on CRDM nozzles by peening and the model applied in MRP-375 [9] to evaluate the reexamination interval for top heads with Alloy 690 penetration nozzles. The reader is directed to MRP-375 for a detailed presentation of the probabilistic model and inputs.

4.1.1 Summary of the Probabilistic Model

The probabilistic model accepts inputs (which may represent a single plant or a subpopulation of plants), conducts lifetime analysis of PWSCC manifesting in various forms at various locations, and returns statistics to describe the risks of key failure modes, e.g., leakage and ejection frequencies. This subsection introduces the various submodels and key modeling assumptions that enable the probabilistic model.

4.1.1.1 Probabilistic Framework and Submodels

The probabilistic model is enabled by a modeling framework. The framework establishes inputs, directs the flow of information between submodels, performs intermediate calculations, performs various logical operations (e.g., to schedule inspections), and stores event predictions, all within a Monte Carlo (MC) simulation framework [40].[7]

[7] MC simulation is commonly used for conducting probabilistic assessment for complex processes involving many uncertainties. MC simulation involves the use of many individual realizations, each considered representative of the modeled process. For each realization, inputs are determined by randomly sampling from distributions that are developed to be representative of available information. After establishing the inputs, each realization is carried out deterministically. After many realizations (e.g., from 10 to 109), the results of individual realizations are combined to describe outputs in a statistical sense.

The probabilistic framework uses submodels that are identical to those applied in MRP-375 with the exception of the changes noted in Section 4.1.1.3. The individual submodels are detailed in Appendix A of MRP-375 [9] and are summarized below:

- *Load and stress calculation.* The total stress profile along each path of potential flaw growth is approximated as a second-order polynomial. Polynomial coefficients have been fit based on the results of FEA studies spanning different nozzle geometries, welding parameters, etc. Stress intensity factors at the deepest point and at the surface tips of cracks are calculated with the standard influence coefficient method [41]. Further details are provided in Section A.5 of MRP-375.
- *Flaw initiation.* The flaw initiation submodel sets an initiation time and an initial size for each flaw that becomes active during the simulated operating lifetime of the RPVH. The initiation model accounts for multiple flaw initiation by incorporating one Weibull-based model to determine the time to first initiation of PWSCC and a second Weibull-based model to determine the time to initiation of multiple distinct flaws on the head (including the possibility for multiple distinct flaws on a single penetration). Details are provided in Section A.4 of MRP-375.
- *PWSCC flaw growth.* The standard PWSCC growth models of MRP-55 [7] for Alloy 600 and of MRP-115 [21] for Alloy 82/182 are adopted in this study. These models account for growth rate dependencies with respect to stress intensity factor and temperature and probabilistically capture the range of growth rates observed in laboratory experiments. Details are provided in Section A.6 of MRP-375.

  Flaws may initiate on the nozzle ID, nozzle OD, or J-groove weld, and each location is treated distinctly to account for differences in material and geometry. Flaws are modeled to grow from their initial size and location until they penetrate into the annulus above the nozzle weld, at which point they are assumed to leak. Once a flaw grows to leak, it is assumed to transition to a circumferential flaw above the weld. Details are provided in Section A.3 of MRP-375.
- *Flaw detection.* UT and BMV inspections are simulated at specified intervals which are guided by the inspection requirements of ASME Code Case N-729-1 [1]. The UT inspection submodel and inputs of MRP-335 Rev. 1 [8] are adopted in this study to express probability of detection as a function of flaw through-wall percentage. Details are provided in Section A.7 of MRP-375.

4.1.1.2 Key Modeling Assumptions

Several assumptions and simplifications are embedded in the probabilistic model of this report. Knowledge of the following simplifications is important for properly interpreting the results given in this section; however, the conclusions drawn from the results are not expected to be dependent on these simplifications. It is noted that each of these key modeling assumptions is shared with the RPVHPN model described in the peening topical report, MRP-335 Rev. 1 [8], and with the Alloy 690 reexamination interval technical basis, MRP-375 [9].

- *Possible flaw locations.* It is assumed that multiple crack initiation on a single RPVHPN can be adequately represented through six possible initiation sites: an axial flaw at the nozzle ID, an axial flaw at the nozzle OD below the weld, and a radial flaw in the weld material (three sites at the uphill azimuthal position and three sites at the downhill azimuthal position, i.e., the locations of largest tensile residual stresses). To account for the cumulative risks of a top head, many RPVHPNs at different angles of incidence relative to the RPV head are modeled. The probability of initiation at any given site is assumed to be equal (i.e., the surface stress dependency of PWSCC initiation is not explicitly modeled).

- *Circumferential flaw initiation.* If any nozzle or weld flaw grows into the annulus above the J-groove weld[8], a circumferential flaw is assumed to initiate immediately with an initial circumferential extent of 30°. This assumption is consistent with MRP-105 [6].
- *Nozzle ejection threshold.* Ejection of a given RPVHPN is assumed to occur once the through-wall circumferential flaw reaches a specified threshold length. Cases presented in this section assume a conservative threshold length equivalent to 300° around the penetration, which is the same value used in MRP-105 [6] and is based on net section collapse (NSC) calculations presented in Appendix D of that report. Additional details are provided in Section A.8 of MRP-375.
- *Detectability by ultrasonic testing (UT) and bare metal visual (BMV) inspections.* UT examinations are assumed to be unable to detect flaws growing in the weld material. Also, the probability of detecting leakage by BMV examination is assumed to be a constant, independent of the leak rate.
- *Nozzle repair.* Repair is assumed to occur immediately at the detection of a surface crack or at the detection of leakage due to a through-annulus crack. Repaired nozzles are assumed to be become essentially immune to PWSCC, i.e., the risk of future leakage or ejection at a repaired nozzle is ignored.

4.1.1.3 Modifications Relative to the MRP-375 Model

The model used for this report features only limited modifications relative to the probabilistic framework described in MRP-375 and differs primarily due to modifications to input parameter values. A summary of the differences is given in this section for the reader that is familiar with the modeling approaches presented in MRP-335 Rev. 1 and MRP-375.

Modification to the Probabilistic Framework

- The BMV scheduling logic is modified to allow the first BMV inspection to be delayed to a specified cycle. This adjustment yields more appropriate scheduling for cases with delayed onset of inspections.
- The framework includes the capability to screen out MC realizations in which ejection occurs before some specified cycle, generating predictions that are conditional on the lack of ejection up to some cycle. This capability is invoked for sensitivity studies that may be considered more representative of the population of U.S. cold head RPVHs (on which nozzle ejection has never occurred).

[8] Flaw growth into the annulus is presumed to occur if an axial ID flaw or radial weld flaw grows to a depth exceeding the material thickness or if an axial OD flaw grows to a length such that its uppermost tip extends to the J-groove weld root.

- Eddy current testing (ET) inspections, only used in a calibration case, encompass the weld wetted surface and nozzle OD surface. This modification is consistent with inspections performed on an Alloy 600 replacement RPVH, to which some probabilistic cases are calibrated.
- The empirical cumulative distribution function for number of repairs per RPVH observed during a MC simulation can be outputted. This output provides a metric for model calibration, as demonstrated in Section 4.2.3.
- The empirical cumulative distribution function for flaw growth rate variation per crack observed during a MC simulation can be outputted, both for base metal and weld metal flaws. These outputs provide additional insight, as demonstrated in Section 4.3.1.3.

Treatment of Uncertainty in Initiation Model

While the governing Weibull equation for time to first initiation remains identical to that in MRP-375 (i.e., Equation [4-1]), the treatment of uncertainty for initiation is different from that described in Section B.2.2.2 of MRP-375.

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$ **[Eq. 4-1]**

In the prior analysis, uncertainty was incorporated in two steps: (1) incorporate variation in Weibull distribution characteristic time parameter (a.k.a. scale parameter) by sampling a standard error for the Weibull intercept parameter[9] and determine the new Weibull characteristic time parameter and (2) incorporate Weibull distribution shape variation by sampling a Weibull slope. Weibull slope may be sampled from a different distribution before and after the anchor point time (which is a user-defined time associated with a user-defined failure fraction, generally representative of the current experience within the component population of interest).

The approach above is convenient and recommended for failure prediction when the number of observed failures in the regression data set (e.g., detected cracks) is modest in comparison to the total number of opportunities for failures (e.g., number of field components exposed to conditions of interest and inspected intermittently). This approach constrains the prediction variation in the neighborhood of the anchor point. Furthermore, a different Weibull slope distribution can be applied before and after the anchor point time to reflect differences between what occurred in the past and what is expected to occur in the future.

A simplified approach is implemented in this analysis given the comprehensive data set associated with PWSCC on RPVHs. In this analysis, uncertainty is incorporated entirely through the Weibull intercept parameter and no anchor point is defined. The Weibull intercept parameter uncertainty is estimated by linearizing the Weibull model form and performing regression to

[9] The Weibull intercept parameter (the product of the Weibull slope parameter and the natural log of the Weibull characteristic time parameter) is the y-intercept of the "linearized" equation that results after log-transforming the Weibull cumulative distribution function twice. This linearization is a common practice in Weibull modeling because it poses the relationship between failure fraction and time in a linear form useful for visualization and regression.

time to first crack data for RPVHs[10]. To make a prediction with the model, the Weibull intercept parameter uncertainty is incorporated, effectively defining a Weibull characteristic time. Then, the initiation time is sampled from the Weibull distribution defined by the Weibull slope and characteristic time parameters.

No Cases with Alloys 690/52/152

Behavior representative of flaw initiation and growth in Alloy 600 and Alloy 82/182 is recovered in this work by setting factor of improvement inputs to unity (1), as opposed to the factors of improvement assumed in MRP-375 to represent Alloy 690 and Alloy 52/152.

4.1.2 Probabilistic Model Inputs

In the base cases of this report, all inputs related to the simulation of component stress states, growth, detection, and crack stability are identical to those given in Appendix B of MRP-375 [9]. Inputs that differ from MRP-375 are stated in Table 4-1 and Table 4-2 for the various distinct cases of this report. These cases are further discussed below.

To demonstrate the continued conservatism of a volumetric inspection interval of RIY = 2.25 (per N-729-1), three temperatures are investigated at their maximum allowed inspection interval: a hot head at 605°F with a 24-month refueling cycle inspected every RFO, a cold head at 563°F with an 18-month refueling cycle inspected every fourth RFO, and a cold head at 555°F with an 18-month refueling cycle inspected every fifth RFO.

To demonstrate the robustness of the N-729-1 inspection requirements and the recommendations of this report to varying PWSCC susceptibility, three distinct initiation models are investigated: the All Material Supplier Weibull model was developed from all available RPVH detection data (see Section 2.1); the B&W Tubular Products Weibull model was developed from the subset of RPVH detection data for RPVHs manufactured with B&W Tubular Products material (see Section 2.1); the Alloy 600 replacement RPVH Weibull is partially based on the B&W Tubular Products Weibull model, but is further calibrated to nominally agree with the experience of an Alloy 600 replacement RPVH (see Section 4.2.2). These different initiation models are presented in Figure 4-1.

In addition to varying operating temperature and initiation model parameters, sensitivity studies are performed with respect to various model parameters to characterize the impact of input uncertainty and modeling assumptions on leakage and nozzle ejection risk predictions. The parameters varied by each of these cases are documented in Table 4-3. Note that sensitivity cases M1 and M3 through M7 are equivalent to sensitivity cases studied in MRP-375.

4.1.3 Introduction to Probabilistic Model Results

The probabilistic model described in the previous sections is implemented within a Monte Carlo simulation framework allowing for the statistical prediction of possible outcomes such as nozzle leakage and ejection. The primary statistics used to assess and compare the results of the probabilistic model are defined below:

[10] As will be detailed later, a few different models are developed to represent different Alloy 600 RPVH subsets, e.g., heads with material from B&W Tubular Products.

- Incremental leakage frequency (ILF) is defined as the average number of new leaking nozzles per year on a RPV top head. A simulated flaw causes leakage if it propagates through the entire material thickness to penetrate the annulus above the J-groove weld before it is detected and repaired. This statistic is derived for any given operational cycle by averaging the predicted number of new leaking nozzles for that operational cycle across all MC realizations. This is adjusted to a probability per year by dividing by the number calendar years per cycle. If no leaks are predicted to occur during a given cycle across all MC realizations, 0.5 leaks are assumed for the sake of stability and conservatism in calculating the statistic.

$$ILF = \frac{\max\{(\text{Number of initial leaks predicted during cycle across all realizations}), 0.5\}}{(\text{Number of realizations})(\text{Cal. yrs per cycle})} \quad \textbf{[Eq. 4-2]}$$

- Average leakage frequency (ALF) is the average of the ILFs across all cycles after the first inspection to the end of the operational service period of the plant.

$$ALF = \frac{\sum_{i_{First}+1}^{N_{cycle}} \max\{(\text{Number of initial leaks predicted during } i\text{th cycle across all realizations}), 0.5\}}{(\text{Number of realizations})(\text{Cal. years per cycle})(N_{cycle} - i_{First})} \quad \textbf{[Eq. 4-3]}$$

N_{cycle} = number of cycles in operational service period

i_{First} = cycle number associated with first simulated inspection

- Likewise, incremental ejection frequency (IEF) is defined as the average number of nozzle ejections per year on a RPV top head. This statistic is derived for any given operational cycle by averaging the predicted number of ejections for that operational cycle across all MC realizations and dividing by the number of years per cycle.

$$IEF = \frac{\max\{(\text{Number of ejections predicted during cycle across all realizations}), 0.5\}}{(\text{Number of realizations})(\text{Cal. yrs per cycle})} \quad \textbf{[Eq. 4-4]}$$

- Average ejection frequency (AEF) is the average of the IEFs across all cycles from the first inspection to the end of the operational service period of the plant.

$$AEF = \frac{\sum_{i_{First}+1}^{N_{cycle}} \max\{(\text{Number of ejections predicted during } i\text{th cycle across all realizations}), 0.5}{(\text{Number of realizations})(\text{Cal. years per cycle})(N_{cycle} - i_{First})} \quad \textbf{[Eq. 4-5]}$$

As discussed in MRP-117 [3] and MRP-105 [6], the effect of nozzle ejection on nuclear safety can be assessed through multiplication of the frequency of nozzle ejection (i.e., the initiating event frequency) with an appropriate conditional core damage probability (CCDP) value. The resulting core damage frequency is typically averaged over long-term operation and compared to the acceptance criteria of Regulatory Guide 1.174 [42]. Regulatory Guide 1.174 specifies an acceptable change in core damage frequency of 1×10^{-6} per reactor year for permanent changes in plant design parameters, technical specifications, etc.

The ILF and IEF statistics are calculated in a manner identical to MRP-375. Leakage and ejection events prior to the first simulated inspection are not incorporated in the ALF and AEF calculated in this report; these events are independent of the inspection interval imposed and therefore it is not informative to include them in the averaged statistics.

Ejections and leakage are counted in two different ways within the simulation framework: in terms of the number of heads with at least one event (by counting only the first instance of leakage or ejection for a given MC realization) and in terms of the number of penetrations with at least one event (by counting the first instance of leakage or ejection for each unique penetration). The latter is used to determine the ALF and AEF reported in this report.

Also, to more precisely relate predictions to operating experience, the number of penetrations where ejection or leakage has occurred due to a flaw that initiated in the nozzle material (as opposed to the J-groove weld) is separately tracked.

Finally, in addition to the primary statistics described above, the simulation framework also tracks the proportion of total repairs and leaks associated with each initiation site. Across multiple simulations, these proportions are used to assess how varying inspections and other parameters may affect which crack locations are most likely to lead to leakage.

Table 4-1
List of Inputs for Base Cases[11]

Symbol	Description	Source	Units	Distrib. Parameter	Value for 563°F Case	Value for 555°F Case	Value for 605°F Case
T	Operating temperature	Selected to result in RIY closest to 2.25 for different inspection intervals typical of Alloy 600 heads in service	°F	type	Normal	Normal	Normal
				mean	563	555	605
				stdev	5.0	5.0	5.0
				min	533	525	575
				max	593	585	635
t	Nozzle thickness	Representative of CEDM nozzle thickness of unit serving as characteristic hot head	m	[redacted]	0.0158	0.0158	0.0158
D_o	Nozzle outer diameter	Representative of CEDM nozzle OD of unit serving as characteristic hot head	m	[redacted]	0.1016	0.1016	0.1016
[redacted]	Number of operating cycles	Selected to yield desired cumulative operating time	Nondim	[redacted]	40	40	30
[redacted]	Nominal cycle length	Typical cycle lengths for US PWR	yr	[redacted]	1.5	1.5	2.0
CF	Operating capacity factor	Reasonable capacity factor for US PWR	Nondim	[redacted]	0.97	0.97	0.97
$i_{First,UT}$	Cycle of first UT inspection	Based on typical operating reactor service histories	# cycles	[redacted]	10	10	10
$i_{First,BMV}$	Cycle of first BMV inspection	Based on typical operating reactor service histories	# cycles	[redacted]	10	10	10
[redacted]	UT inspection frequency for base case	ASME Code Case N–729–1	$(\# \text{cycles})^{-1}$	[redacted]	4 / 2 / 1	5 / 2 / 1	1
[redacted]	BMV inspection frequency before 8 EDY	ASME Code Case N–729–1	$(\# \text{cycles})^{-1}$	[redacted]	3	3	2
[redacted]	BMV inspection frequency after 8 EDY	ASME Code Case N–729–1	$(\# \text{cycles})^{-1}$	[redacted]	1	1	1
N_{pen}	Number of modeled penetrations	Selected based on properties of characteristic cold head	Nondim	[redacted]	78	78	78
[redacted]	Incidence angles for penetrations	Selected based on properties of characteristic cold head	degrees	type	Discrete List	Discrete List	Discrete List
				average	31.8	31.8	31.8
				min	0.0	0.0	0.0
				max	48.8	48.8	48.8
Δt	Time step size for crack increment	See convergence analysis	yr		1/12	1/12	1/12

[11] For these cases, the inspection intervals are set to RIY = 2.25, resulting in inspection intervals of different EFPY for different operating temperatures.

Table 4-2
List of Weibull Model Inputs for Time to PWSCC Initiation

Symbol	Description	Source	Units	Distrib. Parameter	All Mat'l Supplier Weibull	B&W TP Weibull	Repl. RPVH (Calibrated) Weibull
Q_i	Thermal activation energy for PWSCC flaw initiation	Q distribution based on laboratory data and judgment from experience with Weibull analysis	kJ/mole	type	Normal	Normal	Normal
				mean	184.2	184.2	184.2
				stdev	12.8	12.8	12.8
				min	107.3	107.3	107.3
				max	261.1	261.1	261.1
β	Weibull slope for PWSCC flaw initiation on RPVPNs	Flaw initiation data assessed in this report	Nondim		1.379	1.166	1.166
θ	Weibull scale parameter	Flaw initiation data assessed in this report	EDY		23.00	11.03	3.10
σ_c	Standard error in intercept of linearized Weibull fit	Linearized Weibull fit to flaw initiation data assessed in this report	ln(EDY)		0.271	0.361	0.361
β_{flaw}	Weibull slope for PWSCC multiple flaw initiation on RPVHPNs	Based on representative value for formation of PWSCC at multiple locations in industry SGs	Nondim	type	Normal	Normal	Normal
				mean	2.0	2.0	3.0*
				stdev	0.5	0.5	0.5
				min	1.0	1.0	1.0
				max	5.0	5.0	6.0

[12] The mean multiple flaw initiation Weibull slope (βflaw) of the "Repl. RPVH" case is increased relative to the fleet-based Weibull models to reflect the more susceptible material used in the Alloy 600 head at a cancelled plant which was installed as a replacement.

Table 4-3
List of Inputs for Sensitivity Cases

Case Number	Description	Parameter	Units	Distrib. Parameter	All Mat'l Base Value	Sensitivity Case Value
M1	Increased Reactor Head Lifetime	Number of operating cycles	Nondim		40	54
M2	Resample Realizations with Ejections That Would Have Already Occurred	i_{past} Number of ejection free operating cycles	Nondim		0	10
M3	More Rapid Acceleration of Multiple Initiations After First Initiation	β_{flaw} Weibull slope for PWSCC multiple flaw initiation	Nondim	type	Normal	Normal
				mean	2.0	3.0
				stdev	0.5	0.5
				min	1.0	1.0
				max	5.0	6.0
M4	Correlated Initiation and Growth	ρ_{weld} Correlation coefficient for PWSCC initiation and propagation of all cracks in weld material	Nondim		0.0	-0.8
		ρ_{heat} Correlation coefficient for cracks in nozzle material	Nondim		0.0	-0.8
M5	Decreased Maximum UT POD	$p_{max,UT}$ Maximum probability of detection for UT inspection	Nondim		0.95	0.9
M6	Decreased Critical Flaw Size	$\theta_{circ,crit}$ Critical flaw angle for nozzle ejection	degrees		300	275
M7	MRP-55 Crack Growth Rate Model Parameters	$K_{ith,heat}$ K_I Stress intensity factor threshold for Alloy 600	MPa-m$^{0.5}$		0.0	9.0
		α_{heat} Flaw propagation rate equation power law constant for Alloy 600	(m/s)/(MPa-m$^{0.5}$)^{bheat}		1.97E-13	1.34E-12
		b_{heat} Flaw propagation rate equation power law exponent for Alloy 600	Nondim		1.6	1.16
M8	Match Initiation Model to N-729-1 Parameters	Q_i Activation Energy for Initiation	kJ/mole	type	Normal	Normal
				mean	184.23	209.00
				stdev	12.82	12.82
				min	107.32	132.08
				max	261.13	285.92
M9	Decreased Initiation Activation Energy	Q_i Activation Energy for Initiation	kJ/mole	type	Normal	Normal
				mean	184.23	167.48
				stdev	12.82	12.82
				min	107.32	90.56
				max	261.13	244.40

Table 4-3 (continued)
List of Inputs for Sensitivity Cases

Case Number	Description	Parameter	Units	Distrib. Parameter	Base Case Value	Sensitivity Case Value
M10	Decreased Growth Activation Energy	Q_g Activation Energy for Growth	kJ/mole	type	Normal	Normal
				mean	130.0	120.0
				stdev	5.0	5.0
				min	100.0	90.0
				max	160.0	150.0
M11	Decreased Initial Crack Depth	a_0 Initial flaw depth	m	type	Log-Normal	Log-Normal
				linear μ	8.44E-04	1.60E-04
				log-norm μ	-7.14	-8.80
				log-norm σ	0.35	0.35
				min	5.00E-04	0.00E+00
				max	1.58E-02	1.58E-02
M12	Begin Inspections at Start of Simulation	i_{1st}, i_{1stBMV} First cycle for UT and BMV inspections, respectively	Nondim		10	1
M13	MRP-105 Initiation Weibull Parameters	σ_c Standard error in intercept of linearized Weibull fit	ln(EDY)		0.271	N/A
		θ Weibull scale parameter for PWSCC flaw initiation on RPVHPNs	EDY	type	Normal	Triangular
				mean (mode)	23.0	(15.2)
				stdev	see σ_c	-
				min	0	10.55
				max	1E+05	21.70
		β Weibull slope for PWSCC flaw initiation on RPVHPNs	Nondim		1.379	3.0
M14	Increased UT POD Correlation	$\rho_{max,UT}$ Correlation coefficient for successive UT inspections	Nondim		0.5	0.8
M15	Decreased BMV POD	p_{BMV} Probability of detection for visual inspection of leaking nozzle	Nondim		0.9	0.8
M16	Alternate Alloy 600 Replacement RPVH Calibration	σ_c Standard error in intercept of linearized Weibull fit	ln(EDY)		0.271	1.72
		θ Weibull scale parameter for PWSCC flaw initiation on RPVHPNs	EDY	type	Normal	Normal
				mean	23.0	2.590
				stdev	see σ_c	see σ_c
				min	0	0
				max	1E+05	1E+05
		β Weibull slope for PWSCC flaw initiation on RPVHPNs	Nondim		1.379	3.0

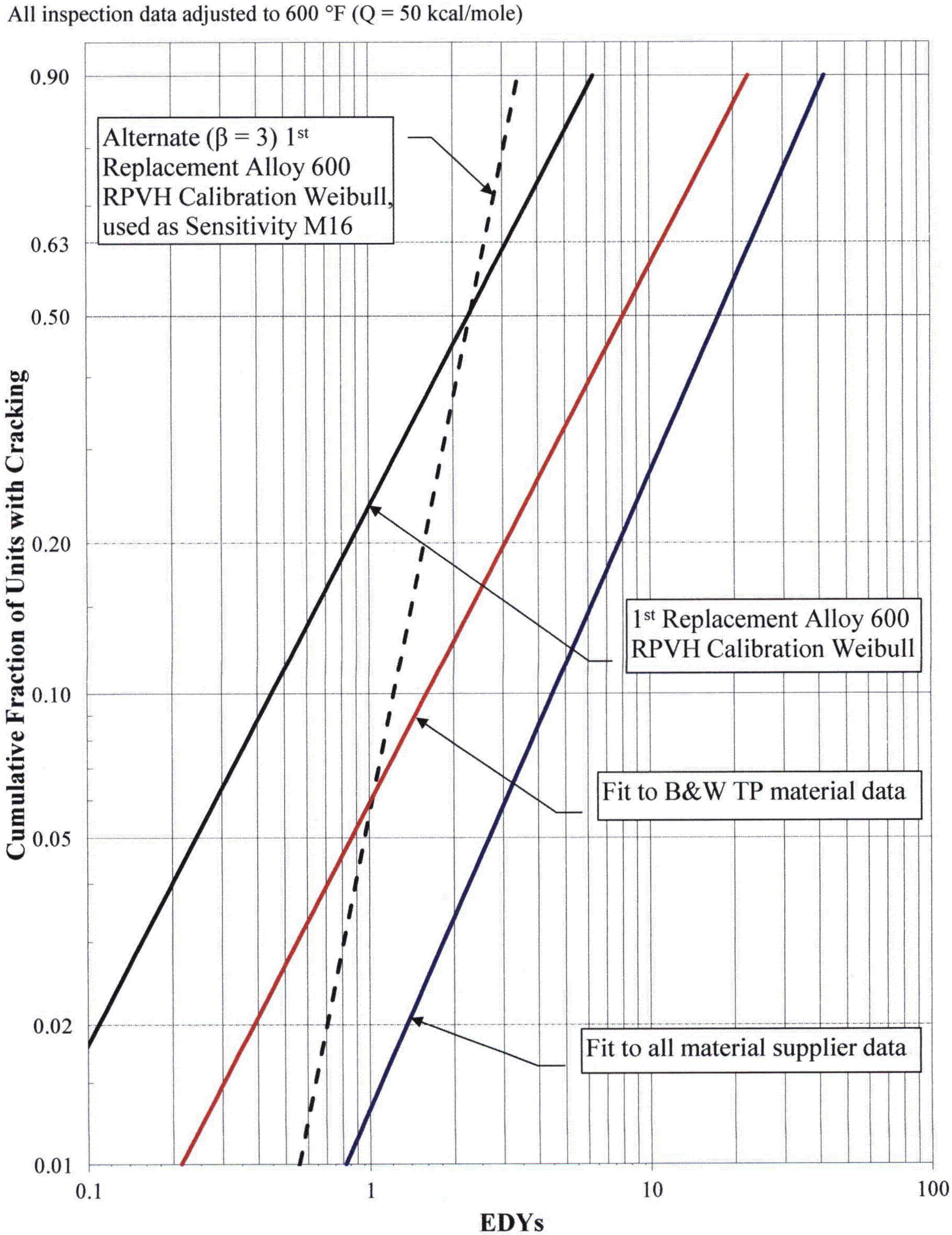

Figure 4-1
Comparison of Initiation Weibull Models Evaluated in the Report for Predicting Time to First PWSCC

4.2 Benchmarking and Calibration

The probabilistic model utilized to develop the technical basis in this report was validated by benchmarking against the predictions of the probabilistic RPVH model developed in MRP-105 [6] and against PWSCC detection experience for an Alloy 600 replacement RPVH.

4.2.1 MRP-105 Benchmarking

The MRP-105 benchmarking studies presented in Section B.2.7 of MRP-375 are directly applicable to the evaluations of this report. The remainder of this section comprises a summary of the inputs and results of these benchmarking studies.

Input:

In order to confirm that the two models produced similar results for similar inputs, the benchmarking case inputs were selected to correspond to cases in MRP-105. The cases nominated for benchmarking were Case 11 and Case 19 as presented in Table 8-1 of MRP-105, which correspond to heads operating at 600°F and 580°F (316°C and 304°C), respectively, and inspected by UT roughly every 4 EDY. The following key parameters are common to both models and their inputs were matched for benchmarking:

- The scheduling of inspections in EFPY
- Operating temperature, activation energies, and reference temperatures
- Basic nozzle and head dimensions
- Initiation Weibull parameters (for time to first PWSCC)
- Correlation between distributed parameters for initiation and growth submodels
- UT probability of detection
- Stress intensity factor and crack growth rate for circumferential through-wall cracking

The treatment of component loading, initiation, growth, and examination is not identical between the probabilistic model of this report and that of MRP-105 due to systematic differences in the modeling approaches of the two reports. Section B.3.3.3 in MRP-375 provides a more comprehensive discussion of the differences between the modeling approaches.

Results:

Figure 4-2 shows both the MRP-375 and MRP-105 ejection predictions and demonstrates reasonable agreement, namely with respect to the relative trends indicated.[13] For instance, the modeled UT inspections result in similar relative reductions in IEF for the MRP-105 and MRP-375 models. However, the MRP-375 model (used in this report) conservatively predicts a higher ejection rate. The deviation between the results for the two models reflects structural differences in the modeling approaches and assumptions. Two of the largest differences are:

[13] MRP-105 presents results in a form equivalent to the IEF statistic of this report (see Section 4.1.3) compiled on a per-head basis such that only the first instance of ejection is counted in each realization, thus allowing comparison of analogous predictions.

- MRP-105 assumes constant rate growth of surface flaws while this report more accurately bases surface flaw growth rate on stress intensity factor calculations performed using representative post-weld residual stress profiles.
- While MRP-105 separately models flaws at uphill and downhill locations, this report augments the approach by separately modeling flaws at nozzle ID, nozzle OD, and weld surfaces. This detailed treatment allows explicit modeling of volumetric inspections of the nozzle base metal without crediting inspection for flaws located in the weld material, resulting in examinations more characteristic of those performed in the field.

4.2.2 Calibration Against Plant Experience

In 2004, an RPVH with Alloy 600 nozzles at one U.S. PWR was replaced with another RPVH with Alloy 600 nozzles from a cancelled plant. The Alloy 600 CRDM nozzles in the replacement head were supplied by B&W Tubular Products. The first inspection of the replacement occurred after six years of operation from 2004 to 2010 and resulted in detection of widespread PWSCC. UT inspection of the RPVH resulted in the detection of flaws in 12 nozzles; surface examination resulted in the detection of flaws in 13 additional nozzles [35]. This operating experience provides a unique data set against which to perform model calibration.

Calibration is performed by first establishing inputs representative of the Alloy 600 replacement RPVH:

- The head geometry and inspection scheduling inputs are set to reflect those of the Alloy 600 replacement RPVH, as defined in Table 4-4.
- A slope of 3 for the multiple flaw Weibull initiation model—instead of 2 used for the all material supplier or B&WTP Weibull initiation models—is assumed to reflect the uniformly more susceptible nature of the nozzle material in the Alloy 600 replacement RPVH, i.e., flaws would tend to spread more quickly after the occurrence of the first PWSCC.
- Two distinct calibration cases are considered with different slopes assumed in the time to first initiation Weibull model (as separated by forward slash in the Table 4-4).
  - *B&W Tubular Products Weibull slope.* The first case assumes that the Weibull slope is equivalent to that derived from the experience at plants with B&W Tubular Products material, as determined in Section 2.1.
  - *Weibull slope of 3:* The second case—evaluated later as sensitivity case M16—assumes a Weibull slope of 3 and results in less variation among simulated heads. For this case, the vertical intercept is refit using the B&W Tubular Products material data, under the constraint of a Weibull slope of 3 (instead of the best-fit Weibull slope).

Then, a single parameter—the characteristic time of the time to first PWSCC Weibull model—is varied to achieve results that correspond with the detection data from the first inspection of the RPVH. ET examination is modeled to occur following the simulation of UT inspection on nozzles without UT crack detections. ET examination is modeled as a probability of detection (POD) versus flaw depth, as seen in Figure 4-3 and identical to the relationship utilized in MRP-335 Rev. 1. Zero detectability is enforced for cracks smaller than 2 mm in surface length. This is consistent with detections by ET of linear indications as small as 2.3 mm reported in the first replacement head inspection [35].

This calibration yields an initiation model that is considered representative of a head with PWSCC susceptibility as conservatively high as the Alloy 600 replacement RPVH.

4.2.3 Calibration Results

The primary result of the calibration cases is a cumulative distribution function (CDF) describing the number of repaired (i.e., detected) nozzles per head. The results for two cases are presented in Figure 4-4: the case assuming the B&W Tubular Products Weibull slope and the case assuming a Weibull slope of 3. For each Weibull slope case, CDFs describe repairs due to only UT examinations and repairs due to both UT and ET examinations. The CDF for only UT examinations is utilized directly to calibrate the Weibull characteristic time parameter, targeting 12 nozzles repaired due to UT examination; the CDF for both UT and ET examinations is evaluated for further comparison with the reported results, targeting 13 nozzles repaired due to surface examinations performed after UT examination.[14]

A median of approximately 12 detections by UT examination is achieved for both cases simply by calibrating the Weibull characteristic time parameter. Conveniently, a median of 12 additional detections resulting from surface examination is achieved for both cases, which agrees well with the Alloy 600 replacement RPVH experience; this is not the result of calibration and helps to further validate the underlying models. The additional variability in the number of nozzle repairs is related to uncertainties modeled in the initiation, growth, and inspections processes.

The calibrated Weibull models for the two cases are shown in Figure 4-5. The median initiation times of the two Weibull models are similar, but the different Weibull slopes lead to different model behavior. For example, with the B&WTP slope, 20% of plants are predicted to initiate PWSCC within 1 EDY compared to only 6% for the case that assumes a Weibull slope of 3. Conversely, with the B&WTP slope, 90% of heads initiate within about 6.3 EDY while it takes 3.4 EDY for the case that assumes a Weibull slope of 3.

As indicated in Section 4.2.2, the calibration results of this section are used to model a case that assumes a RPVH as susceptible to PWSCC initiation as the Alloy 600 replacement RPVH. These conservative cases are evaluated to show that the conclusions drawn in this report are appropriate for even the most susceptible plant. Of the two calibrated Weibull models, the model with the B&WTP value of Weibull slope is used widely in this report, while the model with an assumed slope of 3 is evaluated as sensitivity case M16.

[14] The 13 surface examination detections on the Alloy 600 replacement RPVH were attributed to both ET and dye penetrant testing. However, the ET model assumed in this benchmarking study is presumed representative of the combination of the two surface examination techniques.

Table 4-4
Summary of Alloy 600 Replacement RPVH Benchmarking Inputs

Parameter	Units	Distrib. Parameter	Alloy 600 Replacement RPVH
Number of realizations	Nondim		1.0E+05
CF Plant capacity factor	Nondim		0.91
Cycle duration	Years		2.0
i1st Cycle of first UT inspection	Nondim		3
i1stBMV Cycle of first BMV inspection	Nondim		No BMV
Number of cycles	Nondim		3
T Operating temperature	°F	type	Normal
		mean	613
		stdev	5
		min	583
		max	643
N_{pen} Number of Penetrations	Nondim		69
Incidence angles for penetrations	degrees	type	Discrete List
		average	30.4
		min	0.0
		max	49.6
σ_c Standard error in intercept of linearized Weibull fit	ln(EDY)		0.362 / 1.722
θ Weibull scale parameter for PWSCC flaw initiation on RPVHPNs	EDY	type	Normal
		mean (mode)	3.098 / 2.590
		stdev	see σ_c
		min	0.0
		max	1E+05
β Weibull slope for PWSCC flaw initiation on RPVHPNs	Nondim		1.166 / 3.0
β_{flaw} Weibull slope for PWSCC multiple flaw initiation	Nondim	type	Normal
		mean	3.0
		stdev	0.5
		min	1.0
		max	6.0
isET Perform ET during cycles with UT inspection	Nondim		TRUE

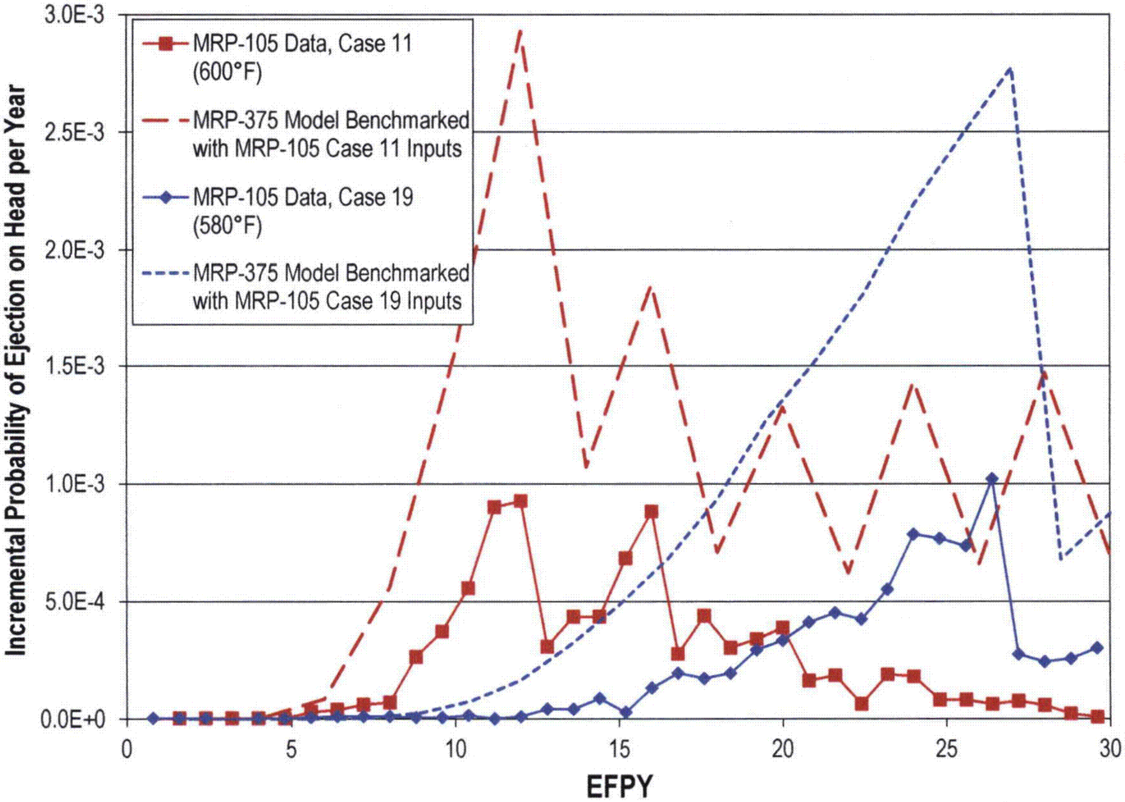

Figure 4-2
Comparison of Incremental Probability of Ejection Prediction with MRP-105 [6] Results (Reprinted from MRP-375 [9])

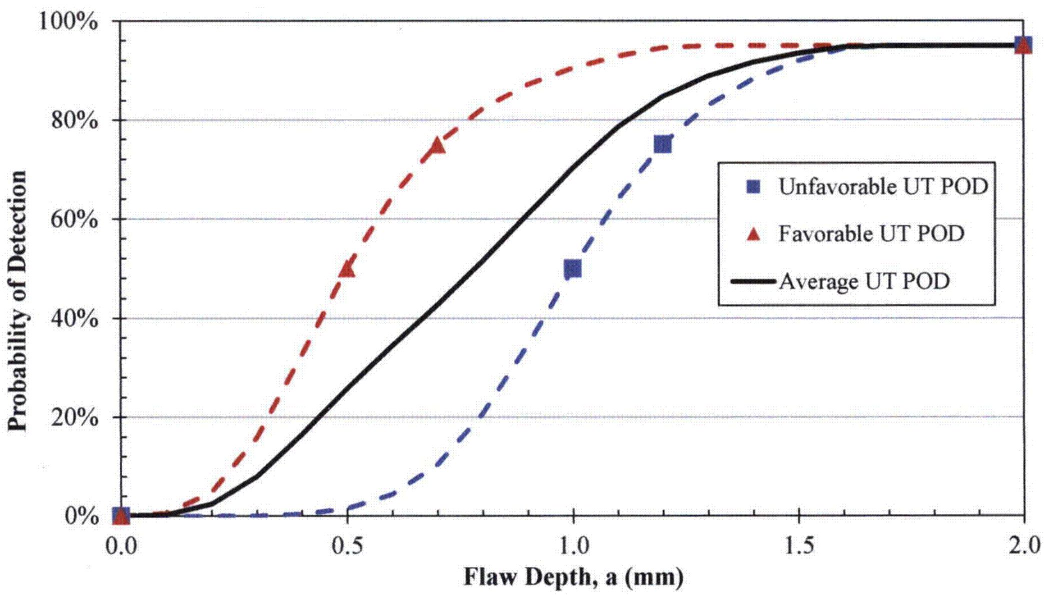

Figure 4-3
ET POD Curve

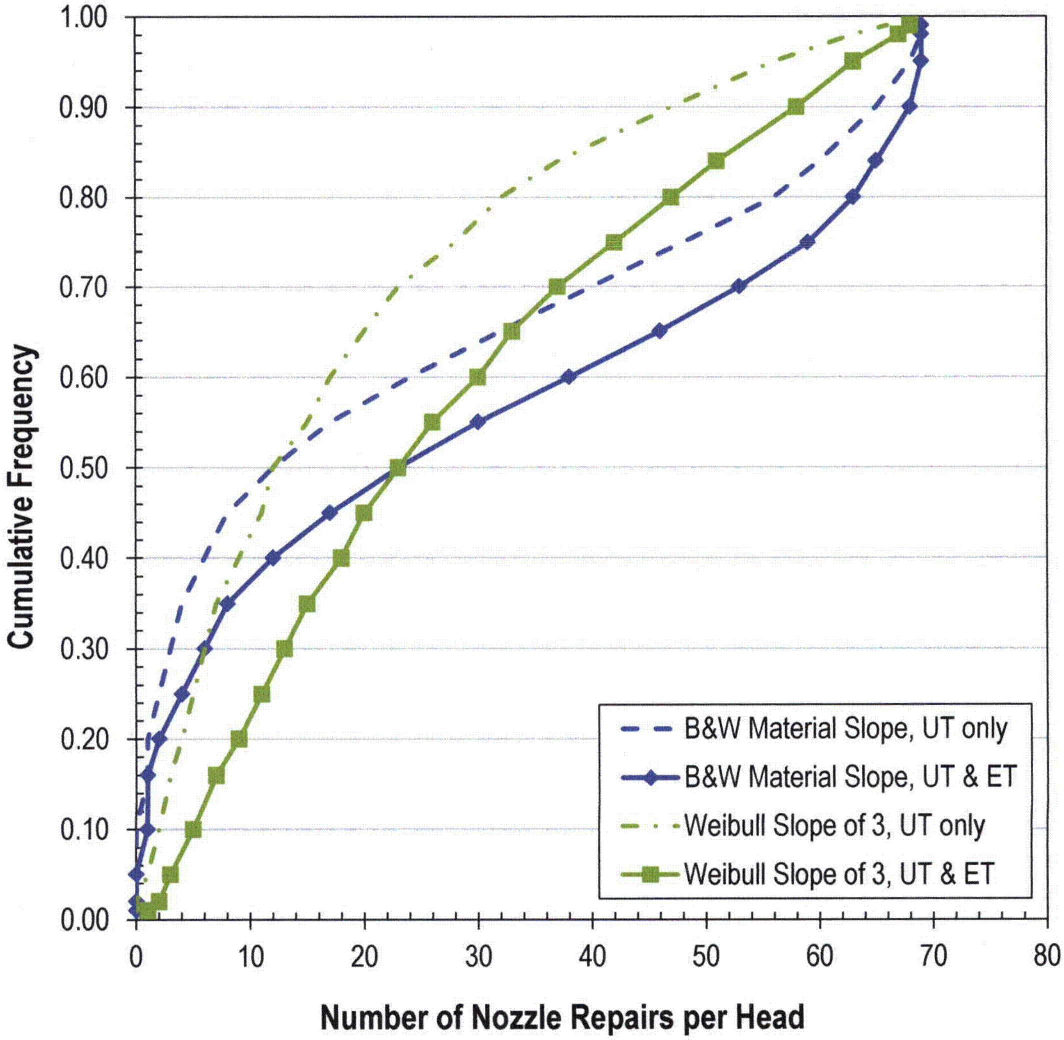

Figure 4-4
Results of Calibration to the Alloy 600 replacement RPVH at the First Inspection

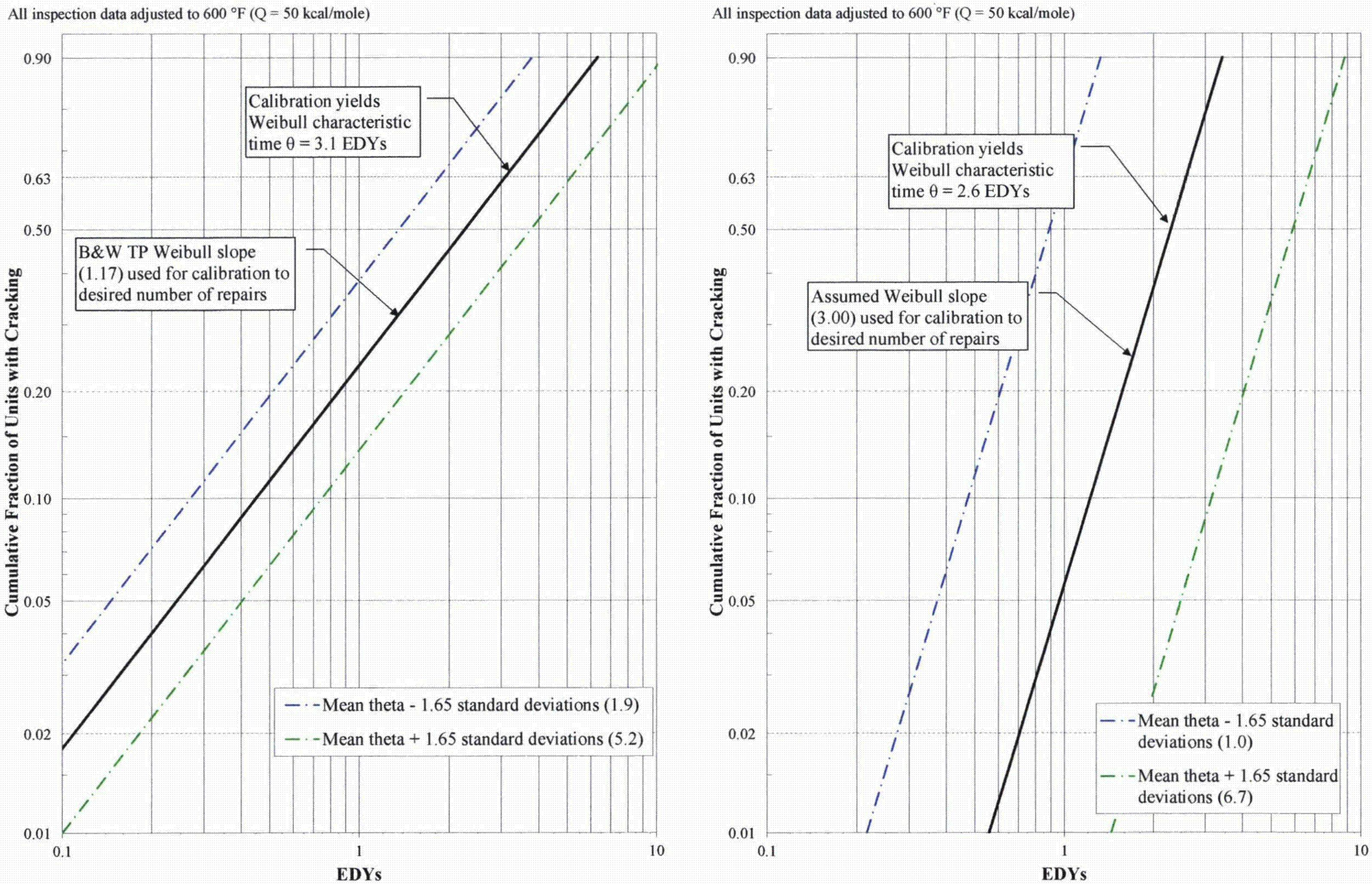

Figure 4-5
Resultant First Flaw Initiation Weibull Models for the Calibration to the Alloy 600 replacement RPVH at the First Inspection

4.3 Results

The remainder of this section presents the results of the probabilistic analysis.

As introduced in Section 4.1.2, three different initiation Weibull models—representative of all material suppliers, B&WTP material, or the Alloy 600 replacement RPVH—are applied for each of three different temperatures—555°F, 563°F, and 605°F. For the two cold head temperatures, three different UT examination intervals are examined—every cycle, every other cycle, and less than or equal to every RIY = 2.25. The cases are summarized by the test matrix of Table 4-5.

4.3.1 Key Results from Base Cases

The main results of all probabilistic analyses are presented in Table 4-6. The AEF, ALF, and ALF of base metal flaws only[15] are presented with bar plots in Figure 4-6 through Figure 4-17 for the different cases. Comparisons of event frequencies versus time for key cases are presented in Figure 4-18 through Figure 4-29.

Results from cases that bound the Alloy 600 RPVHs that remain in operation include:

- For a non-cold head with an operating temperature of 605°F, a 24-month inspection interval is shown in Figure 4-9 to lead to an AEF less than or statistically equivalent to 5E-5 for both the all material supplier and B&WTP material initiation models.
- The limiting T_{cold} head case involves a 563°F operating temperature, UT inspections every 4 cycles, and the Alloy 600 replacement RPVH Weibull initiation model. This case leads to an AEF of 2.1E-05 and an ALF equivalent to 0.4 new leaking penetrations per year. The full set of sensitivity tests is evaluated for this case (see Section 4.3.1.3).

The next subsections provide more focused discussions for specific base case results.

4.3.1.1 Results for Varying Initiation Models

This section studies the results of cases spanning three different Weibull flaw initiation models to draw conclusions about the relationship between ejection and leakage risks and PWSCC initiation susceptibility. The results for different flaw initiation models are depicted with different colors in the bar charts that summarize the statistical predictions of various cases (Figure 4-6 through Figure 4-17).

Figure 4-6 shows the AEF for the base cases at T_{cold}, allowing comparison among initiation models and demonstrating the following:

- The initiation model based on the Alloy 600 replacement RPVH is roughly an order of magnitude more conservative with respect to nozzle ejection risks than the initiation model based on inspection data from all material suppliers.

[15] The assumption that a third of all cracks initiate in the weld metal and that these cracks are not detectable until they grow through-wall is an appropriate conservatism for the evaluation of ejection risks, but results in overly conservative predictions of leakage rates. Experience indicates that these flaws typically grow into the base metal and become detectable as evidenced by the lack of leakage following the onset of volumetric inspection. The much lower rates of leakage due to detectable flaws (in the nozzle material) are shown in the third bar graph for each set of results.

- The initiation model based on plants with material fabricated by B&WTP is roughly two to four times more conservative with respect to ejection risk than the initiation model based on inspection data from all material suppliers.

Figure 4-7 and Figure 4-8 respectively present the ALF related to all flaws and the ALF related to flaws in the base metal only and demonstrate the following:

- The initiation model based on the Alloy 600 replacement RPVH is roughly an order of magnitude more conservative with respect to nozzle leakage risks than the initiation model based on inspection data from all plants.
- The initiation model based on plants with material fabricated by B&WTP is roughly three times more conservative than the initiation model based on inspection data from all plants.

4.3.1.2 Results for Varying UT Inspection Frequency

For the cold head cases, three inspection frequencies are evaluated: every cycle, every other cycle, and every RIY of about 2.25 (i.e., every 4 cycles for the 563°F cases and every 5 cycles for 555°F cases). This section studies cases spanning the different inspection frequencies to draw conclusions about the relationship between ejection and leakage risks and the UT inspection interval.

Figure 4-6 shows the AEF for the base cases at T_{cold}, allowing comparison of the different inspection intervals modeled. While an increase in ejection risk versus inspection interval is evident, results indicate that current RIY intervals in N-729-1 for plants operating near T_{cold} provide sufficient mitigation of ejection risk (e.g., with an AEF less than 5E-5), even with the conservatively aggressive initiation model. Even more aggressive assumptions are studied as sensitivity cases in Section 4.3.1.3.

Figure 4-7 and Figure 4-8 respectively present the ALF related to all flaws and the ALF related to flaws in the nozzle material. Per standard practice, no exams capable of detecting part-depth weld cracks are assumed, and so the benefit of performing more frequent UT inspections to reduce leakage is more apparent for flaws initiating in the nozzle material (Figure 4-8) than for arbitrarily located flaws.

Despite a modest increase in total leakage risk versus inspection interval, an inspection frequency of RIY = 2.25 is shown to be satisfactory. Even under the assumptions that a) initiation on the weld surface is as likely as initiation on nozzle ID or nozzle OD locations and b) flaws initiating on the weld surface cannot become detectable until leakage occurs, the average likelihood of a new leaking penetration is predicted to be 2-3% per year for a general RPVH and 7-9% for a RPVH manufacturing with B&WTP material.

It is important to note that none of these cases assume a reduction in inspection interval to every cycle upon detection of PWSCC on a given head, as is required by ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D). Certainly, if this requirement were to be modeled, leakage and ejection risks would be further reduced. But, on an absolute-risk basis, the cases that use a fixed inspection frequency of RIY = 2.25 yield predictions that suggest that the every cycle inspection frequency after PWSCC detection may be overly conservative. As further evidence of this concept, UT inspections <u>every other</u> refueling cycle are predicted to provide most of the ejection mitigation benefit of performing UT <u>every</u> cycle, relative to the cases with a

RIY of 2.25, as shown in Figure 4-6. The benefit of a shorter inspection interval (in absolute terms) diminishes since AEF predictions are already below 1E-6 for the case of two-cycle inspection intervals.

4.3.1.3 Leakage and Ejection Risks Versus Time

Figure 4-18 through Figure 4-29 depict incremental event frequencies as a function of time for various cases of interest. While the average event frequency is considered the primary metric for assessment in this report, these incremental frequency plots offer other important information, e.g., trends and volatility in risk over time. The following observations are noted:

- Leakage and ejection risks demonstrate a significant peak during the operating cycle directly preceding the first modeled inspection. This peak may be used to demonstrate conservatism of modeled predictions relative to historical operating experience, but are otherwise of little concern in this report.[16]
- After the first inspection, during a regular inspection interval, the leakage and ejection risks are observed to peak in the cycle immediately preceding inspections, due to longer times afforded for undetected flaws to advance. The ratio of the maximum IEF to AEF is between three and six for most cases—some of this disparity is due to the alternating pattern between cycles and some is due to a modest decreasing trend in ejection risk over time. The ratio of maximum ILF and ALF is less than two for nearly all cases studied.
- For all inspection intervals studied, the leakage and ejection risks appear to be stable or decreasing over time (subject to the pattern of variability described in the previous bullet). This is a favorable result that demonstrates the stability of the inspection intervals.
- In fact, leakage risk decreases over time for the more aggressive Weibull model based on the Alloy 600 replacement RPVH experience. This decrease is attributed to the fact that the most susceptible penetrations are predicted to leak and/or be repaired early in the plant operating period.

4.3.2 Key Results from Sensitivity and Convergence Studies

4.3.2.1 Sensitivity Studies

The results of the sensitivity studies are summarized in Table 4-6 and shown in Figure 4-12 through Figure 4-17.[17] The results considered to be of most importance are discussed below.

Correlated Initiation and Growth (Sensitivity Case M4)

The correlation between initiation and growth simulates the expectation that material that has relatively high susceptibility to initiation also is susceptible to relatively high crack growth rates,

[16] Risks preceding inspection are of course insensitive to inspection scheduling, the topic of interest in this report. Furthermore, sensitivity testing (e.g., sensitivity test case M12) demonstrates that behavior after the first inspection is largely insensitive to when the first inspection is simulated. In any case, the time of the first inspection for all base cases is scheduled to correspond with historical plant operation, for which little inspection capability is credited for early operation.

[17] Sensitivity M3 for cases with the Alloy 600 replacement RPVH Weibull is not shown in these figures because it is redundant (i.e., the nominal multiple flaw Weibull slope is already set to 3 in replacement RPVH Weibull cases).

even after accounting for temperature and stress effects [21]. In general, material conditions and microstructures that tend to increase the crack growth rate are also expected to increase the susceptibility to crack initiation. This correlation has demonstrated importance in similar probabilistic modeling efforts performed previously and is therefore emphasized in this report. Figure 4-12 and Figure 4-15 indicate that correlating initiation and growth leads to an increased ejection frequency.[18] This increase is due to postulated faster growth of earlier initiating flaws, which gives increased opportunity for cracks to extend around the CRDM. This effect accounts for a roughly 10 times higher AEF in the case of the initiation model developed from all material supplier data and a 2 times higher AEF in the case of the initiation model developed from the Alloy 600 replacement RPVH inspection data.

Alternate Initiation Weibull Models (Sensitivity Cases M13 and M16)

In sensitivity case M13, the MRP-105 initiation Weibull is utilized. This initiation model is shown to be much less aggressive than the Alloy 600 replacement RPVH Weibull, with significantly lower AEF and ALF results.

In contrast, in sensitivity case M16, the alternate calibration to the Alloy 600 replacement RPVH (calibrated with a Weibull slope of 3.0 instead of 1.17; see Section 4.2.2) results in a higher AEF and ALF. The AEF is roughly 15% higher, which is modest relative to the order of magnitude difference produced when using the initiation model developed from all material supplier data.

Other key takeaways from the sensitivity studies are:

- All cold head sensitivity cases resulted in AEF values less than 5E-05 occurrences per year. Similarly, no cases resulted in a base metal ALF greater than 0.05 new leaking penetrations per year.
- The predicted ALF increases most for the sensitivity case in which the initial flaw depth is decreased. The smaller initial flaw depth results in a longer time to leakage such that fewer cracks are detected at the time of the first scheduled inspection and are therefore incorporated in the ALF statistic. This case demonstrates that "conservatism" in modeling is not always straightforward, e.g., intuition may suggest it to be favorable to have smaller initial flaw depths. Nonetheless, there is only a roughly 30% increase in ALF for this case.
- Simulating inspections over the entire lifetime (case M12) results in a statistically equivalent AEF. The result justifies the use of an imprecisely known time of first credible inspection.
- The initiation activation energy used by this report (184 kJ/mol or 44 kcal/mol) leads to slightly more conservative risk predictions than the activation energy proposed in N-729-1 (209 kJ/mol or 50 kcal/mol), as demonstrated with sensitivity case M8.

4.3.2.2 PWSCC Growth Variability and the Impact of Initiation-Growth Correlation

As detailed in previous probabilistic modeling efforts (e.g., MRP-335 Rev. 1), PWSCC growth variability is modeled with random material factors applied to the PWSCC growth rate. For instance, in this effort, two random material factors are applied: one to represent variability among heads and one to represent variability among penetrations and from location to location

[18] The reduction in ALF is due to the correlation stimulating faster early flaw growth, causing the preponderance of leakages to occur prior to the first simulated inspection (and therefore not be counted toward ALF).

on the same penetration. Separate material factors are applied for Alloy 600 base metal and Alloy 82/182 weld metal PWSCC CGR models.

To validate the modeled PWSCC growth variability, the capability is built into the framework to track the material factors during different realizations and compile an empirical CDF that describes the distribution observed throughout simulation. With this capability, a study was performed to assess the effect of correlating initiation and growth parameters on PWSCC growth variability. To this end, several Monte Carlo experiments were run with varying degrees of correlation between the distributed factors applied to growth and the distributed factors applied to initiation. These experiments were produced with the initiation model developed from all material supplier data, at 563°F, for an operating period of 60 years.

For good measure, the results of these experiments are compared against two separately generated CDFs:

1. A numerical CDF generated by sampling material factors from their underlying (truncated log-normal) distributions, outside of the simulation framework.
2. An analytical solution for the product of the two material factor distributions without truncation.

Figure 4-30 and Figure 4-31 show the results for the PWSCC material factor for the various cases described above. The Monte Carlo simulations that used zero correlation between initiation and growth agree well with numerical solutions generated outside of the simulation framework, as expected. Truncation limits the modeled distributed factor on growth to no more than a factor of 1.3 higher than the maximum factor derived from Alloy 600 CGR data and no more than a factor of 2.3 higher than the maximum factor derived from Alloy 182 CGR data. Truncation is also applied in the numerical validation calculation by resampling.

Cases that introduce correlation demonstrate its effect on the observed PWSCC growth material factor. Negative correlation (i.e., earlier initiation translating to larger CGRs) is demonstrated to lead to generally larger and more dispersed CGRs for flaws that initiate inside of the first 60 years of operation; positive correlation has the inverse effect.[19]

The experiments presented above provide insight into the potential effects of material and microstructural properties that lead to correlation between initiation and growth (beyond that predicted with simple model forms that are typically applied). Probabilistic analysis offers a powerful way to explore correlation.

4.3.2.3 Convergence Studies

To assess the statistical convergence of the Monte Carlo statistics derived from a single Monte Carlo experiment, ten (10) identical but independently seeded Monte Carlo experiments are conducted and their results are compared. This "Monte Carlo convergence testing" was completed for three representative cases, as presented in Table 4-8. For each of the three cases, the number of Monte Carlo realizations used is consistent with that used to generate earlier

[19] While not demonstrated in Figure 4-30 and Figure 4-31, the effect of correlation on the growth factor attenuates as the operating period is extended. This is due to the fact that fewer initiating and growing flaws are exceptionally susceptible to PWSCC.

results. The solutions appear to be well converged for leakage statistics and acceptably converged for ejection statistics.[20]

A second convergence study is performed to verify the adequacy of the integration time step selected to numerically estimate the growth, transitioning, and interaction of flaws. This study is performed for cases with the B&WTP initiation model and an inspection interval of RIY = 2.25. The results of this study (i.e., variation in statistics as a function of the number of growth submodel iterations per year) are shown in Table 4-9 and graphically in Figure 4-32. The use of 12 iterations per year in this report is expected to result in numerical integration convergence errors less than about 1% on the ALF, less than 10% for AEF for cold head cases, and less than about 20% for AEF for hot head cases. This level of convergence is considered sufficient to ensure the validity of the conclusions drawn from the probabilistic analysis.

4.4 Conclusions

The probabilistic results support the current inspection requirements for Alloy 600 RPVH penetration nozzles, including for plants operating at T_{cold}. This probabilistic analysis is a key part of the updated technical basis of ASME Code Case N-729-1 [1], superseding that of MRP-105 [6], to include industry experience since 2004 and to replace the technical letter MRP 2011-034 [43] submitted to U.S. NRC in December 2011. The key conclusions of this section are as follows:

- The risk of ejection is predicted to be acceptably low (below 5E-5 ejections per year per RPVH, averaged across the operating lifetime) when periodic UT examinations are performed per the RIY = 2.25 interval of ASME Code Case N-729-1 [1]. This is true despite taking no credit for more frequent inspections required after PWSCC detection by N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D).
- Average penetration leakage frequencies due to cracks initiating in the nozzle material are below 0.05 new leaking penetrations per year for all the cases evaluated (including cold and non-cold heads), up to and including inspection intervals of RIY=2.25.
- No leaks have occurred since the onset of complete head inspections, so the model provides a conservative evaluation of the potential for PWSCC flaws to grow without detection because the predicted ALF values are on the order of 0.02-0.1 leaks per head per year for non-calibrated initiation models.
- Even assuming a plant that is nominally as susceptible to PWSCC as the Alloy 600 replacement RPVH calibration case, the probabilistic analysis demonstrates that a UT inspection interval based on RIY = 2.25 is sufficient to minimize the risk of leakage and ejection to acceptable levels. The RIY = 2.25 interval generally equates to an inspection interval of four or five 18-month cycles for a head operating at T_{cold}.
- Under various conditions, cases were run to investigate a UT inspection interval of every refueling outage versus every other refueling outage. The absolute difference in average

[20] For a select few cases where the AEF approached the minimum resolution of the simulation (e.g., cold head cases with more frequent UT and less aggressive initiation models), the Monte Carlo simulation was run for 107 realizations; this is believed to yield well-converged solutions, though this is not demonstrated with rigorous convergence testing.

ejection frequency between these cases is generally small (e.g., less than 2E-6 for all conditions evaluated and less than 6E-7 for the conditions that did not assume a most-conservative initiation model based on the experience of the Alloy 600 replacement RPVH calibration case).

- A UT interval of one rather than two refueling outages for top heads operating at T_{cold} that have previously detected PWSCC is concluded to result in an acceptably small effect on ejection and leakage risks. This conclusions is based on a) the acceptable risks achieved when no credit is given to reducing inspection intervals below RIY=2.25 once PWSCC is detected, and b) the comparable benefits achieved when using a one or two cycle UT inspection interval. The probabilistic analyses conservatively assume a high likelihood that many PWSCC flaws are initiated and detected in the head over life.
- The model sensitivity cases did not show significant deviation and support the robustness of conclusions drawn from the results.

4.5 Modeling Conservatisms

The results presented in this section typically use best-estimate modeling, with input distributions to handle uncertainties, per the standard approach, but significant modeling conservatisms are maintained in some cases, namely:

- A through-wall 30° circumferential flaw located at the top of the weld is assumed to be produced immediately upon nozzle leakage (i.e., through-wall cracking to the nozzle annulus). This assumption was maintained from the approach taken in MRP-105 [6] as part of the technical basis for the inspection requirements for unmitigated RPVHPNs in N-729-1 [1]. In most cases, circumferential cracking in the nozzle tube at or near the top of the weld has not been detected for leaking RPVHPNs [4].
- The overall likelihood of flaw detection is conservatively low due to several modeling decisions including:
  - A POD of 0.9 is assumed to model bare metal visual examinations for evidence of leakage of RPVHPNs. A higher POD is typically expected based on plant experience.
  - No credit is taken for the UT leak path exam for the case of RPVHPNs.
- An environmental factor greater than 1 is assumed to increase the growth rate of circumferential cracks in contact with the OD annulus of RPVHPNs. This is assumed because of the possibility of an accelerating effect of the chemical environment on the nozzle OD.
- A zero stress intensity factor threshold is assumed for PWSCC growth.
- Axial ID flaws on RPVHPN tubes are assumed to always initiate at the elevation having the highest hoop stresses.
- Bounding high K solutions are used to predict crack growth of circumferential cracks above the J-groove weld.

Table 4-5
Matrix of Test Cases

Temperature (°F)	UT Interval (cycles)	Initiation Weibull		
		All Material Suppliers	B&W TP Material	Replacement Alloy 600 RPVH
605	1	*Limited*	Base	-
563	1	Base	Base	Base
	2	*Limited*	Base	*Limited*
	4	*Limited*	*Limited*	**Full**
555	1	Base	Base	Base
	2	Base	Base	Base
	5	Base	Base	Base

Notes:

1. "Base" indicates only the base case is evaluated.
2. "*Limited*" indicates that the correlated initiation and growth sensitivity and the increased multiple flaw initiation slope sensitivity studies are evaluated, in addition to the base case.
3. "**Full**" indicates that the entire set of sensitivity studies was evaluated, in addition to the base case. All sensitivity studies are defined in Table 4-3.

Table 4-6
Summary of Results

				Statistics after First Inspections				
Operating Temp. (°F)	UT Inspection Interval	Weibull Model	Other	AEF	ALF (All Material)	ALF (Nozzle Material)	Max IEF	Max ILF
605	1	B&W TP		5.28E-5	2.39E-1	2.37E-2	3.77E-4	3.59E-1
605	1	All Plant		3.15E-5	1.53E-1	1.56E-2	1.71E-4	1.72E-1
555	1	All Plant		4.00E-8	1.57E-2	9.90E-5	1.33E-7	1.90E-2
555	2	All Plant		8.89E-8	1.69E-2	4.48E-4	3.33E-7	2.07E-2
555	5	All Plant		1.04E-6	1.99E-2	2.11E-3	3.11E-6	2.67E-2
555	1	B&W TP		5.67E-8	4.97E-2	3.13E-4	4.67E-7	5.14E-2
555	2	B&W TP		2.24E-7	5.47E-2	1.40E-3	8.67E-7	5.80E-2
555	5	B&W TP		3.73E-6	6.58E-2	6.71E-3	1.22E-5	7.88E-2
555	1	A600 Repl.		1.64E-7	2.26E-1	1.42E-3	1.60E-6	3.08E-1
555	2	A600 Repl.		7.93E-7	2.65E-1	6.42E-3	4.67E-6	3.59E-1
555	5	A600 Repl.		1.60E-5	3.41E-1	3.14E-2	5.56E-5	5.11E-1
563	1	All Plant		7.11E-8	2.41E-2	2.39E-4	8.00E-7	2.80E-2
563	2	All Plant		2.38E-7	2.61E-2	9.88E-4	8.67E-7	3.09E-2
563	4	All Plant		1.84E-6	2.93E-2	2.96E-3	7.33E-6	3.77E-2
563	1	B&W TP		1.56E-7	6.98E-2	6.80E-4	2.07E-6	7.16E-2
563	2	B&W TP		6.98E-7	7.70E-2	2.82E-3	3.67E-6	8.24E-2
563	4	B&W TP		5.30E-6	8.82E-2	8.54E-3	1.80E-5	1.05E-1
563	1	A600 Repl.		4.07E-7	2.78E-1	2.62E-3	6.00E-6	4.43E-1
563	2	A600 Repl.		2.34E-6	3.25E-1	1.11E-2	1.33E-5	5.13E-1
563	4	A600 Repl.		2.10E-5	3.92E-1	3.48E-2	1.28E-4	6.54E-1
563	4	A600 Repl.	Extended Simulation Lifetime	1.55E-5	3.28E-1	2.96E-2	1.09E-4	6.55E-1
563	4	A600 Repl.	Resample Realizations with Past Ejections	1.86E-5	3.98E-1	3.44E-2	1.01E-4	6.58E-1
563	4	A600 Repl.	Increased Multiple Flaw Weibull Slope	2.16E-5	3.92E-1	3.48E-2	1.10E-4	6.56E-1
563	4	A600 Repl.	Correlated Initiation and Growth	2.44E-5	3.65E-1	3.51E-2	1.54E-4	6.53E-1
563	4	A600 Repl.	Decreased Max POD for UT	3.80E-5	3.95E-1	3.77E-2	1.61E-4	6.56E-1
563	4	A600 Repl.	Decreased Critical Flaw Size	3.09E-5	3.92E-1	3.46E-2	1.77E-4	6.55E-1
563	4	A600 Repl.	Use 50%ile MRP-55 Curve for Alloy 600	1.44E-5	4.00E-1	2.91E-2	7.67E-5	6.56E-1
563	4	A600 Repl.	Initiation Activation Energy per N-729-1	1.90E-5	3.57E-1	3.22E-2	8.87E-5	5.66E-1
563	4	A600 Repl.	Decreased Initiation Activation Energy	2.06E-5	4.14E-1	3.64E-2	8.60E-5	7.20E-1
563	4	A600 Repl.	Decreased Growth Activiation Energy	3.22E-5	3.99E-1	4.03E-2	1.71E-4	6.77E-1
563	4	A600 Repl.	Smaller Initial Flaw Size	2.24E-5	5.17E-1	3.45E-2	1.21E-4	7.56E-1
563	4	A600 Repl.	Inspections over Full Simulated Life	2.26E-5	3.96E-1	3.73E-2	1.75E-4	6.77E-1
563	4	A600 Repl.	Initiation Weibull to Match MRP-105	1.11E-6	2.22E-2	2.34E-3	4.00E-6	4.60E-2
563	4	A600 Repl.	Increased UT POD Correlation	2.69E-5	4.02E-1	3.62E-2	1.01E-4	6.57E-1
563	4	A600 Repl.	Decreased BMV POD	3.77E-5	3.91E-1	3.51E-2	1.30E-4	6.54E-1
563	4	A600 Repl.	Alternate A600 Repl. RPVH Calibration	2.40E-5	4.73E-1	4.30E-2	1.38E-4	6.97E-1
563	4	B&W TP	Increased Multiple Flaw Weibull Slope	8.26E-6	1.58E-1	1.47E-2	4.13E-5	1.97E-1
563	4	B&W TP	Correlated Initiation and Growth	2.18E-5	9.50E-2	2.02E-2	8.80E-5	1.32E-1
563	2	A600 Repl.	Increased Multiple Flaw Weibull Slope	2.26E-6	3.25E-1	1.10E-2	1.00E-5	5.14E-1
563	2	A600 Repl.	Correlated Initiation and Growth	2.86E-6	3.06E-1	1.06E-2	2.33E-5	4.99E-1
563	4	All Plant	Increased Multiple Flaw Weibull Slope	2.67E-6	5.65E-2	5.44E-3	9.33E-6	7.43E-2
563	4	All Plant	Correlated Initiation and Growth	1.12E-5	3.50E-2	9.07E-3	4.47E-5	4.69E-2
563	2	All Plant	Increased Multiple Flaw Weibull Slope	2.99E-7	4.88E-2	1.81E-3	1.07E-6	5.86E-2
563	2	All Plant	Correlated Initiation and Growth	1.60E-6	2.88E-2	3.41E-3	8.67E-6	3.36E-2
605	1	All Plant	Increased Multiple Flaw Weibull Slope	4.73E-5	2.71E-1	2.65E-2	2.15E-4	3.32E-1
605	1	All Plant	Correlated Initiation and Growth	6.87E-5	1.57E-1	2.63E-2	4.74E-4	1.78E-1

Table 4-7
AEF for Different Inspection Regimes Normalized by the AEF of their Respective RIY = 2.25 Cases

Case Description	Weibull Model		
	All Supplier	B&W TP	A600 Repl.
555°F, Every Cycle	0.04	0.02	0.01
555°F, Every Other Cycle	0.09	0.06	0.05
563°F, Every Cycle	0.04	0.03	0.02
563°F, Every Other Cycle	0.13	0.13	0.11

Table 4-8
Results of Realization Convergence Study

Statistic	Mean Across 10 Trials	Standard Deviation Across 10 Trials	Precision of Mean (2 * stdev / mean)
555°F, BW Weibull, 5 Cycle UT (3E+6 Realizations)			
Average Yearly Frequency of Leakage on Head	6.57E-02	5.61E-05	0.2%
Average Yearly Frequency of Ejection	3.70E-06	1.62E-07	8.8%
563°F, BW Weibull, 4 Cycle UT (1E+6 Realizations)			
Average Yearly Frequency of Leakage on Head	8.81E-02	2.12E-04	0.5%
Average Yearly Frequency of Ejection	4.95E-06	2.26E-07	9.1%
605°F, BW Weibull, 1 Cycle UT (1E+6 Realizations)			
Average Yearly Frequency of Leakage on Head	2.39E-01	1.12E-04	0.1%
Average Yearly Frequency of Ejection	5.31E-05	1.78E-06	6.7%

Table 4-9
Results of Growth Substep Convergence Study

	Statistic	Absolute Difference	Percent Difference
555°F	*6 to 12 Substeps per year*		
555°F	Average Yearly Frequency of Leakage on Head	+3.71E-04	+0.6%
555°F	Average Yearly Frequency of Ejection	+3.19E-07	+8.5%
555°F	*12 to 18 Substeps per year*		
555°F	Average Yearly Frequency of Leakage on Head	-2.04E-05	-0.0%
555°F	Average Yearly Frequency of Ejection	-1.63E-07	-4.6%
555°F	*12 to 24 Substeps per year*		
555°F	Average Yearly Frequency of Leakage on Head	+6.02E-05	+0.1%
555°F	Average Yearly Frequency of Ejection	-3.41E-07	-10.1%
563°F	*6 to 12 Substeps per year*		
563°F	Average Yearly Frequency of Leakage on Head	+2.47E-04	+0.3%
563°F	Average Yearly Frequency of Ejection	+5.22E-07	+9.8%
563°F	*12 to 18 Substeps per year*		
563°F	Average Yearly Frequency of Leakage on Head	+4.46E-04	+0.5%
563°F	Average Yearly Frequency of Ejection	+2.56E-07	+4.6%
563°F	*12 to 24 Substeps per year*		
563°F	Average Yearly Frequency of Leakage on Head	+7.43E-04	+0.8%
563°F	Average Yearly Frequency of Ejection	-4.67E-07	-9.6%
605°F	*6 to 12 Substeps per year*		
605°F	Average Yearly Frequency of Leakage on Head	+1.54E-03	+0.6%
605°F	Average Yearly Frequency of Ejection	+2.05E-06	+4.2%
605°F	*12 to 18 Substeps per year*		
605°F	Average Yearly Frequency of Leakage on Head	+1.15E-03	+0.5%
605°F	Average Yearly Frequency of Ejection	+6.53E-06	+11.7%
605°F	*12 to 24 Substeps per year*		
605°F	Average Yearly Frequency of Leakage on Head	+1.45E-03	+0.6%
605°F	Average Yearly Frequency of Ejection	+8.00E-06	+14.0%

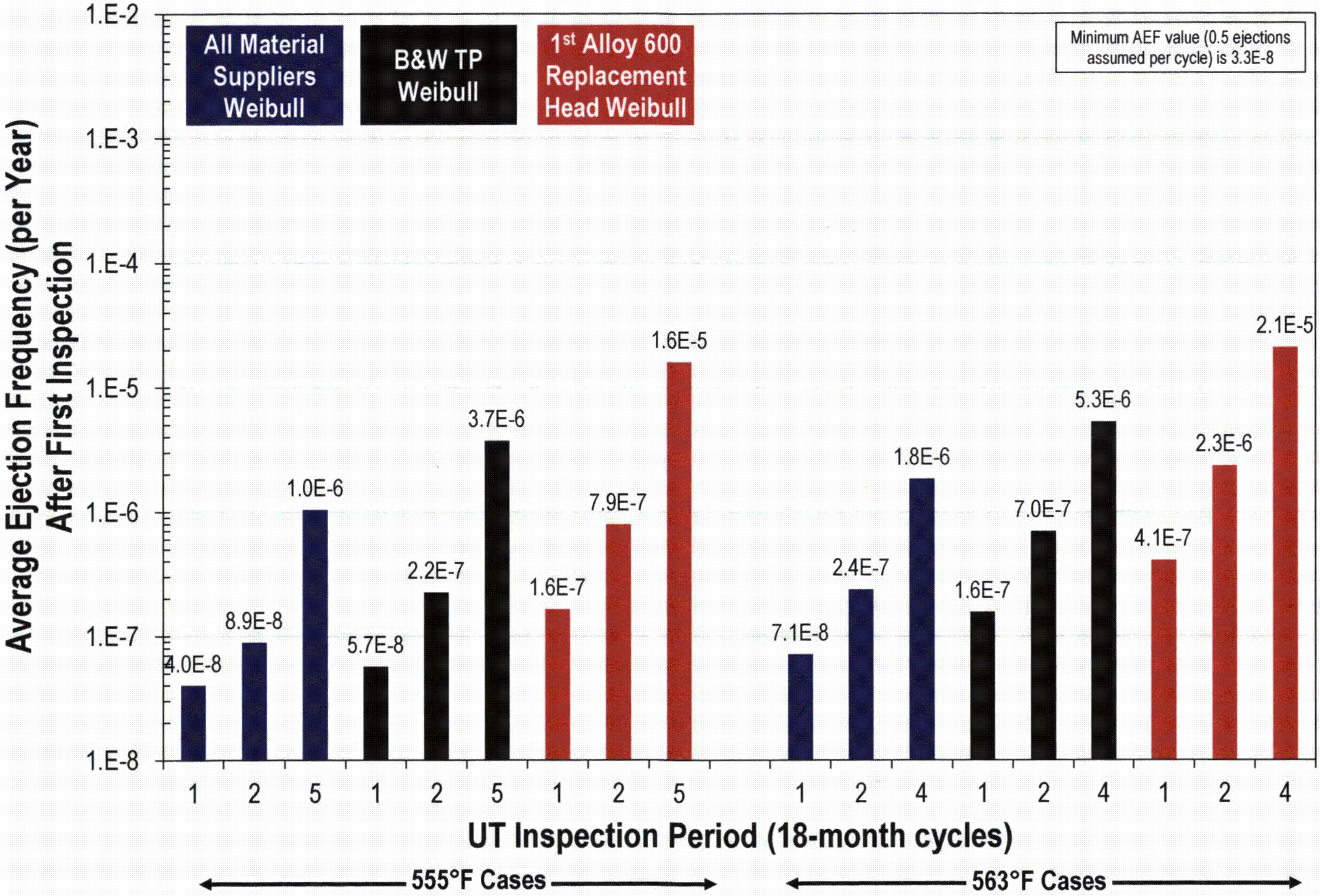

Figure 4-6
AEF Values for Cold Heads with Different Initiation Weibull Models and UT Inspection Intervals

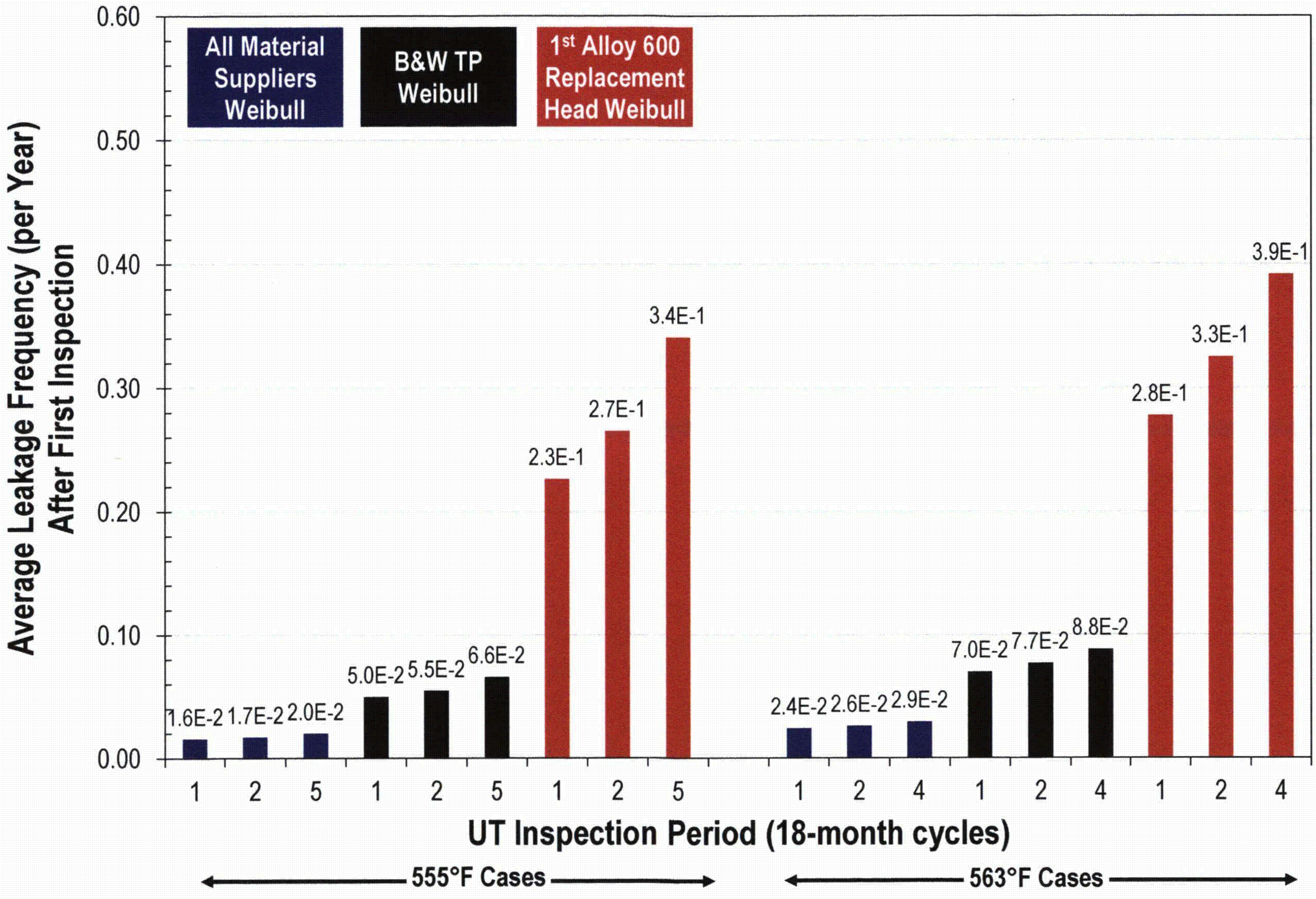

Figure 4-7
ALF Values for Cold Heads with Different Initiation Weibull Models and UT Inspection Intervals

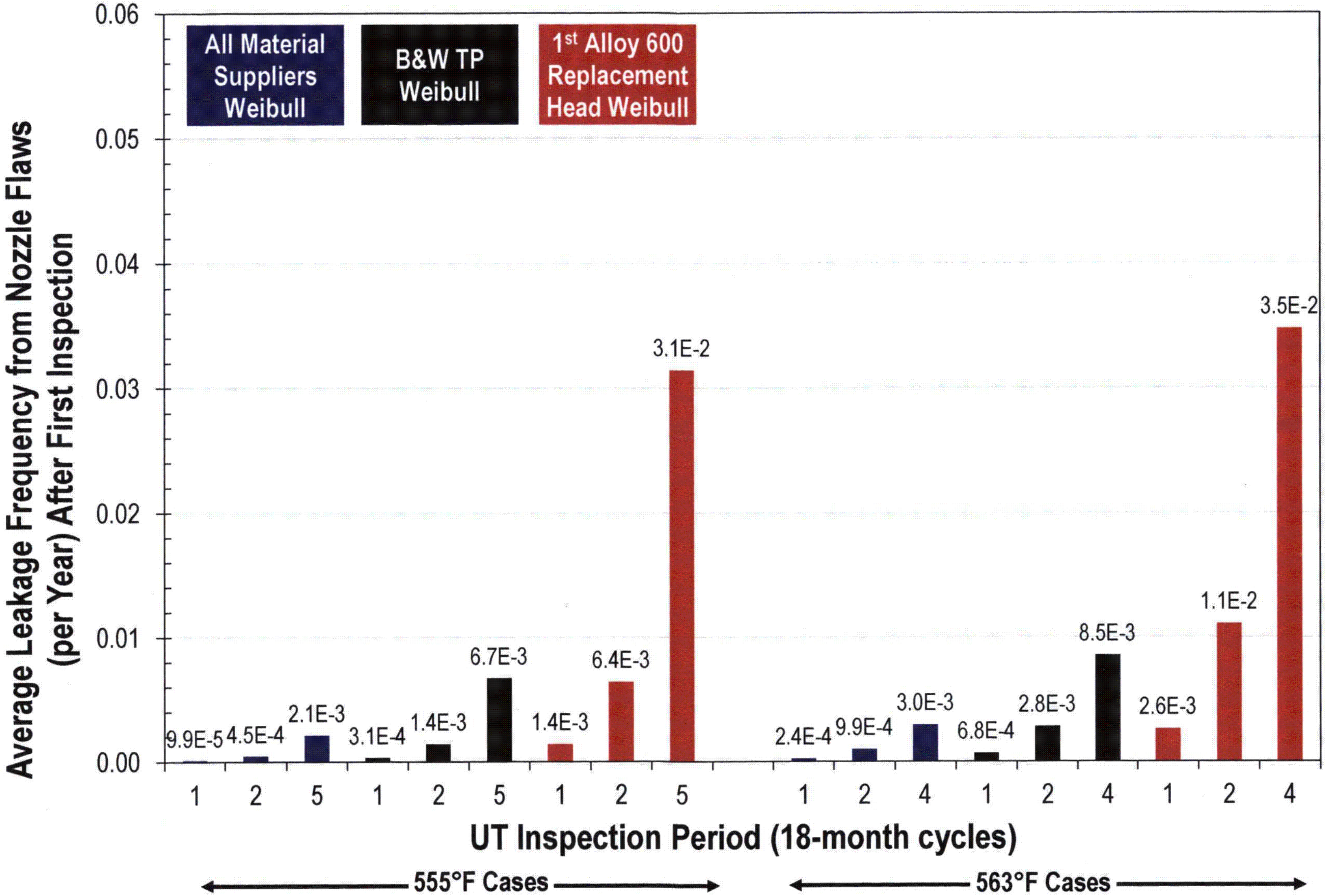

Figure 4-8
ALF Values (Excluding Weld Flaws) for Cold Heads with Different Initiation Weibull Models and UT Inspection Intervals

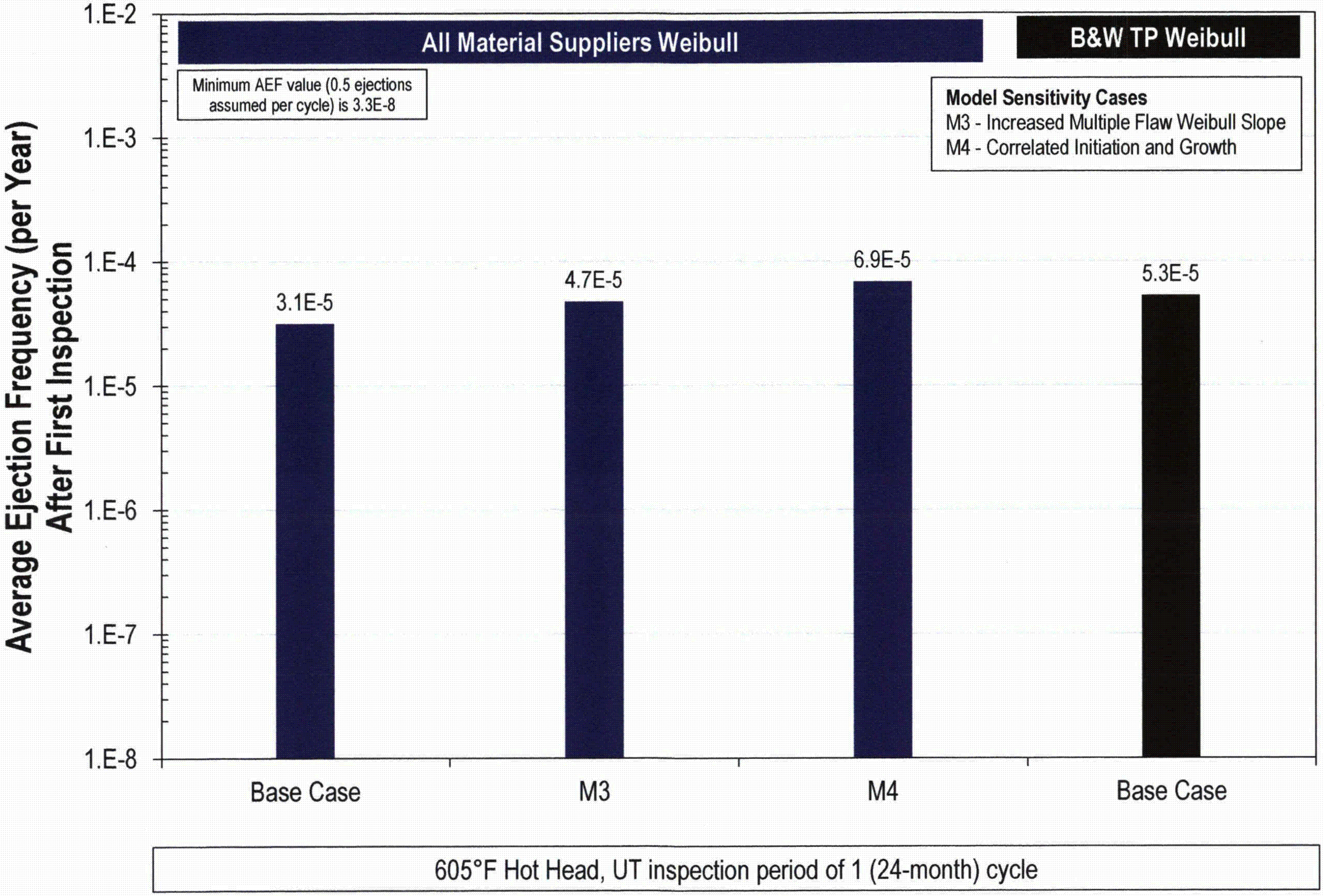

Figure 4-9
AEF Values for Hot Heads

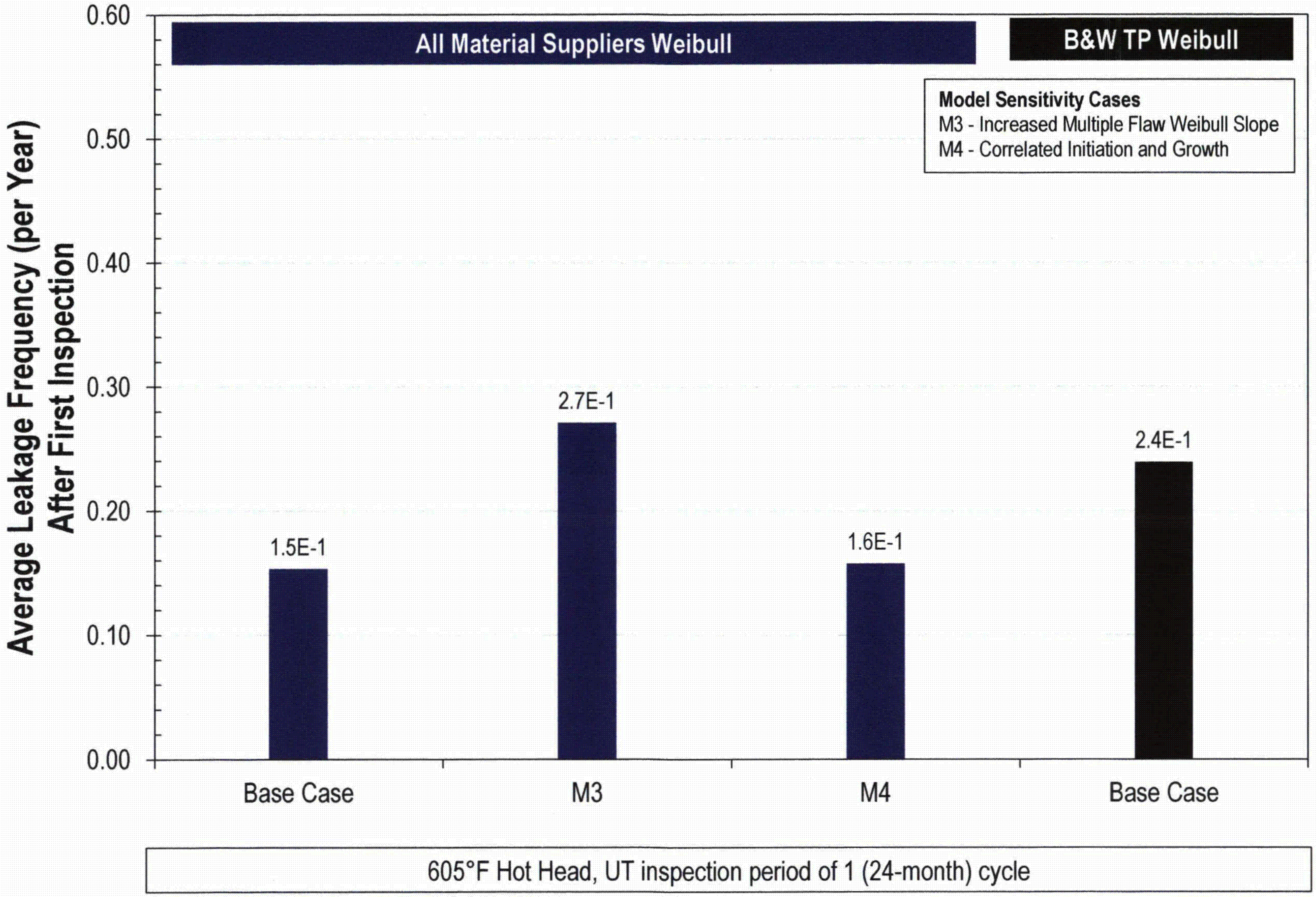

Figure 4-10
ALF Values for Hot Heads

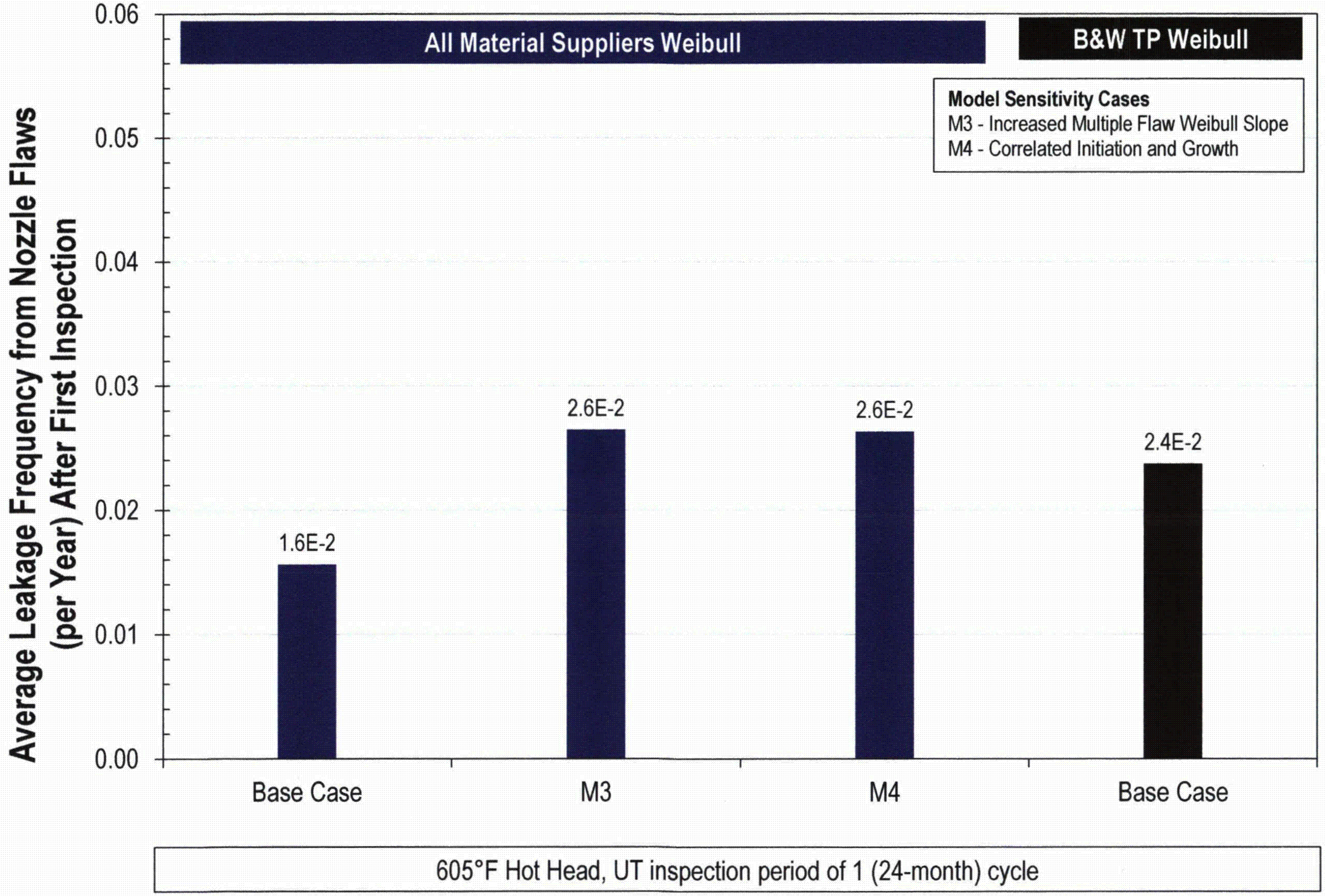

Figure 4-11
ALF Values (Excluding Weld Flaws) for Hot Heads

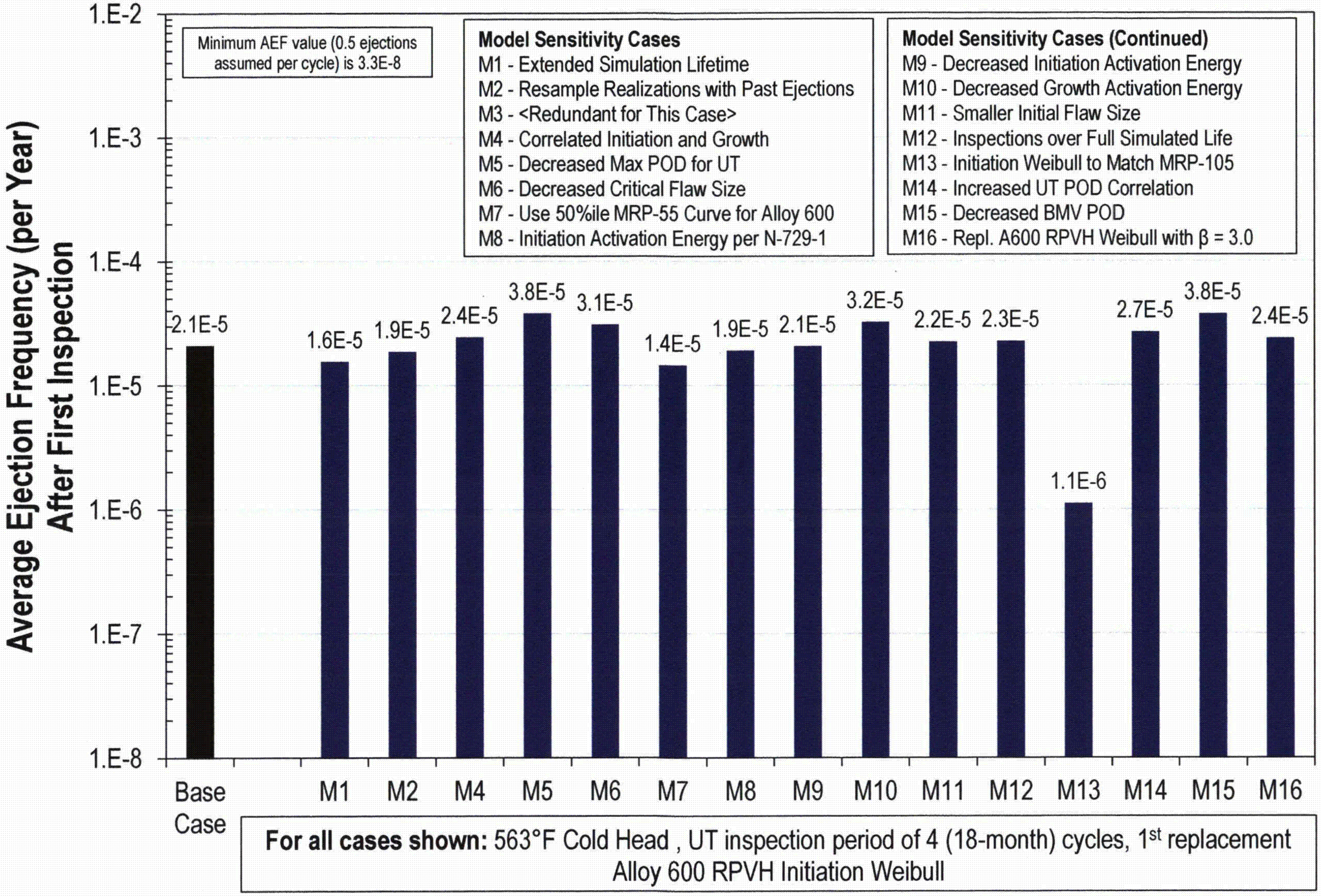

Figure 4-12
AEF Values for Full Set of Sensitivity Studies on Case with 563°F, UT Interval of 4 Cycles, and A600 Replacement RPVH Weibull

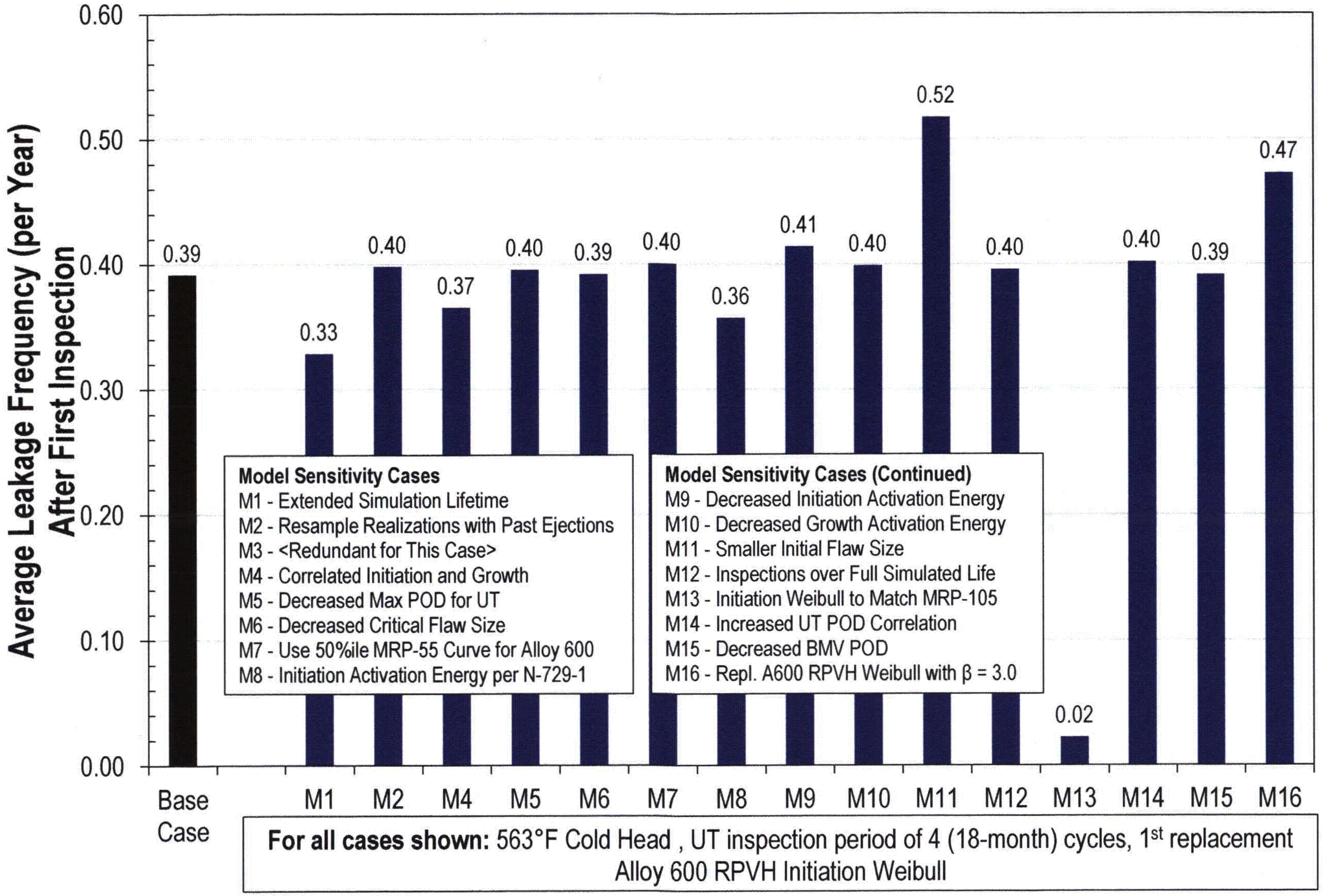

Figure 4-13
ALF Values for Full Set of Sensitivity Studies on Case with 563°F, UT Interval of 4 Cycles, and A600 Replacement RPVH Weibull

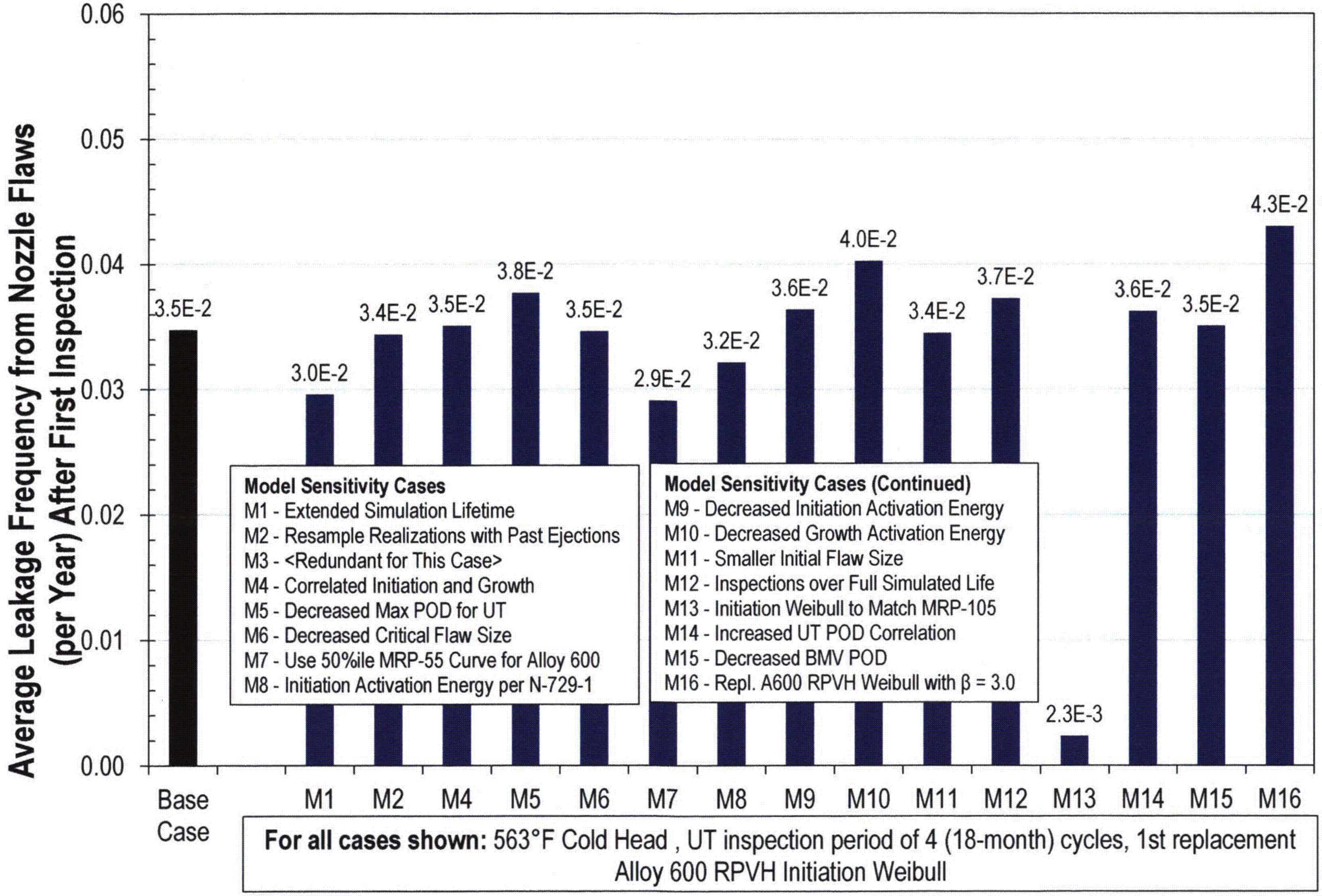

Figure 4-14
ALF Values (Excluding Weld Flaws) for Sensitivities on 563°F, UT Interval of 4 Cycles, and A600 Replacement RPVH Weibull

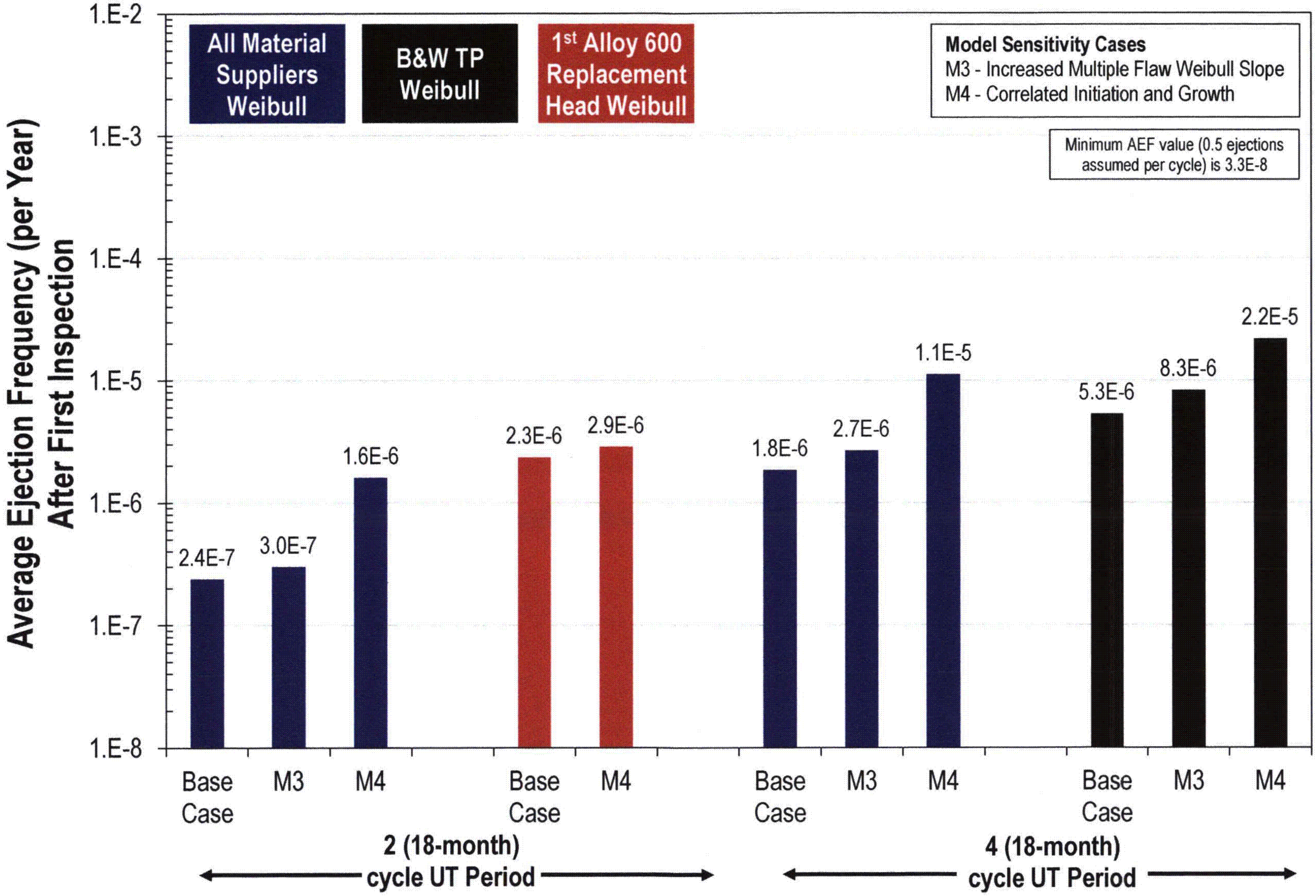

Figure 4-15
AEF Values for Limited Sensitivity Studies on Assorted Cases at 563°F

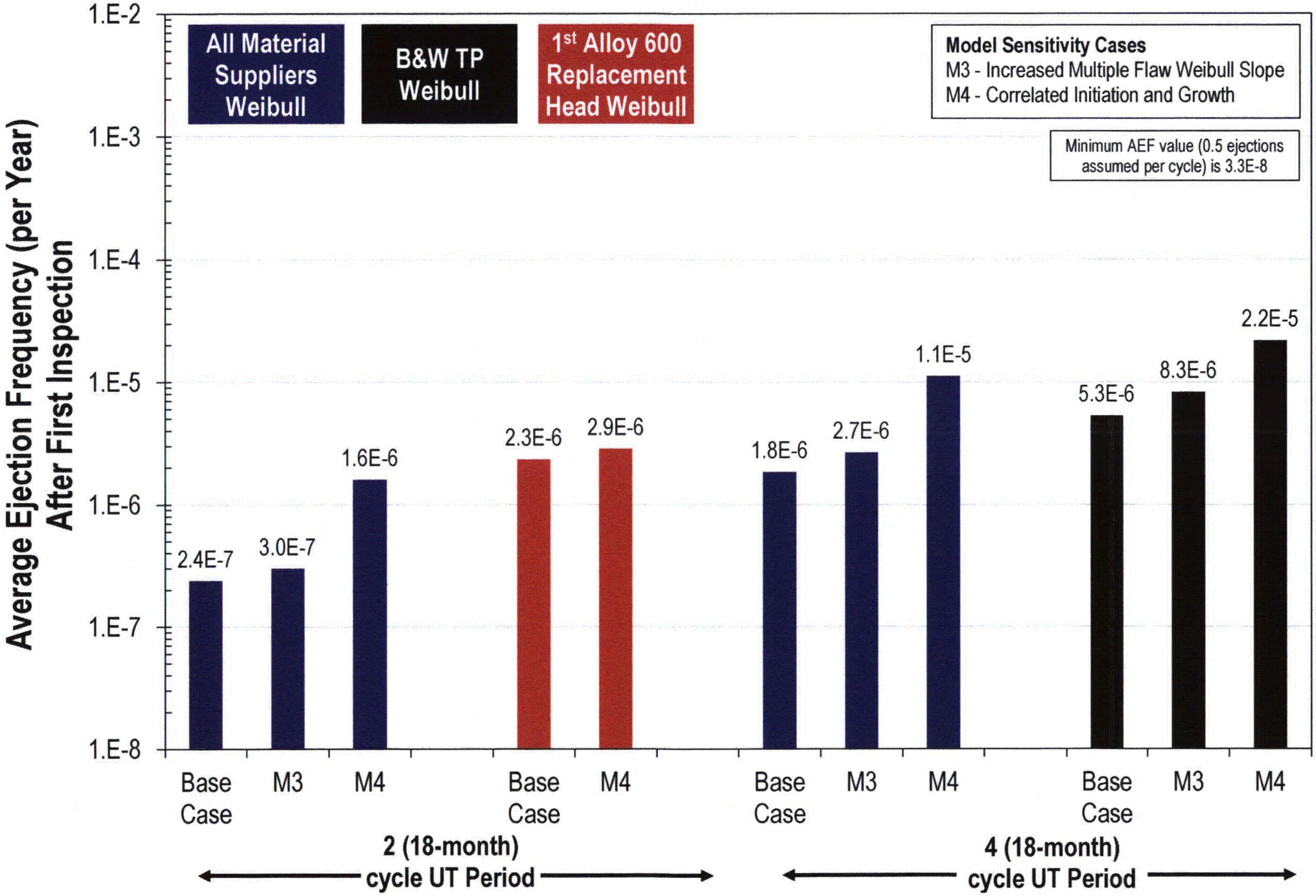

Figure 4-15
AEF Values for Limited Sensitivity Studies on Assorted Cases at 563°F

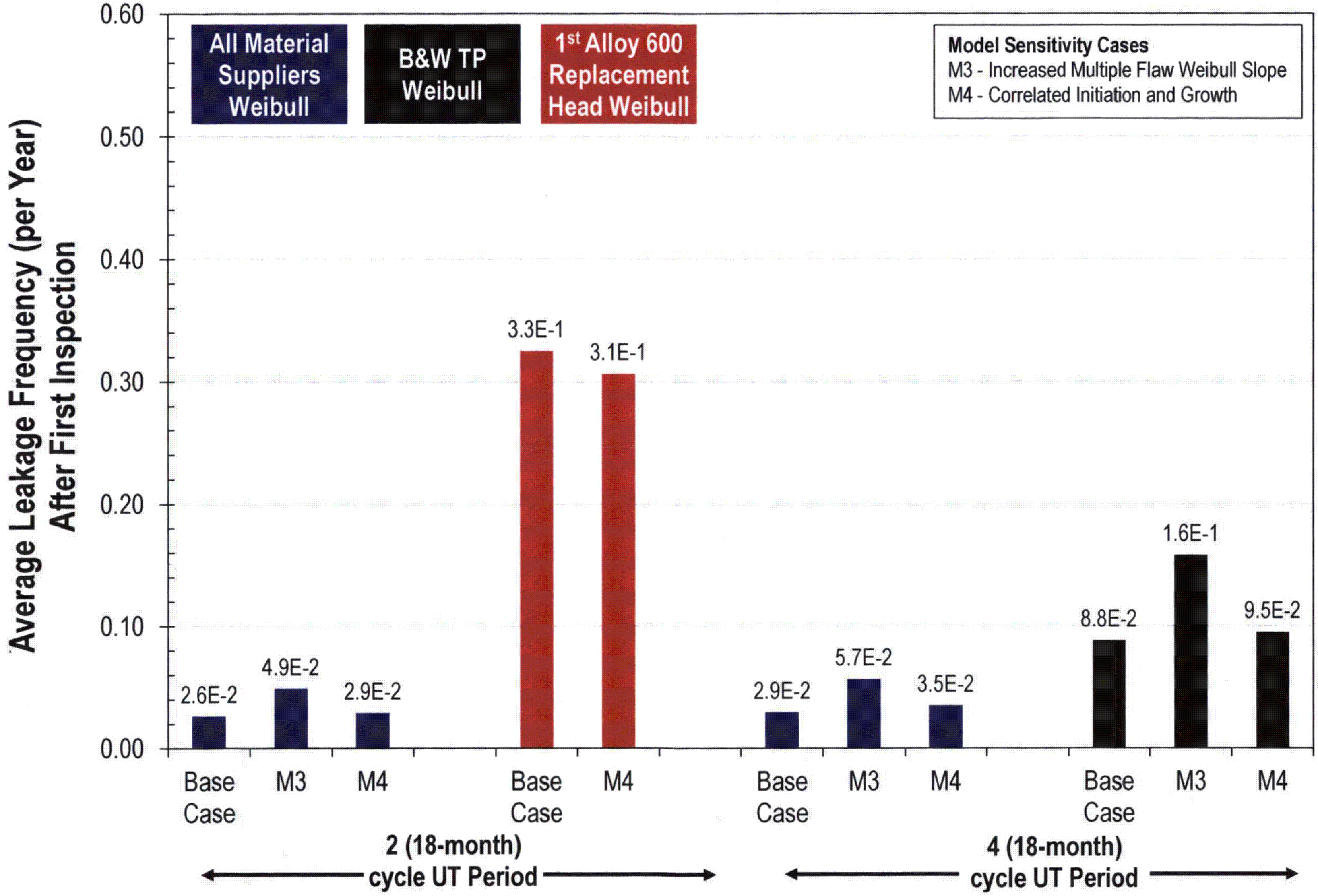

Figure 4-16
ALF Values for Limited Sensitivity Studies on Assorted Cases at 563°F

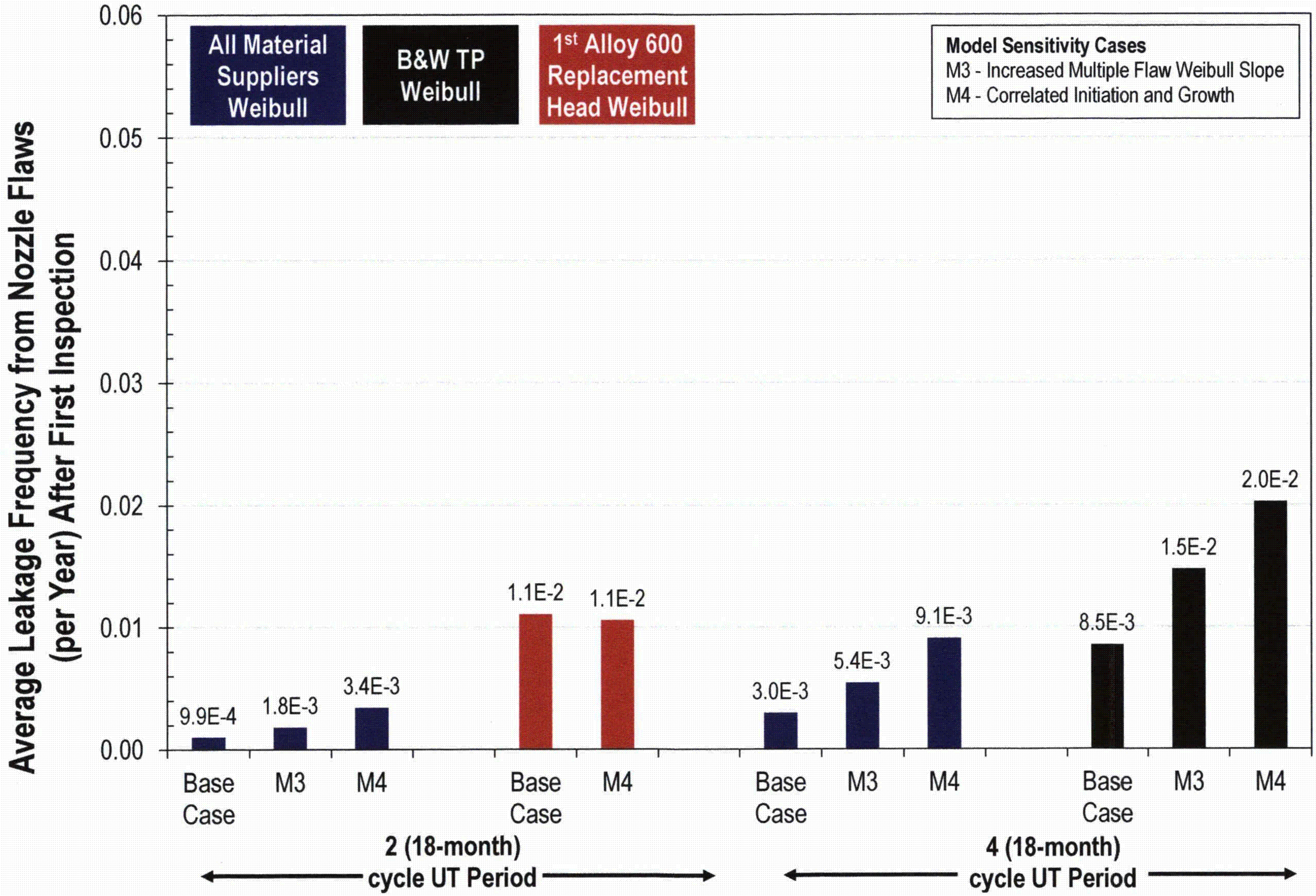

Figure 4-17
ALF Values (Excluding Weld Flaws) for Limited Sensitivity Studies on Assorted Cases at 563°F

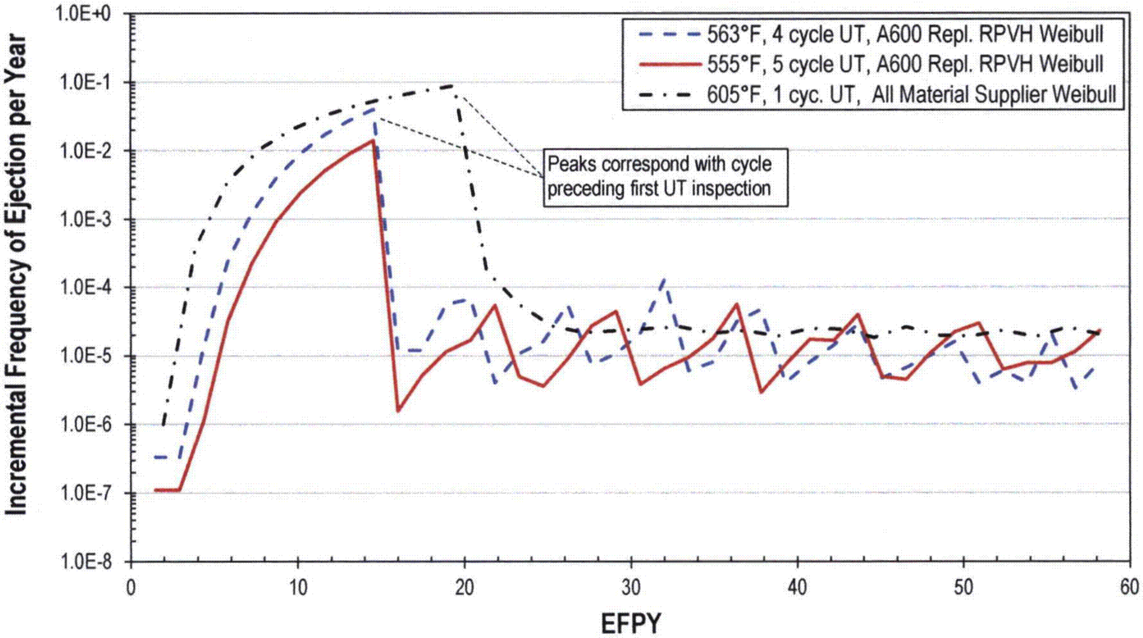

Figure 4-18
Incremental Frequency of Ejection for Different Temperatures with Inspections Every RIY = 2.25

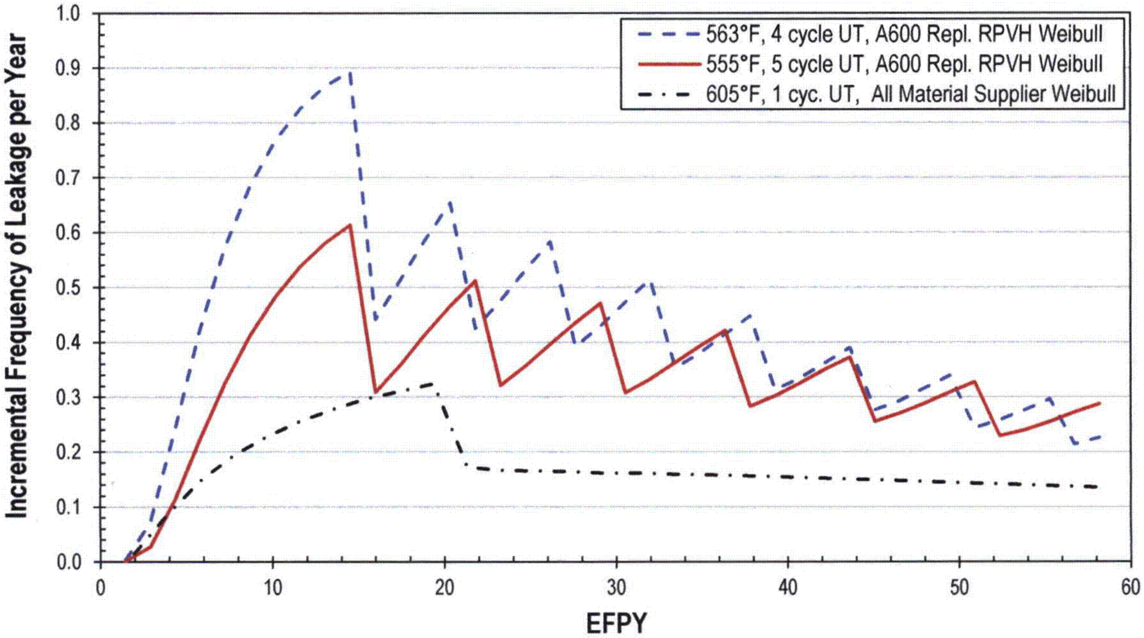

Figure 4-19
Incremental Frequency of Leakage for Different Temperatures with Inspections Every RIY = 2.25

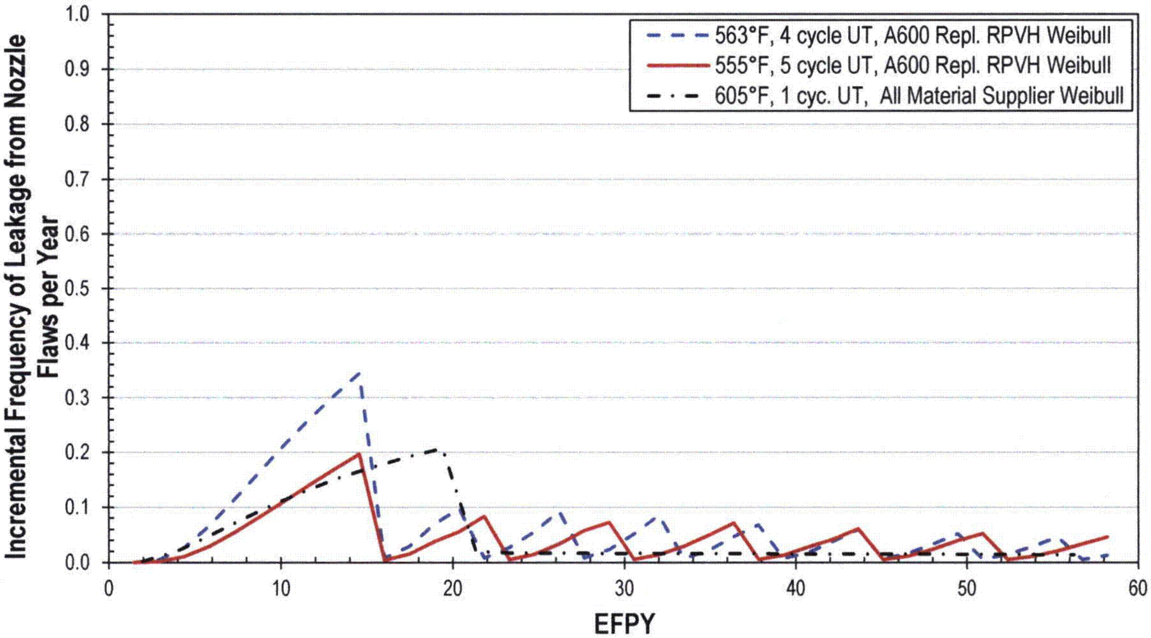

Figure 4-20
Incremental Frequency of Leakage due to Nozzle Flaws (Excludes Weld Flaws) for Different Temperatures with Inspections Every RIY = 2.25

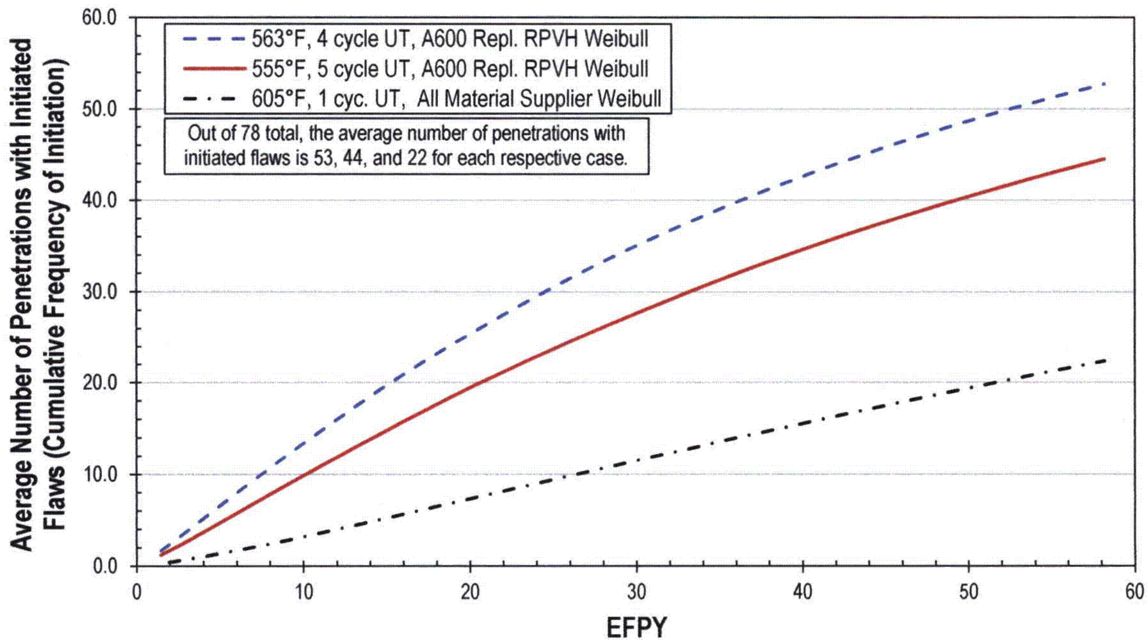

Figure 4-21
Cumulative Number of Penetrations with at Least One Initiated Crack for Different Temperatures with Inspections Every RIY = 2.25

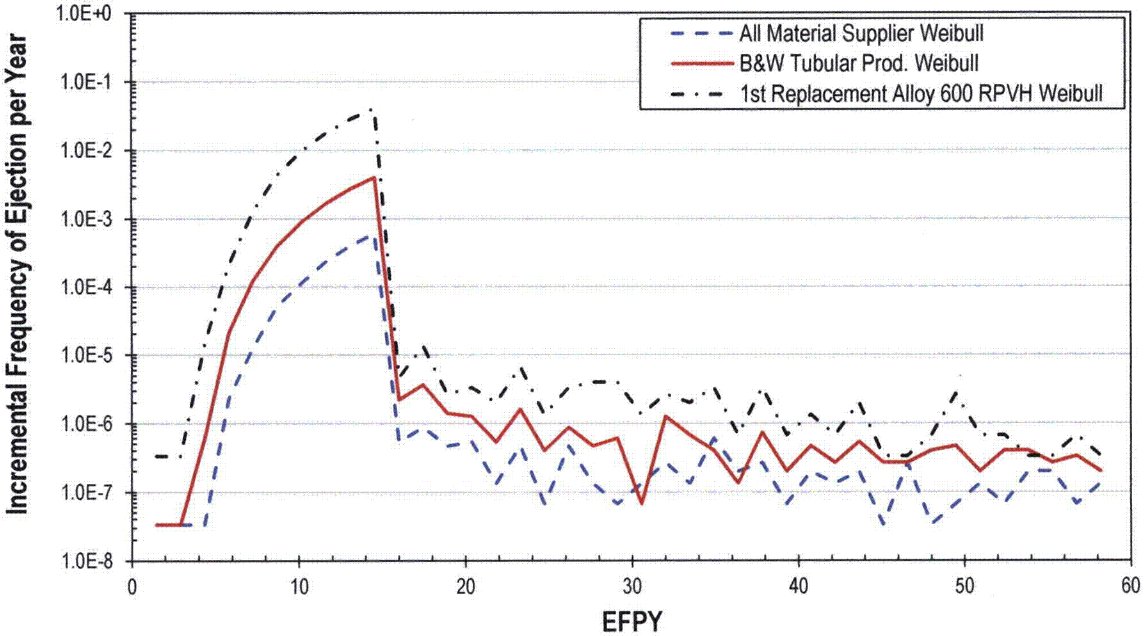

Figure 4-22
Incremental Frequency of Ejection for 563°F and a UT Interval of 2 Cycles

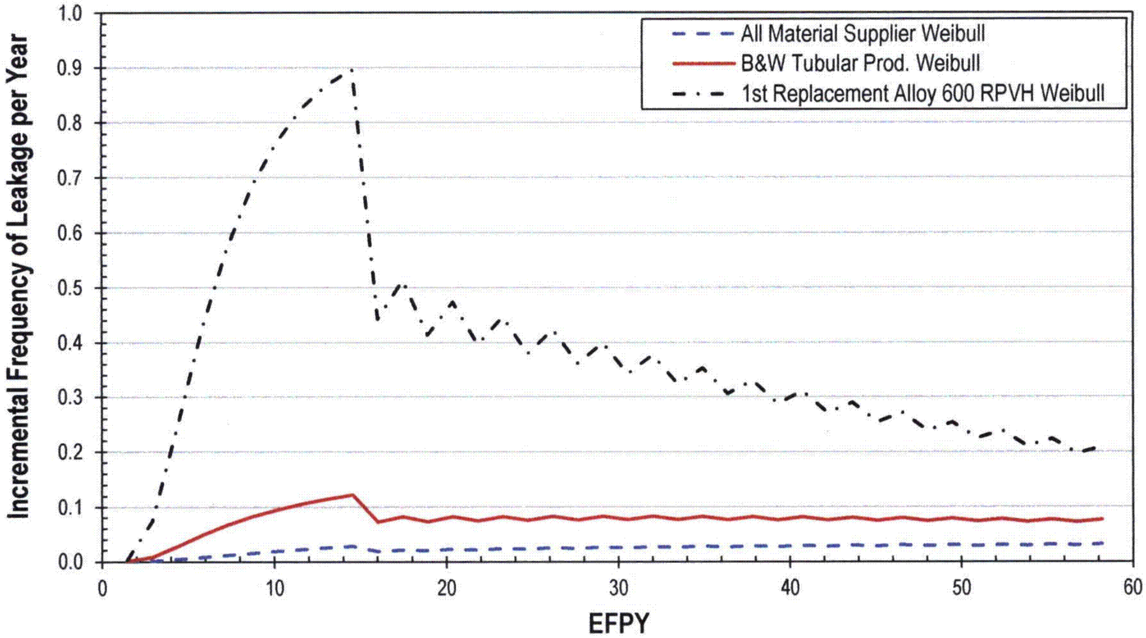

Figure 4-23
Incremental Frequency of Leakage for 563°F and a UT Interval of 2 Cycles

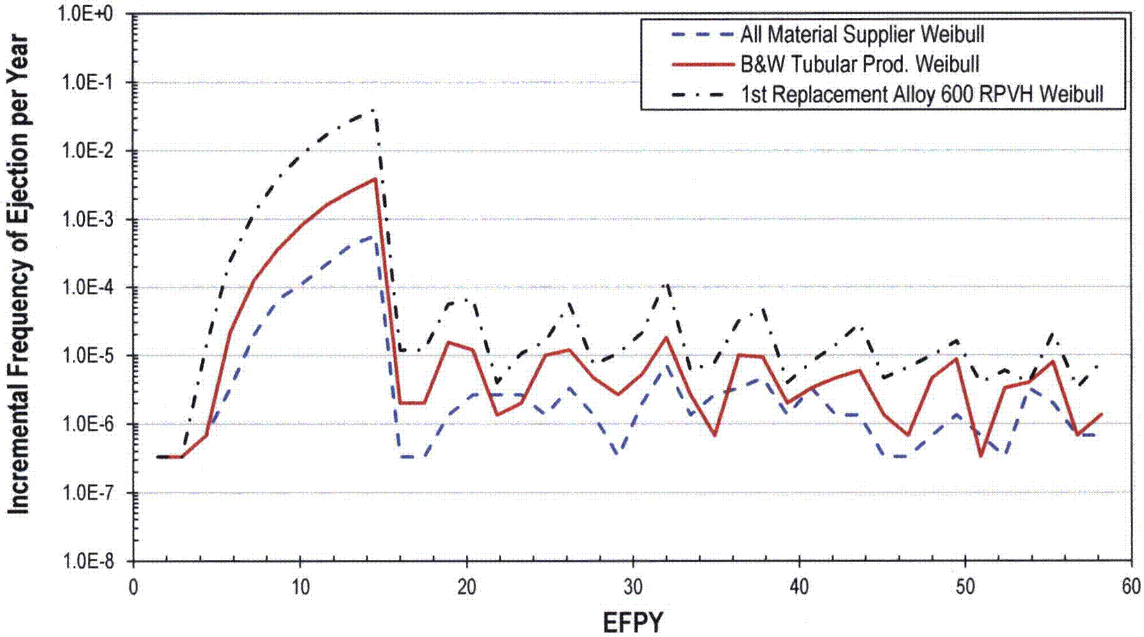

Figure 4-24
Incremental Frequency of Ejection for 563°F and a UT Interval of 4 Cycles

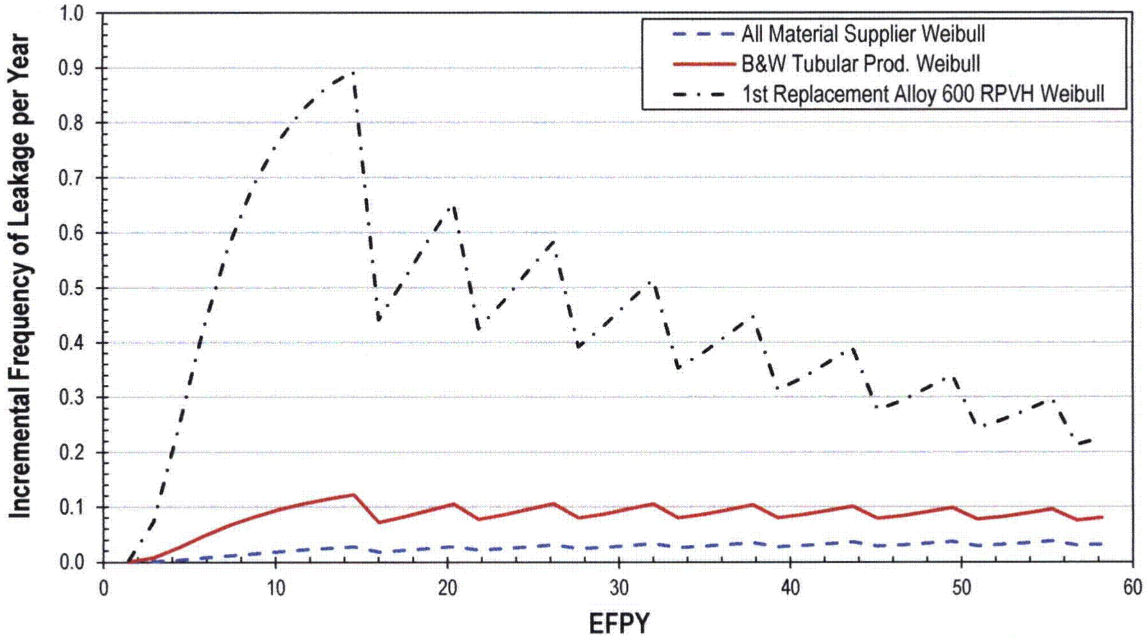

Figure 4-25
Incremental Frequency of Leakage for 563°F and a UT Interval of 4 Cycles

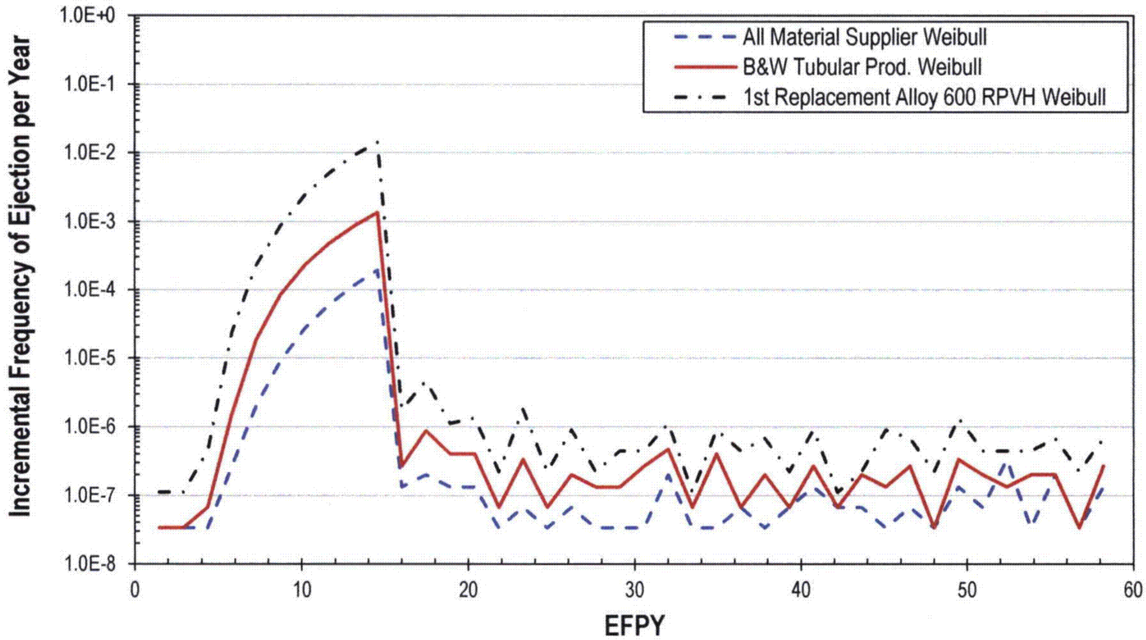

Figure 4-26
Incremental Frequency of Ejection for 555°F and a UT Interval of 2 Cycles

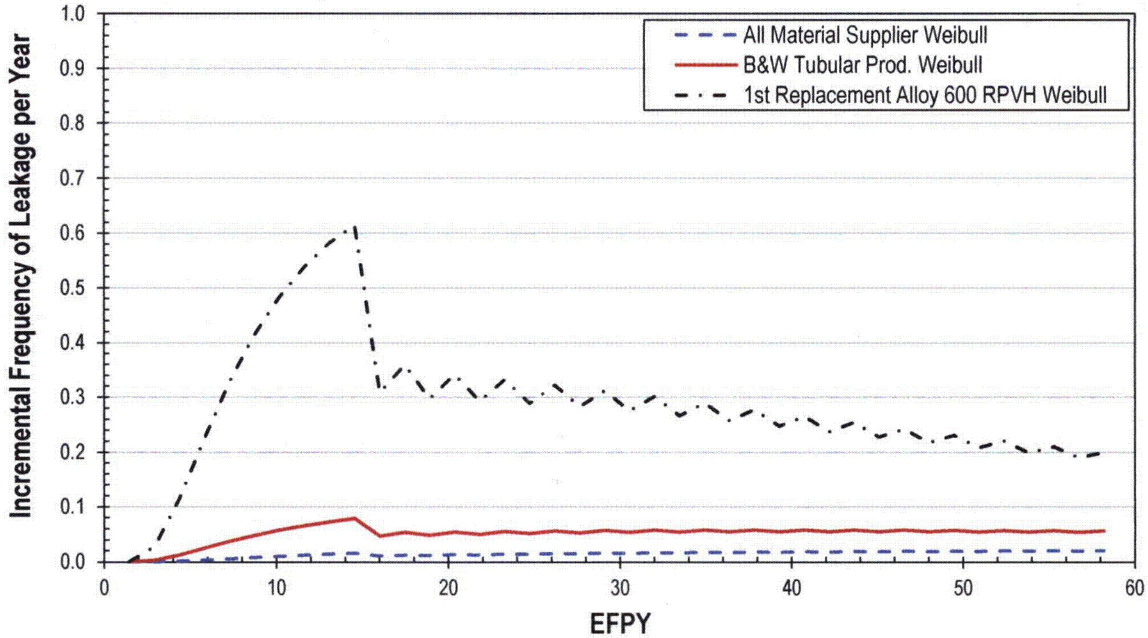

Figure 4-27
Incremental Frequency of Leakage for 555°F and a UT Interval of 2 Cycles

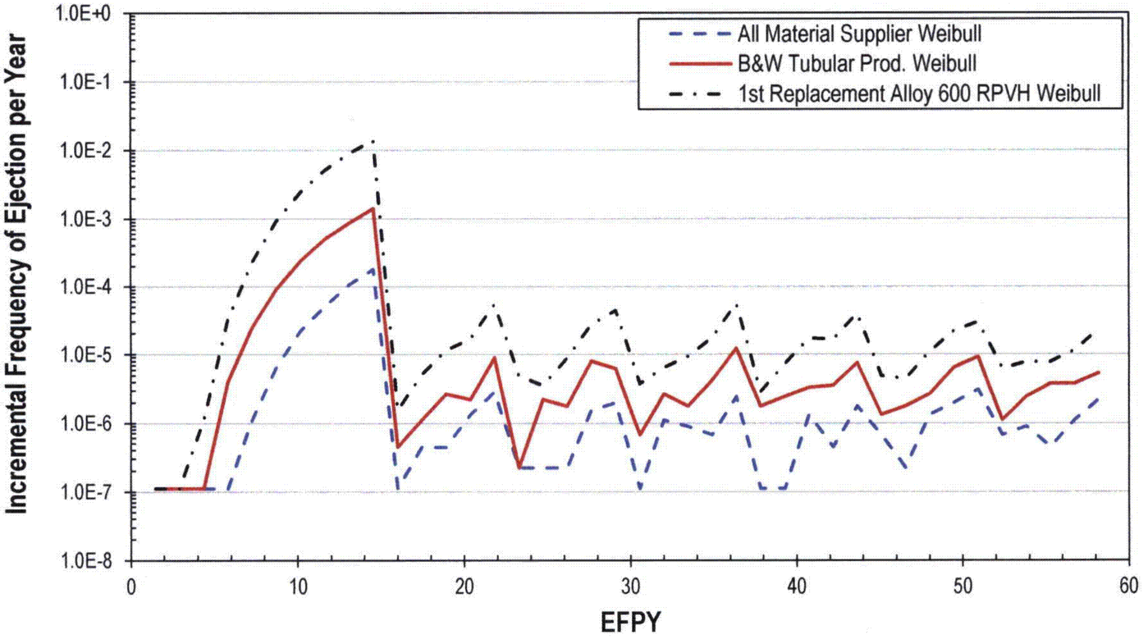

Figure 4-28
Incremental Frequency of Ejection for 555°F and a UT Interval of 5 Cycles

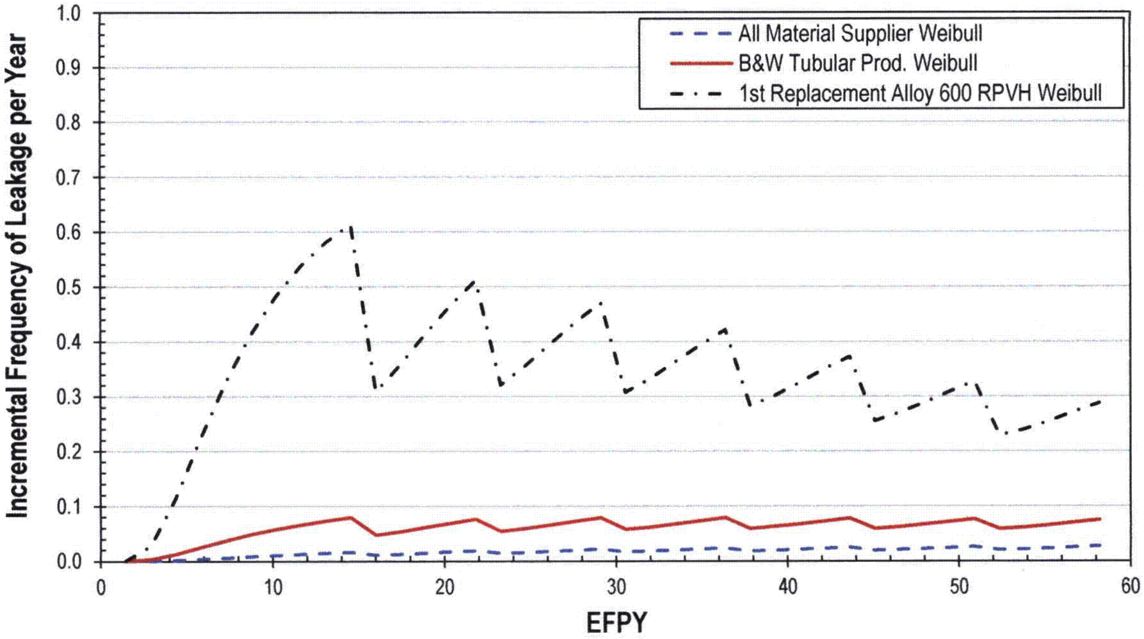

Figure 4-29
Incremental Frequency of Leakage for 555°F and a UT Interval of 5 Cycles

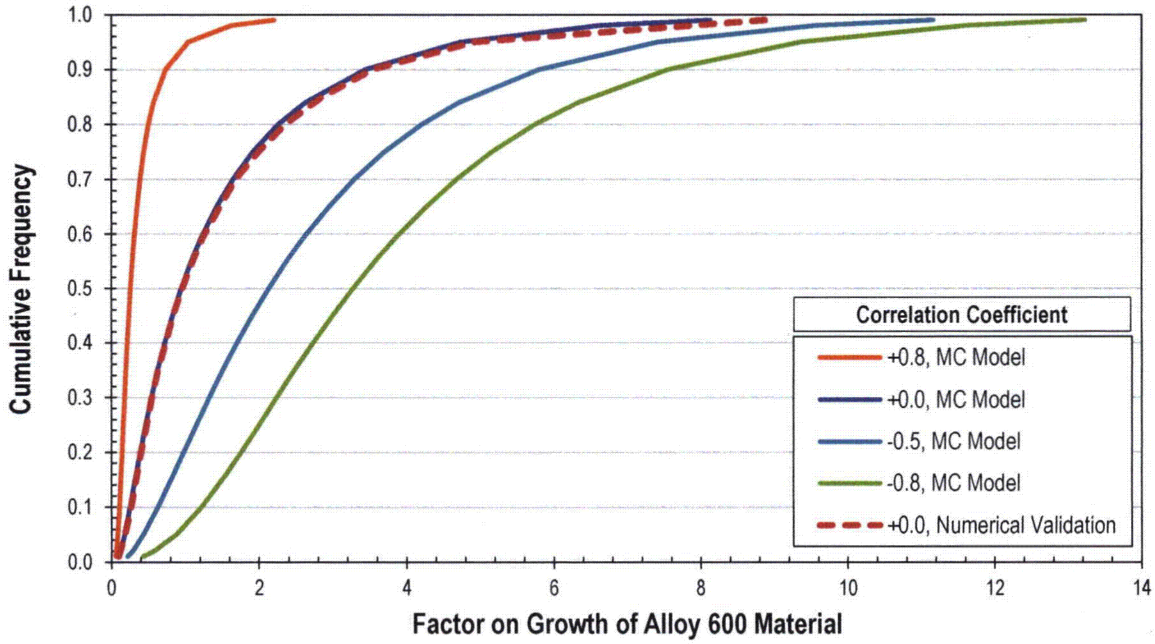

Figure 4-30
CDF of the Distributed Factor on Crack Growth in Alloy 600 for Different Correlations for Time to Initiation after 40 Cycles

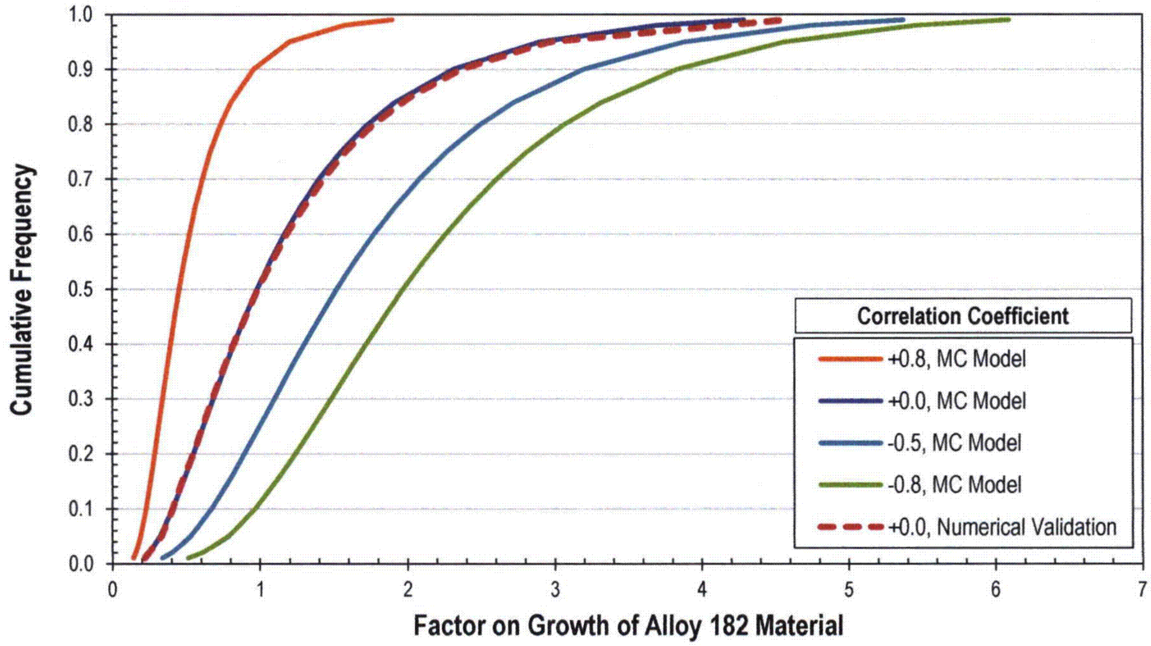

Figure 4-31
CDF of the Distributed Factor on Crack Growth in Alloy 182 for Different Correlations for Time to Initiation after 40 Cycles

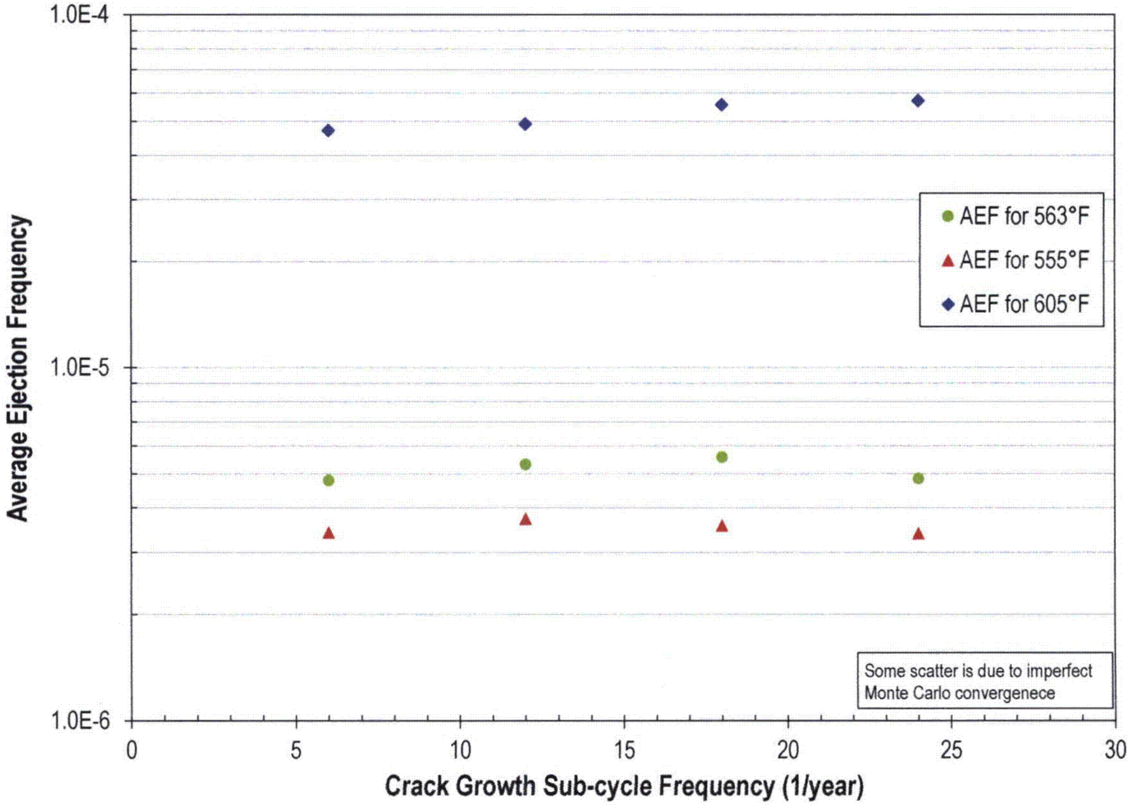

Figure 4-32
Convergence Study on the Number of Crack Growth Substeps per Year

5 ASSESSMENT OF CONCERN FOR BORIC ACID CORROSION

Section 5 assesses the concern for boric acid corrosion of the low-alloy steel head material due to primary coolant leakage at a through-wall PWSCC flaw. The concern for structural integrity of the pressure boundary directly due to circumferential PWSCC is addressed in Sections 3 and 4 above.

5.1 Original Technical Basis (MRP-117 [3], 2004)

The original technical basis that the periodic visual examinations for evidence of pressure boundary leakage of ASME Code Case N-729-1 [1] conservatively address the concern for boric acid corrosion was summarized in Section 3.4 of MRP-117 [3]. Section 7 of the 2004 top-level safety assessment report (MRP-110 [4]) describes the evaluations performed at that time that verify that protection against boric acid wastage is provided by periodic bare metal visual examinations for evidence of leakage. This conclusion was supported by the experience with over 50 leaking CRDM nozzles, including the observation that the large wastage cavity in one head that operated at relatively high temperature would have been detected relatively early in the wastage progression had bare metal visual examinations been performed at each refueling outage, and likely even if performed less frequently, with appropriate corrective action. In addition, the wastage modeling presented in MRP-110 [4] supported the adequacy of periodic bare metal visual examinations. For plants other than those categorized as low susceptibility on the basis of cumulative EDYs, Code Case N-729-1 [1] requires that bare metal visual examinations be performed during every refueling outage. MRP-117 concluded that the bare metal visual examination interval of every third refueling outage or 5 calendar years, whichever occurs first, for heads with low EDY (effectively those operating at reactor cold-leg temperature) and no previously detected PWSCC is appropriate given:

- the very low probability of leakage calculated for such heads [6],
- the greater time required for crack growth to occur to the point that the leak rate increases to a rate that may support rapid boric acid wastage (see Section 7 of MRP-110 [4]), and
- the general visual assessment including under the insulation from multiple access points that is required during the other refueling outages to check for gross evidence of the buildup of boron and/or corrosion product deposits.

5.2 Implications of MRP Boric Acid Corrosion Test Program 2003-2010

As described in Section 3.4 of MRP-117 [3], the boric acid corrosion concern for PWR reactor vessel top heads is principally addressed through the requirement for periodic direct visual examinations. Adequate protection against structurally significant boric acid corrosion through periodic visual examinations at appropriate intervals is supported by plant experience [44] and by deterministic and probabilistic models of the boric acid corrosion process, including those presented in MRP-110 [4]. Since MRP-110 was published in 2004, the MRP sponsored an extensive program of boric acid corrosion testing and additional analysis work ([45], [46], [47], [48], [49], [50]),[21] including full-scale mockups of leaking CRDM nozzles with careful attention to obtaining thermal-hydraulic conditions representative of a leaking CRDM nozzle in an operating PWR. MRP-308 [50] assesses the implications of the test program with regard to inspection requirements for reactor vessel top head penetration nozzles and reactor vessel bottom-mounted nozzles (BMNs).

This test program, which was completed in 2010, confirms the previous conclusions based on plant experience and analytical work [4] that structurally significant volumes of material loss (1) require a reasonably long period of time to develop and (2) are preceded by evidence of leakage and corrosion that is readily visible. Furthermore, the corrosion rates and resulting conditions observed were found to be consistent with key assumptions made in the original analytical work [4]. Thus, the results of this MRP test program support the adequacy of the current visual inspection requirements for top heads to address the possibility of boric acid corrosion.

5.3 Implications of Latest Set of Plant Experience and Analyses Regarding the Likelihood of Leakage Due to PWSCC

Plant experience with Alloy 600 reactor vessel top head nozzles (Section 2) continues to demonstrate a low probability of pressure boundary leakage due to PWSCC given the periodic examinations required by ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D). No through-wall cracking has been observed in the U.S. after the first in-service volumetric or surface examination was performed of all CRDM or CEDM nozzles in a given head. Moreover, the more general PWR plant experience for PWSCC of Alloy 600 J-groove nozzles, including that for reactor vessel top head nozzles, [44] shows that periodic visual examinations performed under the insulation at appropriate intervals are highly effective in detecting any leakage caused by PWSCC before any discernible material loss is produced via boric acid corrosion of carbon or low-alloy steel pressure boundary components. Recent cases showing the effectiveness of periodic direct visual examinations include the 2010 case of CRDM nozzle leakage discussed in Section 2.3 and the 2013 case of reactor vessel bottom-mounted nozzle leakage at a U.S. PWR [52].

The deterministic and probabilistic analyses presented in this technical basis report support the plant experience in demonstrating the adequacy of the current visual examination requirements (per ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D)) as a second method in addition to periodic volumetric or surface examinations to address the concern for boric acid corrosion. In particular, the deterministic crack growth calculations presented in Section 3 demonstrate the substantial benefit of operation at reactor cold-leg temperature in increasing the time required for a part-depth flaw to grow through-wall and cause leakage. The probabilistic calculations documented in Section 4 show that periodic volumetric examinations of the nozzle tube base metal with a frequency corresponding to RIY = 2.25 are effective in maintaining a low probability of leakage due to PWSCC of the nozzle tube. Plant experience has demonstrated that there is a low probability of leakage overall considering the possibility of

[21] ANL [51] has also completed boric acid corrosion testing under sponsorship of NRC with results consistent with those for the MRP program.

through-weld cracking. Furthermore, any leaks that might occur due to through-weld PWSCC that is not detectable via the periodic volumetric examinations of the nozzle tube are expected to be relatively small. Such small leak rates are unlikely to be sufficient to produce the amount of local cooling necessary for substantial boric acid corrosion to occur. The visual examination requirements for heads with low EDY, which include either the VE or VT-2 examination of N-729-1 [1] during each refueling outage, are appropriate given the reduced risk of substantial boric acid corrosion rates affecting a head operating at T_{cold} in comparison to one operating at higher temperature. Finally, the periodic "leak path assessment" examination required by 10 CFR 50.55a(g)(6)(ii)(D)(*3*) is a second method for detecting through-wall PWSCC and leakage that is independent of the visual examinations, resulting in increased overall confidence in detecting any leakage in a timely fashion.

5.4 Conclusion

It is concluded that the current requirements for periodic visual examinations for evidence of pressure boundary leakage (per ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D)) remain valid to address the concern for potential boric acid corrosion. For heads with EDY $\geq$ 8 and/or previously detected PWSCC, the visual examination (VE) frequency of every refueling outage is appropriately conservative. For heads with EDY < 8 (effectively all heads with Alloy 600 nozzles operating in U.S. at T_{cold}) and no previously detected PWSCC, the original basis for extending the interval to every third refueling outage or 5 calendar years, whichever is less, remains valid.

This approach is supported by the demonstrated low probability of pressure boundary leakage for heads operating at T_{cold} and the supplemental requirement for the VT-2 visual examination of the head under the insulation through multiple access points in outages that the VE is not completed. Given the large amounts of boric acid deposits that necessarily accompany substantial rates of boric acid corrosion, the VT-2 requirement is an effective supplement to the periodic VE examinations. It is emphasized that this conclusion is not dependent on the volumetric or surface reexamination interval for heads operating at T_{cold} with previously detected PWSCC being one rather than two 18-month fuel cycles. Plant experience and analyses show that the probability of leakage would be low for heads operating at T_{cold}, regardless if the volumetric reexamination interval for heads with previously detected PWSCC were one or two 18-month fuel cycles.

6 CONCLUSIONS

Section 6 presents the conclusions of this technical basis report. The conclusions are based on a detailed review of plant experience with PWSCC, including assessments of the frequency of occurrence of PWSCC in heads with Alloy 600 nozzles and of the associated crack growth rates.

6.1 Adequacy of Current ASME Code Case N-729-1 Inspection Interval for Volumetric Examinations (RIY = 2.25)

It is concluded on the basis of plant experience and deterministic and probabilistic analyses that the current inspection requirements of ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D) are still sufficient to address the PWSCC concern. In particular, the Re-Inspection Year (RIY) = 2.25 interval for periodic volumetric or surface examination remains valid for all heads without previously detected PWSCC, including heads that operate at reactor cold-leg temperature (T_{cold}).

The RIY = 2.25 interval has been clearly successful in managing the PWSCC concern for top heads. No through-wall cracking has been observed in the U.S. after the first in-service volumetric or surface examination was performed of all CRDM or CEDM nozzles in a given head. Since 2004, no circumferential PWSCC indications in the nozzle tube and located near or above the top of the weld have been detected. Moreover, the RIY-dependent periodicity of volumetric or surface examinations performed on heads operating at T_{cold} and on non-cold heads (operating substantially above T_{cold}) alike have been effective in detecting the PWSCC degradation reported in its relatively early stages, with modest numbers of nozzles affected by part-depth cracking, often located below the weld, where the nozzle tube is inside (not directly a part of) the pressure boundary.

The deterministic and probabilistic analyses also demonstrate the acceptability of the RIY = 2.25 interval. The RIY = 2.25 interval maintains an acceptably low effect on nuclear safety, even for probabilistic cases assuming frequencies of PWSCC crack initiation at the most susceptible end of the range of plant experience. Furthermore, the probabilistic analyses show that periodic volumetric examinations of the nozzle tube base metal with a frequency corresponding to RIY = 2.25 are effective in maintaining a low probability of leakage due to PWSCC of the nozzle tube. Plant experience has demonstrated that there is a low probability of leakage overall considering the possibility of through-weld cracking.

6.2 Acceptability of Performing Volumetric Examination Every Other Refueling Outage for Heads Operating at T_{cold} with Prior PWSCC

A volumetric or surface reexamination interval of two fuel cycles for heads with previously detected PWSCC that operate at T_{cold} would provide a sufficient level of conservatism considering the acceptability of the safety risk results for an interval of four or five 18-month cycles for such heads (as discussed in Section 4.4). The current requirement for a volumetric or surface reexamination interval of every fuel cycle for a head with previously detected PWSCC regardless of head operating temperature is overly conservative for the case of heads operating at T_{cold}. The detailed probabilistic analyses presented in this study support use of the RIY = 2.25 interval (i.e., an interval of four or five 18-month cycles for heads operating at T_{cold}) regardless of whether PWSCC has been previously detected. The probabilistic analyses assume a high likelihood that many PWSCC flaws are initiated in the head over life. Reducing the interval to two 18-month cycles in the case of previously detected PWSCC in a head operating at T_{cold} represents a substantial conservatism relative to the interval of RIY = 2.25 supported by the assessments of this report. All currently operating U.S. PWRs having heads that operate at T_{cold} operate on a nominal 18-month fuel cycle.

The analyses presented in Sections 3 and 4 do not explicitly model repaired nozzles. However, as discussed in the following, a reexamination interval of two 18-month cycles in the case of previously detected PWSCC in a head operating at T_{cold} is also justified for the periodic NDE required for individual nozzles that have been repaired using either of the two main methods that have historically been used. These repair methods are (1) "embedded flaw repair," with application of a weld overlay on the outer nozzle and weld surfaces and (2) the "ID temper bead mid-wall repair." Current practice per NRC safety evaluations in response to relief requests associated with these repair methods is for NDE of each repaired nozzle to be performed during each refueling outage when all nozzles are examined per the volumetric or surface examination requirement of ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D). As discussed below, it is justified that the NDE specific to repaired areas also be performed every other refueling outage in cases where an interval of two cycles is justified for the general volumetric or surface examination of N-729-1 [1] per this technical basis report:

- The "embedded flaw repair" for a flaw connected to the nozzle outer surface involves applying PWSCC-resistant weld metal (e.g., Alloy 52) over the OD of the Alloy 600 nozzle tube and the wetted surfaces of the J-groove weld, overlapping the vessel cladding and extending to the bottom of the nozzle, to isolate the susceptible material from primary coolant. (The large majority of reactor vessel penetration nozzle PWSCC that has been detected has been located on the nozzle outer surface.) Without contact with coolant, further PWSCC-induced growth is prevented. This repair is unlikely to affect significantly the stress state at the nozzle ID, and to the extent there is an effect on the stress at the ID, the squeezing of the nozzle tube by shrinkage of the weld overlay upon cooling would tend to reduce the magnitude of the tensile stress at the nozzle ID.

  Periodic UT on the nozzle ID, per the standard N-729-1 approach as conditioned by 10 CFR 50.55a(g)(6)(ii)(D), monitors the potential for growth of an embedded flaw originally located in the nozzle tube, or checks for growth into the nozzle tube of an embedded flaw originally located in the weld (e.g., [53], [54]). The embedded flaw repair technique has been applied in over 45 different instances throughout the world, and the flaw being repaired has never come into contact with water after repair. These repairs have been in place up to 10 years in some cases. Even in the unlikely case that the embedded flaw were to become wetted, any growth due to PWSCC would occur at a significantly reduced rate at T_{cold} compared to heads operating at temperatures similar to reactor hot-leg temperature (e.g., 2.8 times slower at 560°F compared to 600°F for the standard growth activation energy of 31 kcal/mole [7]). The standard UT on the nozzle ID also addresses the potential for new flaws initiating on the nozzle ID in the same manner as for an unrepaired nozzle. Plant experience has shown the embedded flaw repair to be a reliable approach, as long as consideration is given to ensuring that the overlay covers all of the susceptible material (see Section C.7 of MRP-110 [4]). There are a number of reasons discussed here that periodic inspection every other outage is more than sufficient to address the concerns expressed by the NRC for periodic NDE after the embedded flaw repair (e.g., [53], [54]):

- The coverage of the entire outer nozzle surfaces with PWSCC-resistant material,
- The benefit of operating at T_{cold} for PWSCC crack growth rates, and
- The favorable plant experience, with over 45 repairs, some remaining in service for over 10 years so far.

- The "ID temper bead mid-wall repair" involves relocating the pressure boundary from the original J-groove weld at the inside surface of the head to a new weld using PWSCC-resistant material (e.g., Alloy 52) at the mid-wall of the head. With this repair approach, the original J-groove weld and buttering is left in the head, but it is no longer part of the pressure-retaining load path for the nozzle. Consequently, the inspections performed typically exclude this remnant weld. The remaining section of Alloy 600 nozzle above the mid-wall weld that is subject to substantial stresses or strains from the repair is abrasive water jet conditioned to induce compressive surface stresses and mitigate the PWSCC susceptibility. The surface conditioning is applied along the entire region from above the nozzle section that was roll-expanded during the repair to below the Alloy 52 mid-wall weld toe [55]. Periodic UT examination of the repaired region is required to monitor the integrity of the repaired area [56]. The ID temper bead process has been used extensively in the U.S. to repair CRDM nozzles, and no such cases have been identified in which new leaks or cracks were detected (see Section C.7 of MRP-110 [4]). Considering the surface conditioning applied, the benefit of operating at T_{cold} for PWSCC crack growth rates, and the favorable plant experience, performance of the NDE specific to the repaired nozzle every other outage in the case of heads operating at T_{cold} is sufficient to address the concerns expressed by NRC for periodic NDE addressing the reliability of the repair (e.g., [55], [56]).

6.3 Adequacy of Current ASME Code Case N-729-1 Requirements for Periodic Visual Examinations for Evidence of Pressure Boundary Leakage

Per the assessment presented in Section 5, it is concluded that the current requirements for periodic visual examinations for evidence of pressure boundary leakage (per ASME Code Case N-729-1 [1] as conditioned by 10 CFR 50.55a(g)(6)(ii)(D)) remain valid to address the concern for potential boric acid corrosion. For heads with EDY $\geq$ 8 and/or previously detected PWSCC, the visual examination (VE) frequency of every refueling outage is appropriate. For heads with EDY < 8 (effectively all heads with Alloy 600 nozzles operating in the U.S. at T_{cold}) and no previously detected PWSCC, the original basis for extending the interval to every third refueling outage or 5 calendar years, whichever is less, remains valid.

This approach is supported by the demonstrated low probability of pressure boundary leakage for heads operating at T_{cold} and the supplemental requirement for the VT-2 visual examination of the head under the insulation through multiple access points in outages that the VE is not completed. Given the large amount of boric acid deposits that necessarily accompanies substantial rates of boric acid corrosion, the VT-2 requirement is an effective supplement to the periodic VE examinations. It is emphasized that this conclusion is not dependent on the volumetric or surface reexamination interval for heads operating at T_{cold} with previously detected PWSCC being one rather than two 18-month fuel cycles. Plant experience and analyses show that the probability of leakage would be low for heads operating at T_{cold}, regardless if the volumetric reexamination interval for heads with previously detected PWSCC were one or two 18-month fuel cycles.

6.4 Recommended Changes to Latest Approved Version of ASME Code Case N-729 (N-729-4 [2])

As discussed above, it is concluded that the current inspection requirements as defined in ASME Code Case N-729-1 [1] conditioned by 10 CFR 50.55a(g)(6)(ii)(D) remain appropriate, with one exception. This technical basis report supports the following change to the latest ASME-approved version of Code Case N-729 to implement a volumetric or surface reexamination interval of two 18-month fuel cycles in the case of previously detected PWSCC in a head operating at T_{cold}:

Replace Note 8 of Table 1 of ASME Code Case N-729-4 [2] as follows:

> *Current Note (8): "If flaws are attributed to PWSCC, whether or not acceptable for continued service in accordance with -3130 or -3140, the reinspection interval shall be each refueling outage. Additionally, repaired areas shall be examined during the next refueling outage following the repair."*
>
> *Replacement Note (8): "If flaws are attributed to PWSCC, whether or not acceptable for continued service in accordance with -3130 or -3140, the reinspection interval shall be each refueling outage. However, for heads with operating temperature less than 570°F (300°C) and a nominal cycle length no greater than 18 calendar months, the reinspection interval shall be every second refueling outage. Additionally, repaired areas shall be examined during the next refueling outage following the repair."*
>
> *-OR-*
>
> *Replacement Note (8): "If flaws are attributed to PWSCC, whether or not acceptable for continued service in accordance with -3130 or -3140, the reinspection interval shall be each refueling outage. However, for heads with operating temperature less than 570°F (300°C), the reinspection interval shall be every second refueling outage or before 3.3 effective full power years (EFPYs) are accumulated since the previous inspection, whichever is less. Additionally, repaired areas shall be examined during the next refueling outage following the repair."*

It is noted that ASME Code Case N-729-1 [1] specified that the volumetric or surface reexamination interval be two fuel cycles or before RIY = 2.25, whichever is sooner, in the case of previously detected PWSCC requiring repair. In the same manner as the current technical basis, the ceiling of two cycles in N-729-1 was a conservative choice that was originally made in MRP-117 [3] to provide additional margin on the risk modeling results in MRP-105 [6]. The probabilistic calculations of MRP-105 [6] showed the RIY = 2.25 interval to result in an acceptably small effect on nuclear safety regardless of whether PWSCC has been previously detected. The conditions imposed by 10 CFR 50.55a(g)(6)(ii)(D) on N-729-1 modify the interval for heads with previously detected PWSCC (whether requiring repair or not) to be each refueling outage. Code Case N-729-4 [2] (not currently accepted by NRC) reflects this NRC condition.

6.5 Support of Licensee Relief Requests or Direct Change by NRC to 10 CFR 50.55a(g)(6)(ii)(D)(*5*)

Because ASME Code Case N-729-1 [1] is made mandatory by 10 CFR 50.55a(g)(6)(ii)(D), a revised version of N-729-4 [2] incorporating the change recommended above would require NRC acceptance before it could be applied. In the meantime, individual licensees may apply this technical basis report for heads operating at T_{cold} with previously detected PWSCC in relief requests to NRC requesting modification of the volumetric or surface reexamination interval, including for individual previously repaired nozzles, to two cycles. Similarly, this technical basis report supports a direct change to the NRC condition imposing the more frequent interval, i.e., a change to 10 CFR 50.55a(g)(6)(ii)(D)(*5*) implementing one of the "Replacement Note (8)" options shown above. Of course, prior NRC approval would be required in either of these approaches.

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A

UPDATE OF WEIBULL STATISTICAL ASSESSMENT OF U.S. ALLOY 600 CRDM/CEDM NOZZLE INSPECTION EXPERIENCE

A.1 Purpose

The objective of this appendix is to describe the results of a 2014 update to the Weibull statistical analysis originally performed as part of MRP-105, *Materials Reliability Program Probabilistic Fracture Mechanics Analysis of PWR Reactor Pressure Vessel Top Head Nozzle Cracking* [A-1]. The purpose of MRP-105 was to determine appropriate volumetric re-examination intervals to address the concern for primary water stress corrosion cracking (PWSCC) of Alloy 600 CRDM, CEDM, and other top head nozzles, including through-wall crack penetration (i.e., leakage) and the potential for nozzle ejection due to circumferential cracking. This update follows recent key CRDM nozzle experience, specifically the findings of Alloy 600 CRDM nozzle cracking in the first replacement reactor vessel top head at one plant in 2010 and at the top heads of multiple other plants that operate at the reactor cold leg temperature in recent years.[22]

A.2 Previous Weibull Assessments

A.2.1 MRP-105 Weibull Analysis

Section 4 of MRP-105 [A-1] described the analysis of field experience in the U.S. with reactor vessel head CRDM/CEDM nozzle cracking through early 2003. U.S. plants were prioritized for baseline volumetric examination using an approximate susceptibility ranking for top head nozzle cracking based on a parameter known as effective degradation years (EDYs). This parameter adjusts operating time for the key effect of differences in operating head temperature. As described in MRP-105, a Weibull statistical analysis was used to develop a distribution describing the variability in the EDYs from initial operation to the time of detectable cracking (i.e., first crack). The heads that were inspected and found not to have reportable indications were treated as "suspended items" in the analysis, in accordance with the standard approach described by Abernethy [A-2]. Suspended item analysis takes appropriate statistical credit for inspections in which failures were not observed.

The population of heads used for this analysis included only plants that had performed non-visual non-destructive examination (NDE) (i.e., surface and/or volumetric examinations). Plants that had only performed bare metal visual (BMV) examination without reported leakage are not included because of the possibility of significant part-depth cracking.

[22] Reactor vessel top heads that operate at the reactor cold leg temperature are commonly referred to as "cold heads."

A.2.2 2005 Weibull Analysis Update

In 2005, the MRP-105 Weibull statistical assessment was updated to consider an additional two years of head experience. Specifically, Table 4-2 (which displays the results of the Weibull analysis) and Figure 4-2 (which plots the cumulative fraction of units with cracking—including leaking cracks—versus EDYs) of MRP-105 were revised. Figure A-1 and Figure A-2 are the 2003 and 2005 versions of Figure 4-2, respectively.

A.3 2014 Weibull Analysis Update

A.3.1 Tabulation of Head Experience

In early 2014, the set of U.S. top head experience was updated to reflect inspections performed through fall 2013 and the addition of a first replacement reactor vessel head having Alloy 600 CRDM nozzles to the fleet. The tabulated experience is shown in Table A-1, which is similar to Table 4-1 of MRP-105. However, for the 2014 assessment, the experience with through-wall cracking and leakage has been divided into a separate assessment from the more general case of cracking experience. Since only the experience resulting from both part-wall and through-wall PWSCC is of interest for the current scope, Table A-1 contains only NDE inspection results.

The sources for NDE and visual inspection results are the plant submittals and outage reports to the NRC in response to the following NRC orders and bulletins:

- NRC Order EA-03-009, Rev. 1, February 2004 (Rev. 0 was issued February 2003), "Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors"
- NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles"
- NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity"
- NRC Bulletin 2002-02, "Reactor Pressure Vessel Head Penetration Nozzle Inspection Programs"

An additional source of inspection experience was the MRP-219 [A-3] series of PWR inspection data survey reports. It is noted that shallow surface indications (e.g., surface craze cracking) were not counted as cracks in Table A-1 since such indications are not considered to be PWSCC degradation. It is also noted that the design data (number of J-groove nozzles by type, head fabricator, etc.) and operating head temperatures in Table A-1 (with the exception of the heads discussed in Section A.3.1.3 below) were taken from MRP-48 [A-4], and that the head replacement dates in Table A-1 for replacements, both past and planned, are per MRP-219 [A-3].

A.3.1.1 Number of Cracked CRDM Nozzles for First Replacement Alloy 600 Head

A spring 2010 NDE of a first replacement head having Alloy 600 CRDM nozzles ([A-5], [A-6]) (Plant V in Table A-1) resulted in 12 of its 69 CRDM nozzles reported to have PWSCC indications in the Alloy 600 base metal material. These nozzles were subsequently repaired prior to the head being returned to service. In addition, another 12 CRDM nozzles were repaired based on flaw indications detected through dye penetrant (PT) and eddy current (ET) examinations of the wetted surface of the J-groove attachment welds. However, the reported sizes for these weld indications (0.375 inch or smaller) were below that generally resulting in reports of PWSCC for previous industry experience for CRDM nozzle J-groove welds. Thus, to maintain consistency with the set of previous industry experience, the number of cracked CRDM nozzles for this first replacement head (Plant V) was taken to be 12 for the purpose of this Weibull assessment.

A.3.1.2 Number of Cracked CRDM Nozzles for Cold Head Experience

- A PWSCC indication was identified in a single CRDM nozzle at one cold head plant in 2007 ([A-7], [A-8]) (Plant N in Table A-1), but was concluded to have initiated at a subsurface location that was wetted through lack-of-fusion fabrication defects.
- The spring 2011 volumetric or surface examination of one cold head [A-9] (Plant AK in Table A-1) resulted in 4 of its 78 CRDM nozzles reported to have PWSCC indications (some of which were considered to be in the reactor coolant system pressure boundary region). No indications of leakage were detected. The nozzles were subsequently repaired prior to the head being returned to service.
- The spring 2012 volumetric or surface examination at one cold head plant [A-10] (Plant AI in Table A-1) resulted in the detection of one PWSCC indication in a single CRDM nozzle, which was subsequently repaired during the same outage.
- During the spring 2012 examinations at another cold head plant [A-11] (Plant X in Table A-1), four nozzles were detected with indications of PWSCC. The nozzles were subsequently repaired prior to the head being returned to service.
- During the fall inspections of the same year, another cold head plant (Plant BR in Table A-1) observed 10 indications of PWSCC in four CRDM nozzles [A-12]. The nozzles were subsequently repaired prior to the head being returned to service.
- In the spring of 2013, while at power, an independent third-party review of the 2012 inspection data from Plant X in Table A-1 discovered a previously unidentified PWSCC indication in a nozzle that had not yet been repaired [A-11]. Because the indication was identified while the plant was at power, a reactor shut down was required. The nozzle was subsequently repaired prior to the head being returned to service.
- The fall 2013 volumetric or surface examination of that same cold head plant [A-13] (Plant X in Table A-1) resulted in the detection of one PWSCC indication in a single CRDM nozzle, which was subsequently repaired during the same outage. An indication at the same location was observed during the inspections in the previous outage, but was below the threshold to call [A-14].

A.3.1.3 B&W Plant Head Temperature Assumptions

The 613°F head temperature for the original (Plant BL) and first replacement (Plant V) heads at increase of 8°F above the hot leg operating temperature previously assumed to apply for these heads. This difference was reported to MRP by the licensee following its root cause assessment of the CRDM nozzle PWSCC detected in spring 2010, and reflects channeling of water directly from fuel assemblies toward the top head. The licensee reported the 613°F operating head temperature as an appropriate nominal value for the head considering both time (within fuel cycle and cycle-to-cycle) and spatial (nozzle location) variations in temperature. Using the 613°F head temperature value, the EDY value for the first replacement head was determined to be 9.17 at the time of the spring 2010 refueling outage, as shown in Table A-1.

The recent information regarding the temperature for the replacement head for which PWSCC was detected in 2010 indicates that the Alloy 600 heads in the other six B&W plants (now all replaced with PWSCC-resistant Alloy 690 heads) most likely also have had nominal head operating temperatures significantly greater than the hot leg temperatures previously assumed. Thus, the Weibull cases for the 2014 analysis were performed under the assumption that each of these other six B&W plant heads also operated at a temperature 8°F higher than its respective hot leg temperature. The cases assuming that these six B&W plant heads operated at hot leg temperature are designated as "original temperatures" cases, while the cases assuming they operated at a temperature 8°F higher than hot leg temperature are designated as "B&W + 8°F" cases.

A.3.2 Methodology

A.3.2.1 Calculation of Effective Degradation Years (EDYs)

PWSCC is a thermally activated process ([A-1], [A-4]). Thus, data for the plants included in the Weibull analysis are sorted by EDYs at the time of the most recent inspection, calculated in accordance with the standard Arrhenius relationship that describes thermally activated processes:

$$\dot{r} = \dot{r}_0 \exp\left(-\frac{Q}{RT}\right) \qquad \textbf{[Eq. A-1]}$$

where $\dot{r}$ is the cracking rate, $\dot{r}_0$ is a constant, Q is an activation energy, R is the universal gas constant, and T is the absolute temperature. Using the EDY model, it may be shown that a plant operating at a 560°F head temperature requires more than 50 years to accumulate the same effective degradation as a plant with a 600°F head temperature would accumulate in 10 years. This example illustrates the temperature dependence inherent in the EDY model.

In this 2014 update of the Weibull assessment of top head inspection experience, as was also done in the Weibull analysis performed as part of MRP-105 [A-1], the effective full power years of operating time are normalized to a reference temperature of 600°F and are determined from plant effective full power years (EFPYs) at various head temperatures using a standard thermal activation energy. The activation energy of 50 kcal/mole is an accepted industry best-estimate activation energy for SCC initiation in primary water environments (e.g., see [A-15]).

Specifically, the EDY parameter is defined as follows ([A-1], [A-4]):

$$EDY = \sum_{j=1}^{n} \left\{ \Delta EFPY_j \exp\left[-\frac{Q_i}{R}\left(\frac{1}{T_{head,j}} - \frac{1}{T_{ref}} \right) \right] \right\} \qquad \textbf{[Eq. A-2]}$$

where:

EDY	=	total effective degradation years, normalized to a reference temperature of 600°F
$\Delta EFPY_j$	=	effective full power years accumulated during time period j
Q_i	=	activation energy for crack initiation (50 kcal/mole)
R	=	universal gas constant (1.103×10^{-3} kcal/mol-°R)
$T_{head,j}$	=	100% power head temp. during time period j (°R = °F + 459.67)
T_{ref}	=	reference temperature (600°F = 1059.67°R)

In order to estimate the EDYs at the time of the inspection outages listed in Table A-1, the EDYs tabulated in MRP-48 [A-4] per Equation [A-2] were extrapolated forward in time from the March 1, 2001, reference date of MRP-48 assuming an overall reactor thermal power capacity factor of 92%. However, for 18 of the 70 total heads in Table A-1, the EDY extrapolation was instead based on the EDY figure reported to the NRC in an outage report per NRC Order EA-03-009. Finally, the EDYs for the original (Plant BL) and first replacement (Plant V) heads at the plant where PWSCC was observed in the first replacement head in spring 2010 were based on EFPY data (15.8 EFPYs for the original head at time of replacement in 2002-03; 5.46 EFPYs for the first replacement head at time of spring 2010 refueling outage) and revised head temperature figures (613°F in both cases) provided by the licensee.

A.3.2.2 Weibull Fit Cases

Following the same type of methodology as applied in MRP-105 [A-1], a Weibull statistical fit was applied to the tabulated head experience. For example, the heads that were inspected and found not to have reportable indications were treated as "suspended items" in the analysis, in accordance with the standard approach described by Abernethy [A-2]. Below is listed key information for the cases considered:

- *Weibull Failure Criterion.* As indicated in Section A.3.1, the data for the case of indications of cracking per surface/volumetric NDE and the case of indications of leakage (through-wall cracking) per BMV examination (and in some cases per surface/volumetric NDE) were treated separately. As reflected in the detailed Weibull analysis table (Table A-2, which is similar to Table 4-2 of MRP-105 [A-1]), only the surface/volumetric NDE data is of interest in the current assessment. Therefore, , the Weibull failure criterion was defined as the detection of one or more PWSCC indications through surface/volumetric NDE and the population of heads was limited to those plants that have performed volumetric and/or surface NDE (63 of the 70 Alloy 600 heads in the complete database).
- *Weibull Specific to B&W Tubular Products Material.* Because the CRDM nozzles fabricated using material supplied by B&W Tubular Products (B&WTP) have shown the highest relative incidence of PWSCC, separate inspection statistics were developed this subset of CRDM nozzles. Fourteen of the 18 heads with some or all nozzles fabricated using B&WTP material have reported PWSCC to date. Of the 14 heads with detected PWSCC and B&WTP nozzles, nine operated at temperatures relatively close to reactor hot-leg temperature (T_{hot}) and are no longer in service, and the other five operate at reactor cold-leg temperature (T_{cold}) and are still in service. Three of the four that have not reported PWSCC have been already

removed from service, and two of these three were exposed to zinc addition for a substantial period of time, which may have had a substantial mitigative effect on PWSCC.[23]

- *Assumed vs. Computed Weibull Slope.* The Weibull slope parameter β reflects the degree of scatter inherent in the EDYs to first cracking. In MRP-105 [A-1] Weibull assessment, a WeiBayes approach was taken in which the Weibull slope for the distribution describing the time to first cracking/leakage was assumed to have a value of 3. The value of 3 is a typical value for other PWSCC experience in Alloy 600, including laboratory data and steam generator tube cracking in PWRs and was used due to uncertainty in the CRDM nozzle inspection data (e.g., less than half of the units had performed inspections as of the time of the analysis, few or no inspections prior to 2000 may have resulted in late detection of many or all of the indications, etc.).

  It was judged that with the additional data since 2004, especially the PWSCC experience for four cold heads, it was appropriate to consider a fitted slope rather than a standard value of 3. Therefore, the least-squares fit procedure was applied to fit both the Weibull slope and Weibull characteristic time together ("computed" slope cases). Finally, as described below, in every case, the EDY data for each failure point in the Weibull fit was adjusted backward in time to the point at which cracking or leakage was estimated to first have occurred.

A.3.2.3 Extrapolation Back to Time of First Cracking

In all cases included in the original MRP-105 [A-1] analysis, the time of first cracking/leakage was estimated for each head with reported cracking/leakage through a back extrapolation process. In all cases it was assumed that the "back extrapolation" Weibull slope has the typically expected value of 3. The back extrapolation process was implemented as follows:

- The data are inserted into the two-parameter Weibull equation [A-2]:

  $$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}} \qquad \textbf{[Eq. A-3]}$$

  where F is the cumulative failure fraction, and t is the time of operation. The Weibull slope parameter (designated by beta or β) is related to the rate at which degradation spreads through the nozzle population after it first becomes detectable. High values of β correspond to degradation that spreads rapidly through the nozzle population. The other Weibull parameter, the characteristic time (designated as theta or θ), is a measure of the time scale for the degradation; it defines the time at which 63.2% of the population is predicted to be degraded.

- Assuming a slope of 3, a "time factor" is computed for each of the plants in which cracking was observed. For example, for Plant BO in Table A-1 ([A-16], [A-17]), in which 14 cumulative cracked nozzles (out of 69) were observed during an inspection performed at 12.4 EDYs (see Table A-1), the fraction of nozzles cracked, in accordance with the median ranking equation, is $F = (14\text{-}0.3)/(69\text{+}0.4) = 0.1974$ (see Table A-2). If just one nozzle were cracked, the fraction would be $F = (1\text{-}0.3)/(69\text{+}0.4) = 0.0101$. Applying the Weibull

[23] In consideration of the extensive use of zinc addition at these two plants, they were excluded from the Weibull fits for the subset of heads with B&WTP material.

equation with a slope of 3, the time to reach $F = 0.0101$ is predicted to take only 0.3586 of the time necessary to reach $F = 0.1974$ (time factor = 0.3586). Thus, since 14 nozzles were found cracked at 12.4 EDYs, it is predicted that the first cracked nozzle in the Plant BO head occurred at 4.43 EDYs (12.4 x 0.3586 = 4.43), as shown in Table A-2. This approach was used for each of the plants that had multiple cracked nozzles to determine the predicted times to first cracking. The greater the number of cracked or leaking nozzles found, the smaller the time factor, and thus the greater the difference between inspection EDYs and predicted EDYs to first cracking (or first leakage).

A.3.3 Weibull Fit Results

Table A-3 summarizes the fit parameters of the various Weibull analysis cases. Figure A-3 and Figure A-4 show the Weibull plots of the time to first cracking as fit to the plant experience:

- Figure A-3 shows the updated 2014 Weibull distribution based on a best-fit slope to the adjusted time to first cracking for all CRDM nozzle supplier data[24], assuming that all seven B&W plants have a representative operating head temperature 8°F higher than the hot leg temperature. The fitted slope of 1.38 for the cracking case results in a somewhat higher probability of cracking for relatively small cumulative EDY values compared to the MRP-105 fit (see Section 2.1). The relatively small best-fit Weibull slope in Figure A-3 (1.38) indicates a relatively wide range of PWSCC susceptibility across the U.S. fleet, consistent with the fact that the U.S. feet represents several material suppliers and vessel fabricators.
- Figure A-4 shows the updated 2014 Weibull distribution based on a best-fit slope to the adjusted time to first cracking data for CRDM nozzles with material supplied by B&WTP, assuming that all seven B&W plants have a representative operating head temperature 8°F higher than the hot leg temperature. The relatively small best-fit Weibull slope in Figure A-4 (1.17) indicates a relatively wide range of PWSCC susceptibility for the heads with nozzles fabricated using material supplied by B&WTP. This variation in susceptibility likely reflects the substantial differences in the susceptibility of different material heats supplied by B&WTP.

A.4 References

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A-2. Abernethy, R. B., *The New Weibull Handbook*, Second Edition, Published and Distributed by Robert B. Abernethy, North Palm Beach, Florida, July 1996.

A-3. *Materials Reliability Program: Inspection Data Survey Report (MRP-219, Revision 9)*. EPRI, Palo Alto, CA: 2013. 3002000686.

A-4. *PWR Materials Reliability Program Response to NRC Bulletin 2001-01 (MRP-48)*, EPRI, Palo Alto, CA: 2001. 1006284. [freely available on www.epri.com]

[24] For the best-fit slope cases, a slope of 3 still was applied for the adjustment of multiple nozzles with detected PWSCC back to the time of first cracking/leakage. This is appropriate in that the scatter in initiation time across multiple material suppliers and head fabricators is generally expected to be greater than for the nozzles in a single head.

A-5. Letter from A. T. Boland (U. S. Nuclear Regulatory Commission) to B. Allen (FirstEnergy Nuclear Operating Company), "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]

A-6. Letter from B. S. Allen (FirstEnergy Nuclear Operating Company) to U. S. Nuclear Regulatory Commission, "Davis-Besse Nuclear Power Station; Docket Number 50-346, License Number NPF-3; Licensee Event Report 2010-002 Revision 01," L-10-258, dated September 30, 2010. [NRC ADAMS Accession No. ML102800416]

A-7. Letter from D. M Hoots (Exelon) to U. S. Nuclear Regulatory Commission, "Licensee Event Report (LER) 455-2007-001-00, 'Reactor Pressure Vessel Head Control Drive Mechanism Penetration Nozzle Weld Indication Due to an Initial Construction Weld Defect Allowing the Initiation of Primary Water Stress Corrosion Cracking," dated June 8, 2007. [NRC ADAMS Accession No. ML071590211]

A-8. Letter from D. M Hoots (Exelon) to U. S. Nuclear Regulatory Commission, "Byron Station, Unit 2, 60-Day Response to First Revised NRC Order EA-03-009, 'Issuance of First Revised NRC Order (EA-03-009) Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors'," dated June 20, 2007. [NRC ADAMS Accession No. ML071730458]

A-9. Letter from T. J. Tulon (Exelon) to U. S. Nuclear Regulatory Commission, "Licensee Event Report 2011-002-00, Unit 1 Reactor Pressure Vessel Head Penetration Nozzle Weld Flaws Attributed to Primary Water Stress Corrosion Cracking," dated May 18, 2011. [NRC ADAMS Accession No. ML111380417]

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A-11. Letter from E. J. Kapopoulos, Jr. (Duke Energy) to U. S. Nuclear Regulatory Commission, "Licensee Event Report 2013-001-00," dated July 12, 2013. [NRC ADAMS Accession No. ML13193A347]

A-12. Letter form T. D. Gatlin (SCE&G) to the U. S. Nuclear Regulatory Commission, "Virgil C. Summer Nuclear Station (VCSNS) Unit 1 Docket No. 50-395 Operating License No. NPF-12 Licensee Event Report (LER 2012-003-00) Reactor Vessel Head Penetrations not Meeting Requirements of 10CFR50.55a(g)(6)(ii)(D)," dated December 6, 2012. [NRC ADAMS Accession No. ML12348A054]

A-13. Letter from E. J. Kapopoulos, Jr. (Duke Energy) to U. S. Nuclear Regulatory Commission, "Licensee Event Report 2013-003-00 — Reactor Head Nozzle 37 Indication," dated January 15, 2014. [NRC ADAMS Accession No. ML14015A256]

A-14. E-mail from K. Riley (Duke) to C. Harrington (EPRI), dated November 20, 2013.

A-15. J. A. Gorman, R. A. Ogren, and J. P. N. Paine, "Correlation of Temperature with Steam Generator Tube Corrosion Experience," *Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors*, E. Simonen and D. Cubicciotti, eds., American Nuclear Society, LaGrange Park, Illinois, 1992.

A-16. Letter from J. A. Price (Dominion Nuclear Connecticut, Inc.) to U.S. Nuclear Regulatory Commission, "Millstone Nuclear Power Station, Unit Nos. 2 and 3, Response to NRC Bulletin 2002-01, Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," dated April 2, 2002. http://www.nrc.gov/reactors/operating/ops-experience/vessel-head-degradation/vessel-head-degradation-files/millstone-15day-resp-bl2002-01.pdf

A-17. Letter from L. N. Hartz (Dominion Nuclear Connecticut, Inc.) to U.S. Nuclear Regulatory Commission, "Dominion Nuclear Connecticut, Inc., Millstone Power Station, Unit 2, Sixty-Day Report, NRC Order EA-03-009," Serial No. 04-044, Rev. 0, dated January 23, 2004. [NRC ADAMS Accession No. ML040340409]

Table A-1
Alloy 600 CRDM/CEDM Nozzle Inspection Data through Fall 2013 (Original Temperatures)

					No. J-Groove Nozzles											NDE Date, Scope, and Results				
Head #	Code	NSSS	Cold Head?	Nozzle Material Supplier	CRDM/CEDM	ICI	Vent	TC	J-AHA	DGL	Total	Head Temp (°F) (MRP-48)	Fabricator	Replace Date		Outage	Year	EDY	NDE CRDM/CEDM	Cum. Cracked
1	Plant A	W	Cold	Huntington	78	0	1	0	0	0	79	559.9	CE			Fall	2006	2.56	78	0
2	Plant B	W	Cold	B&W	78	0	1	0	0	0	79	552.0	B&W			Spring	2011	2.63	78	0
3	Plant C	CE	NonCold	Huntington	65	8	1	0	0	0	74	593.7	CE	Spring	2007	Spring	2005	16.67	65	0
4	Plant D	W	Cold	Sandvik	78	0	1	0	0	0	79	557.0	Rotterdam			Fall	2012	3.87	78	0
5	Plant E	B&W	NonCold	B&W	69	0	0	8	0	0	77	602.0	B&W	Fall	2003	Spring	2002	23.16	23	5
6	Plant F	W	Cold	Huntington	78	0	1	0	0	0	79	560.0	CE			Fall	2012	4.30	78	0
7	Plant G	W	NonCold	Huntington	78	0	1	0	0	0	79	594.1	CE	Spring	2005	NONE			0	0
8	Plant H	CE	NonCold	Huntington	45	8	1	0	0	0	54	586.4	CE			Spring	2009	12.05	45	2
9	Plant I	W	Cold	Huntington	78	0	1	0	0	0	79	556.8	CE	Fall	2014	Spring	2007	3.21	78	0
10	Plant J	W	NonCold	Huntington	78	0	0	0	0	0	78	593.5	CE			Spring	2013	19.09	78	0
11	Plant K	W	NonCold	Huntington/B&W	65	0	1	0	0	0	66	595.0	B&W/CE	Spring	2006	Fall	2004	15.01	65	4
12	Plant L	W	Cold	Huntington	78	0	1	0	0	0	79	560.0	CE			Spring	2013	4.00	78	0
13	Plant M	W	NonCold	Huntington	65	0	1	0	0	0	66	594.4	B&W	Fall	2004	Spring	2003	18.17	65	0
14	Plant N	W	Cold	B&W	78	0	1	0	0	0	79	550.4	B&W			Fall	2011	2.61	78	1
15	Plant O	W	NonCold	Sandvik	65	0	1	0	0	0	66	600.1	Rotterdam	Spring	2003	Fall	2001	19.89	30	1
16	Plant P	W	NonCold	Huntington	65	0	1	0	0	0	66	597.8	B&W/Rotterdam	Spring	2003	Fall	2001	19.12	16	6
17	Plant Q	W	NonCold	Huntington	65	0	1	0	0	0	66	595.0	CE	Spring	2017	Fall	2009	14.84	65	2
18	Plant R	CE	NonCold	Standard Steel	97	0	1	0	0	0	98	591.7	CE	Fall	2009	Spring	2008	14.65	97	0
19	Plant S	CE	NonCold	Standard Steel/Huntington	81	8	1	0	0	0	90	594.8	CE			Fall	2013	19.10	81	0
20	Plant T	CE	NonCold	Standard Steel	97	0	1	0	0	0	98	592.2	CE	Fall	2010	Spring	2009	15.19	97	0
21	Plant U	CE	NonCold	Standard Steel/Huntington	91	10	1	0	0	0	102	590.6	CE			Fall	2008	18.74	91	0
22	Plant V	B&W	NonCold	B&W	69	0	0	0	0	0	69	613.0	B&W	Fall	2011	Spring	2010	9.17	69	12
23	Plant W	W	Cold	Huntington	78	0	1	0	0	0	79	558.4	CE			Spring	2013	3.54	78	0
24	Plant X	W	Cold	B&W	65	0	1	0	0	0	66	558.0	CBI			Fall	2013	4.00	65	6
25	Plant Y	W	Cold	Sandvik	78	0	1	0	0	0	79	557.3	Rotterdam			Spring	2008	1.76	78	0
26	Plant Z	W	NonCold	Huntington	74	0	1	0	0	1	76	561.0	CE	Fall	2009	Fall	2006	11.70	74	0
27	Plant AA	W	NonCold	Huntington	65	0	1	0	0	0	66	594.4	B&W	Spring	2005	Fall	2003	18.50	65	0
28	Plant AB	W	NonCold	Westinghouse	78	0	1	0	0	0	79	600.7	CBI	Fall	2007	Spring	2006	14.43	78	1
29	Plant AC	W	NonCold	Huntington/B&W	40	0	1	0	0	0	41	583.1	B&W/CE	Fall	2004	NONE			0	0
30	Plant AD	B&W	NonCold	B&W	69	0	0	0	0	0	69	602.0	B&W	Spring	2004	Fall	2002	23.61	69	19
31	Plant AE	W	NonCold	Huntington	79	0	1	0	0	0	80	594.7	CE	Fall	2005	Spring	2004	12.90	79	0
32	Plant AF	W	NonCold	Aubert et Duval	40	0	1	0	0	0	41	580.2	CL	Spring	2005	NONE			0	0
33	Plant AG	W	Cold	Sandvik	78	0	1	0	0	0	79	557.0	Rotterdam			Fall	2012	3.94	78	0
34	Plant AH	W	NonCold	Huntington	79	0	1	0	0	0	80	590.0	CE	Fall	2010	Spring	2009	13.24	79	0
35	Plant AI	W	Cold	B&W	78	0	1	0	0	0	79	556.0	B&W			Spring	2012	3.11	78	1
36	Plant AJ	W	NonCold	B&W/Sandvik	65	0	1	0	0	0	66	597.8	B&W/Rotterdam	Fall	2003	NONE			0	0
37	Plant AK	W	Cold	B&W	78	0	1	0	0	0	79	551.0	B&W			Spring	2011	2.76	78	4

Table A-1 (continued)
Alloy 600 CRDM/CEDM Nozzle Inspection Data through Fall 2013 (Original Temperatures)

					No. J-Groove Nozzles											NDE Date, Scope, and Results				
Head #	Code	NSSS	Cold Head?	Nozzle Material Supplier	CRDM/C EDM	ICI	Vent	TC	J-AHA	DGL	Total	Head Temp (°F) (MRP-48)	Fabricator	Replace Date		Outage	Year	EDY	NDE CRDM/ CEDM	Cum. Cracked
38	Plant AL	B&W	NonCold	B&W	69	0	0	0	0	0	69	601.0	B&W	Fall	2003	Fall	2001	16.20	9	1
39	Plant AM	W	Cold	Sandvik	78	0	1	0	4	0	83	547.0	Rotterdam			Fall	2007	1.94	78	0
40	Plant AN	W	NonCold	Huntington/B&W	69	0	1	0	0	0	70	596.5	B&W/CE	Fall	2004	Spring	2003	17.46	69	0
41	Plant AO	W	NonCold	Huntington/B&W	49	0	1	0	0	0	50	591.6	B&W/CE	Spring	2005	Fall	2003	16.60	49	0
42	Plant AP	W	NonCold	C.L. Imphy	40	0	1	0	0	0	41	580.2	CL	Spring	2006	NONE			0	0
43	Plant AQ	W	NonCold	Sandvik	65	0	1	0	0	0	66	600.1	Rotterdam	Spring	2003	Fall	2002	19.71	65	45
44	Plant AR	B&W	NonCold	B&W	69	0	0	8	0	0	77	601.0	B&W	Fall	2003	Fall	2001	18.08	12	8
45	Plant AS	W	Cold	Huntington	78	0	1	0	0	0	79	561.0	CE			Spring	2011	3.11	77	0
46	Plant AT	W	Cold	Huntington	78	0	1	0	0	0	79	561.0	CE	Spring	2007	NONE			0	0
47	Plant AU	W	Cold	Huntington	78	0	1	0	0	0	79	557.0	CE			Fall	2013	3.79	78	0
48	Plant AV	W	NonCold	Huntington	69	0	0	0	0	0	69	599.7	CE	Fall	2005	Spring	2004	21.69	69	0
49	Plant AW	W	Cold	Huntington	78	0	1	0	0	0	79	558.0	CE			Spring	2013	4.08	78	0
50	Plant AX	W	NonCold	Huntington	79	0	1	0	0	0	80	578.0	CE	Fall	2006	Spring	2005	8.70	79	0
51	Plant AY	CE	NonCold	Huntington	69	8	1	0	0	0	78	590.6	CE	Fall	2005	Spring	2004	16.70	69	0
52	Plant AZ	W	Cold	Sandvik	78	0	1	0	4	0	83	547.0	Rotterdam			Fall	2006	1.86	78	0
53	Plant BA	CE	NonCold	Standard Steel/Huntington	91	10	1	0	0	0	102	590.5	CE	Fall	2012	Fall	2009	19.78	91	0
54	Plant BB	W	NonCold	Huntington	37	0	1	0	0	0	38	580.2	B&W	Fall	2003	NONE			0	0
55	Plant BC	CE	NonCold	Standard Steel	97	0	1	0	0	0	98	592.0	CE	Spring	2010	Fall	2008	15.29	97	0
56	Plant BD	W	Cold	Huntington	78	0	1	0	0	0	79	557.0	CE			Spring	2013	4.02	78	0
57	Plant BE	W	NonCold	B&W/Huntington	69	0	1	0	0	0	70	596.9	B&W/CE	Fall	2005	Spring	2004	16.80	69	0
58	Plant BF	W	NonCold	Huntington	97	0	0	0	0	0	97	585.5	CE			Spring	2012	12.70	97	0
59	Plant BG	W	NonCold	Huntington	78	0	1	0	0	0	79	593.0	CE	Fall	2009	Spring	2008	14.37	78	0
60	Plant BH	CE	NonCold	Standard Steel/Huntington	91	10	1	0	0	0	102	595.6	CE	Fall	2007	Spring	2006	16.40	91	5
61	Plant BI	CE	NonCold	Huntington	65	8	1	0	0	0	74	593.7	CE	Spring	2006	Spring	2004	16.42	65	0
62	Plant BJ	B&W	NonCold	B&W/Huntington	69	0	0	0	0	0	69	602.0	B&W	Fall	2005	Spring	2004	22.62	69	8
63	Plant BK	W	NonCold	Huntington	49	0	1	0	0	0	50	591.6	B&W	Fall	2005	Spring	2004	15.50	49	1
64	Plant BL	B&W	NonCold	B&W/Huntington	69	0	0	0	0	0	69	613.0	B&W	Fall	2003	Spring	2002	26.50	69	5
65	Plant BM	W	NonCold	Huntington/B&W	74	0	1	0	0	1	76	561.0	CE	Spring	2010	Spring	2007	12.19	74	0
66	Plant BN	CE	NonCold	Standard Steel/Huntington	91	10	1	0	0	0	102	599.7	CE	Fall	2012	Fall	2012	24.68	91	0
67	Plant BO	CE	NonCold	Huntington	69	8	1	0	0	0	78	593.9	CE	Spring	2005	Fall	2003	12.36	69	14
68	Plant BP	CE	NonCold	Huntington	41	6	1	0	0	0	48	588.0	CE	Fall	2006	Spring	2005	13.09	41	0
69	Plant BQ	B&W	NonCold	B&W	69	0	0	0	0	0	69	602.0	B&W	Spring	2003	Fall	2001	22.39	69	16
70	Plant BR	W	Cold	B&W	65	0	1	0	0	0	66	557.3	CBI			Fall	2012	4.08	65	4

Note that the temperatures listed for both the Plant BL/V original and first replacement heads have been revised from MRP-48 to reflect plant input.
Further note that the only nozzle fabricated from B&W supplied material at Plant BM is the degas line nozzle.
Key: B&W (Babcock & Wilcox), CE (Combustion Engineering), CL (C.L. Imphy), DGL (De-Gas Line [Nozzle]), ICI (Incore Instrumentation [Nozzle]), J-AHA (J-Groove Auxiliary Head Adapter), NSSS (Nuclear Steam Supply System), TC (Small-Diameter Thermocouple [Nozzle]), W (Westinghouse)

Table A-2
Inspection Data Through Fall 2013 Extrapolated Back to Predicted Time to First Crack/Leak (Based on Weibull Slope $\beta = 3$)

					NDE Data, Scope, and Results																		
								All Nozzle Materials								B&W Tubular Products Material							
														at Detection of Cracking	at 1st Crack Extrapolated Back using b=3							at Detection of Cracking	at 1st Crack Extrapolated Back using b=3
Head #	Code	No. CRDM/ CEDM Nozzles	Replace Date		Outage	Year	EDY	NDE CRDM/ CEDM	Cum. Cracked	CDF (1st Crack)	CDF (# Cracked)	Time Factor (# Cracked)	EDYs at 1st Crack or Inspection (+8°F for all B&W Heads)	CDF of Units with Cracks (+8°F for all B&W Heads)	CDF of Units with Cracks (+8°F for all B&W Heads)	NDE CRDM/ CEDM	Cum. Cracked	CDF (1st Crack)	CDF (# Cracked)	Time Factor (# Cracked)	EDYs at 1st Crack or Inspection (+8°F for all B&W Heads)	CDF of Units with Cracks (+8°F for all B&W Heads)	CDF of Units with Cracks (+8°F for all B&W Heads)
1	Plant A	78			Fall	2006	2.56	78	0	0.0089			2.5559			0	0						
2	Plant B	78			Spring	2011	2.63	78	0	0.0089			2.6252			78	0	0.0089			2.6252		
3	Plant C	65	Spring	2007	Spring	2005	16.67	65	0	0.0107			16.6688			0	0						
4	Plant D	78			Fall	2012	3.87	78	0	0.0089			3.8692			0	0						
5	Plant E	69	Fall	2003	Spring	2002	23.16	23	5	0.0299	0.2009	0.5136	16.3672	0.86	0.45	23	5	0.0299	0.2009	0.5136	16.3672	0.87	0.82
6	Plant F	78			Fall	2012	4.30	78	0	0.0089			4.3015			0	0						
7	Plant G	78	Spring	2005	NONE			0	0	1.7500			.			0	0						
8	Plant H	45			Spring	2009	12.05	45	2	0.0154	0.0374	0.7412	8.9293	0.15	0.20	0	0						
9	Plant I	78	Fall	2014	Spring	2007	3.21	78	0	0.0089			3.2092			0	0						
10	Plant J	78			Spring	2013	19.09	78	0	0.0089			19.0900			0	0						
11	Plant K	65	Spring	2006	Fall	2004	15.01	65	4	0.0107	0.0566	0.5696	8.5493	0.23	0.16	64	4	0.0109	0.0675	0.5695	8.5482	0.43	0.42
12	Plant L	78			Spring	2013	4.00	78	0	0.0089			3.9989			0	0						
13	Plant M	65	Fall	2004	Spring	2003	18.17	65	0	0.0107			18.1659			0	0						
14	Plant N	78			Fall	2011	2.61	78	1	0.0089	0.0089	1.0000	2.0854	0.01	0.04	78	1	0.0089	0.0089	1.0000	2.0854	0.04	0.16
15	Plant O	65	Spring	2003	Fall	2001	19.89	30	1	0.0230	0.0230	1.0000	19.8859	0.44	0.56	0	0						
16	Plant P	65	Spring	2003	Fall	2001	19.12	16	6	0.0427	0.3476	0.4675	8.9394	0.34	0.22	0	0						
17	Plant Q	65	Spring	2017	Fall	2009	14.84	65	2	0.0107	0.0260	0.7420	11.0115	0.20	0.33	0	0						
18	Plant R	97	Fall	2009	Spring	2008	14.65	97	0	0.0072			14.6502			0	0						
19	Plant S	81			Fall	2013	19.10	81	0	0.0086			19.1000			0	0						
20	Plant T	97	Fall	2010	Spring	2009	15.19	97	0	0.0072			15.1860			0	0						
21	Plant U	91			Fall	2008	18.74	91	0	0.0077			18.7386			0	0						
22	Plant V	69	Fall	2011	Spring	2010	9.17	69	12	0.0101	0.1686	0.3801	3.4853	0.11	0.10	69	12	0.0101	0.1686	0.3801	3.4853	0.37	0.36
23	Plant W	78			Spring	2013	3.54	78	0	0.0089			3.5400			0	0						
24	Plant X	65			Fall	2013	4.00	65	6	0.0107	0.0872	0.4905	1.9615	0.07	0.03	65	6	0.0107	0.0872	0.4905	1.9615	0.24	0.10
25	Plant Y	78			Spring	2008	1.76	78	0	0.0089			1.7611			0	0						
26	Plant Z	74	Fall	2009	Fall	2006	11.70	74	0	0.0094			11.7029			0	0						
27	Plant AA	65	Spring	2005	Fall	2003	18.50	65	0	0.0107			18.4957			0	0						
28	Plant AB	78	Fall	2007	Spring	2006	14.43	78	1	0.0089	0.0089	1.0000	10.1300	0.13	0.27	0	0						
29	Plant AC	40	Fall	2004	NONE			0	0	1.7500						0	0						
30	Plant AD	69	Spring	2004	Fall	2002	23.61	69	19	0.0101	0.2695	0.3184	10.3475	0.93	0.29	69	19	0.0101	0.2695	0.3184	10.3475	0.95	0.56
31	Plant AE	79	Fall	2005	Spring	2004	12.90	79	0	0.0088			12.8951			0	0						
32	Plant AF	40	Spring	2005	NONE			0	0	1.7500						0	0						
33	Plant AG	78			Fall	2012	3.94	78	0	0.0089			3.9403			0	0						
34	Plant AH	79	Fall	2010	Spring	2009	13.24	79	0	0.0088			13.2412			0	0						
35	Plant AI	78			Spring	2012	3.11	78	1	0.0089	0.0089	1.0000	3.1055	0.05	0.08	78	1	0.0089	0.0089	1.0000	3.1055	0.17	0.29

Table A-2 (continued)
Inspection Data Through Fall 2013 Extrapolated Back to Predicted Time to First Crack/Leak (Based on Weibull Slope β = 3)

					NDE Date, Scope, and Results																		
								All Nozzle Materials								B&W Tubular Products Material							
														at Detection of Cracking	at 1st Crack Extrapolated Back using b=3							at Detection of Cracking	at 1st Crack Extrapolated Back using b=3
Head #	Code	No. CRDM/ CEDM Nozzles	Replace Date		Outage	Year	EDY	NDE CRDM/ CEDM	Cum. Cracked	CDF (1st Crack)	CDF (# Cracked)	Time Factor (# Cracked)	EDYs at 1st Crack or Inspection (+8°F for all B&W Heads)	CDF of Units with Cracks (+8°F for all B&W Heads)	CDF of Units with Cracks (+8°F for all B&W Heads)	NDE CRDM/ CEDM	Cum. Cracked	CDF (1st Crack)	CDF (# Cracked)	Time Factor (# Cracked)	EDYs at 1st Crack or Inspection (+8°F for all B&W Heads)	CDF of Units with Cracks (+8°F for all B&W Heads)	CDF of Units with Cracks (+8°F for all B&W Heads)
36	Plant AJ	65	Fall	2003	NONE			0	0	1.7500						0	0						
37	Plant AK	78			Spring	2011	2.76	78	4	0.0089	0.0472	0.5703	1.5747	0.03	0.01	78	4	0.0089	0.0472	0.5703	1.5747	0.11	0.04
38	Plant AL	69	Fall	2003	Fall	2001	16.20	9	1	0.0745	0.0745	1.0000	22.3057	0.51	0.71	9	1	0.0745	0.0745	1.0000	22.3057	0.51	0.92
39	Plant AM	78			Fall	2007	1.94	78	0	0.0089			1.9383			0	0						
40	Plant AN	69	Fall	2004	Spring	2003	17.46	69	0	0.0101			17.4581			0	0						
41	Plant AO	49	Spring	2005	Fall	2003	16.60	49	0	0.0142			16.5959			47	0	0.0148			16.5959		
42	Plant AP	40	Spring	2006	NONE			0	0	1.7500						0	0						
43	Plant AQ	65	Spring	2003	Fall	2002	19.71	65	45	0.0107	0.6835	0.2107	4.1523	0.39	0.12	0	0						
44	Plant AR	69	Fall	2003	Fall	2001	18.08	12	8	0.0565	0.6210	0.3913	9.7426	0.58	0.24	12	8	0.0565	0.6210	0.3913	9.7426	0.58	0.49
45	Plant AS	78			Spring	2011	3.11	77	0	0.0090			3.1111			0	0						
46	Plant AT	78	Spring	2007	NONE			0	0	1.7500						0	0						
47	Plant AU	78			Fall	2013	3.79	78	0	0.0089			3.7900			0	0						
48	Plant AV	69	Fall	2005	Spring	2004	21.69	69	0	0.0101			21.6900			0	0						
49	Plant AW	78			Spring	2013	4.08	78	0	0.0089			4.0800			0	0						
50	Plant AX	79	Fall	2006	Spring	2005	8.70	79	0	0.0088			8.7004			0	0						
51	Plant AY	69	Fall	2005	Spring	2004	16.70	69	0	0.0101			16.7000			0	0						
52	Plant AZ	78			Fall	2006	1.86	78	0	0.0089			1.8551			0	0						
53	Plant BA	91	Fall	2012	Fall	2009	19.78	91	0	0.0077			19.7833			0	0						
54	Plant BB	37	Fall	2003	NONE			0	0	1.7500						0	0						
55	Plant BC	97	Spring	2010	Fall	2008	15.29	97	0	0.0072			15.2946			0	0						
56	Plant BD	78			Spring	2013	4.02	78	0	0.0089			4.0200			0	0						
57	Plant BE	69	Fall	2005	Spring	2004	16.80	69	0	0.0101			16.8000			0	0						
58	Plant BF	97			Spring	2012	12.70	97	0	0.0072			12.7000			0	0						
59	Plant BG	78	Fall	2009	Spring	2008	14.37	78	0	0.0089			14.3701			0	0						
60	Plant BH	91	Fall	2007	Spring	2006	16.40	91	5	0.0077	0.0514	0.5261	8.6281	0.28	0.18	0	0						
61	Plant BI	65	Spring	2006	Spring	2004	16.42	65	0	0.0107			16.4150			0	0						
62	Plant BJ	69	Fall	2005	Spring	2004	22.62	69	8	0.0101	0.1110	0.4417	13.7499	0.79	0.36	67	7	0.0104	0.0994	0.4637	14.4336	0.80	0.75
63	Plant BK	49	Fall	2005	Spring	2004	15.50	49	1	0.0142	0.0142	1.0000	15.5000	0.25	0.42	0	0						
64	Plant BL	69	Fall	2003	Spring	2002	26.50	69	5	0.0101	0.0677	0.5248	13.9070	0.65	0.39	60	5	0.0116	0.0778	0.5240	13.8857	0.65	0.69
65	Plant BM	74	Spring	2010	Spring	2007	12.19	74	0	0.0094			12.1918			0	0						
66	Plant BN	91	Fall	2012	Fall	2012	24.68	91	0	0.0077			24.6800			0	0						
67	Plant BO	69	Spring	2005	Fall	2003	12.36	69	14	0.0101	0.1974	0.3586	4.4309	0.17	0.14	0	0						
68	Plant BP	41	Fall	2006	Spring	2005	13.09	41	0	0.0169			13.0947			0	0						
69	Plant BQ	69	Spring	2003	Fall	2001	22.39	69	16	0.0101	0.2262	0.3406	10.4982	0.72	0.31	69	16	0.0101	0.2262	0.3406	10.4982	0.73	0.62
70	Plant BR	65			Fall	2012	4.08	65	4	0.0107	0.0566	0.5696	2.3210	0.09	0.06	65	4	0.0107	0.0566	0.5696	2.3210	0.30	0.23

Table A-3
Summary of Weibull Distribution Fit Parameters

Weibull Fit Case			No. Heads in Weibull Fit (with volumetric exam)	No. Heads with Cracks or Leaks	Weibull Slope β			Weibull Characteristic Time Θ	
Analysis Date	Failure Considered to be Crack or Leak	Material Types Considered			Description	Original Temps. (Note 1)	B&W + 8°F (Note 2)	Original Temps. (Note 1)	B&W + 8°F (Note 2)
Spring 2003	Cracks (incl. leaks)	All	30	14	Assumed	3.00	--	15.21	--
Spring 2005	Cracks (incl. leaks)	All	41	18	Assumed	3.00	--	15.18	--
2014	Cracks (incl. leaks)	All	63	23	Fit	--	1.38	--	23.0
2014	Cracks (incl. leaks)	B&WTP	16	14	Fit	--	1.17	--	11.0

Notes:

(1) It is assumed for these cases that the head temperature for each head is as reported in MRP-48.

(2) The temperature for both the Plant BL/V original and first replacement heads were revised to reflect plant input. It is also assumed for these cases that the head temperature for the each other B&W plant head is 8°F higher than the hot leg temperature.

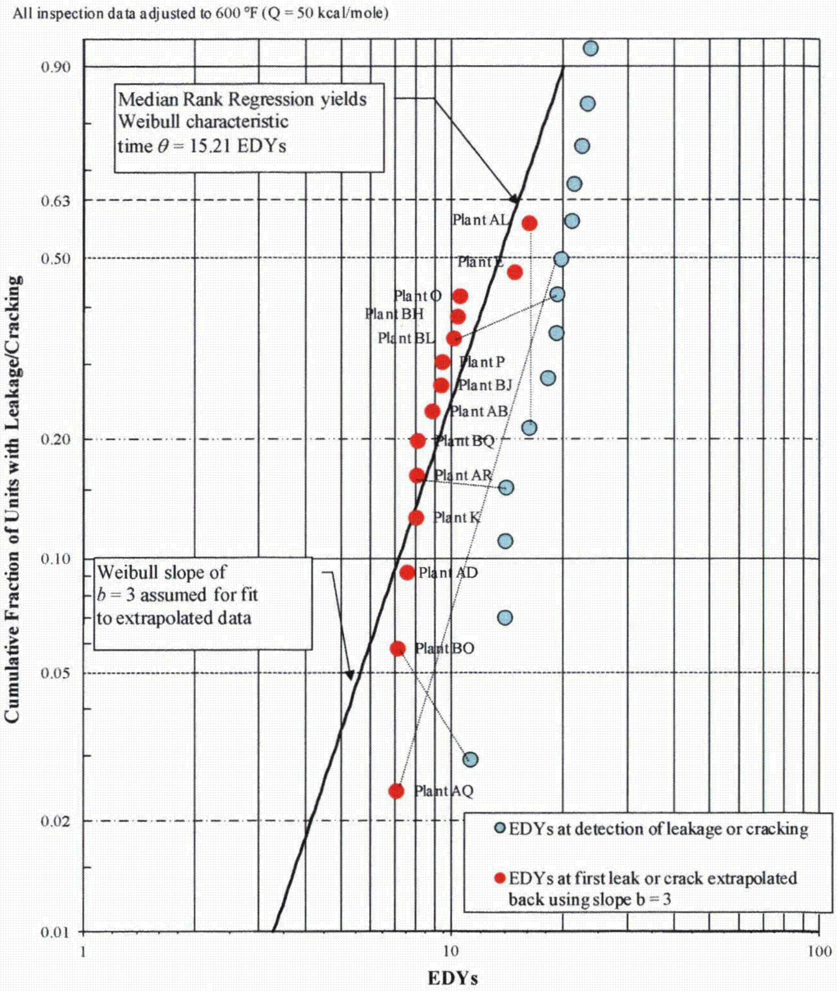

Figure A-1
Original (Spring 2003), All Materials,
NDE+BMV: 30 Heads; 14 w/cracks or leaks

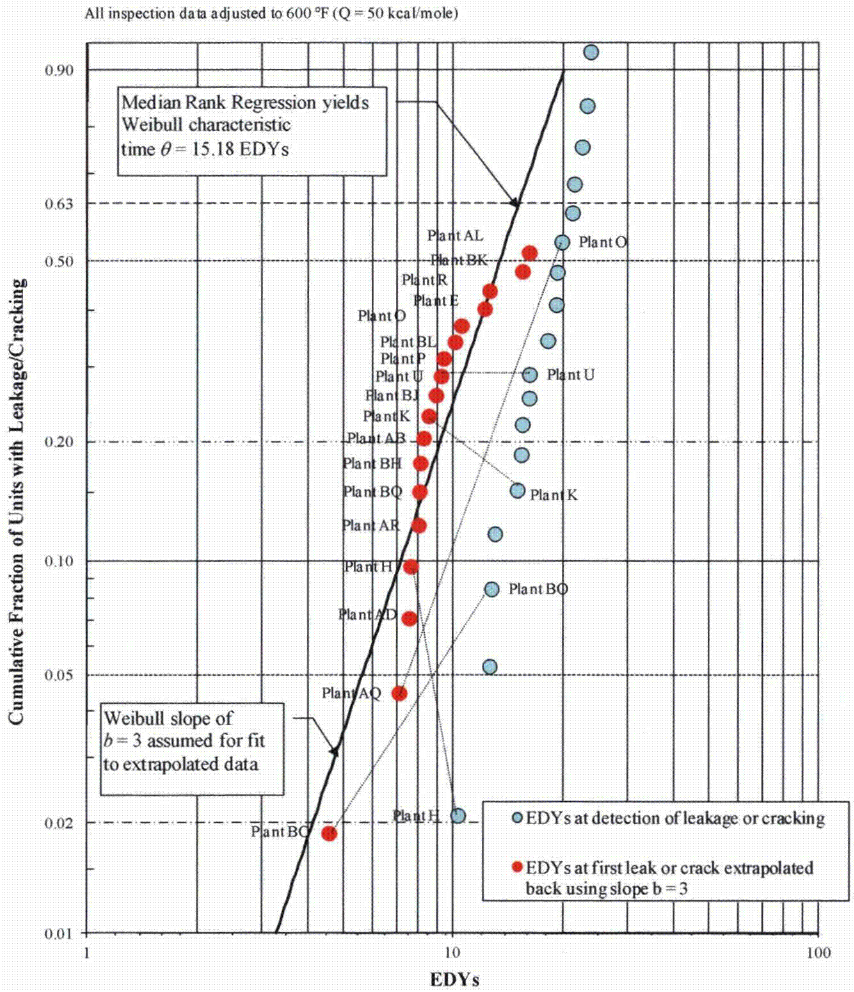

Figure A-2
Prior Update (Spring 2005), All Materials,
NDE+BMV: 41 Heads; 18 w/cracks or leaks

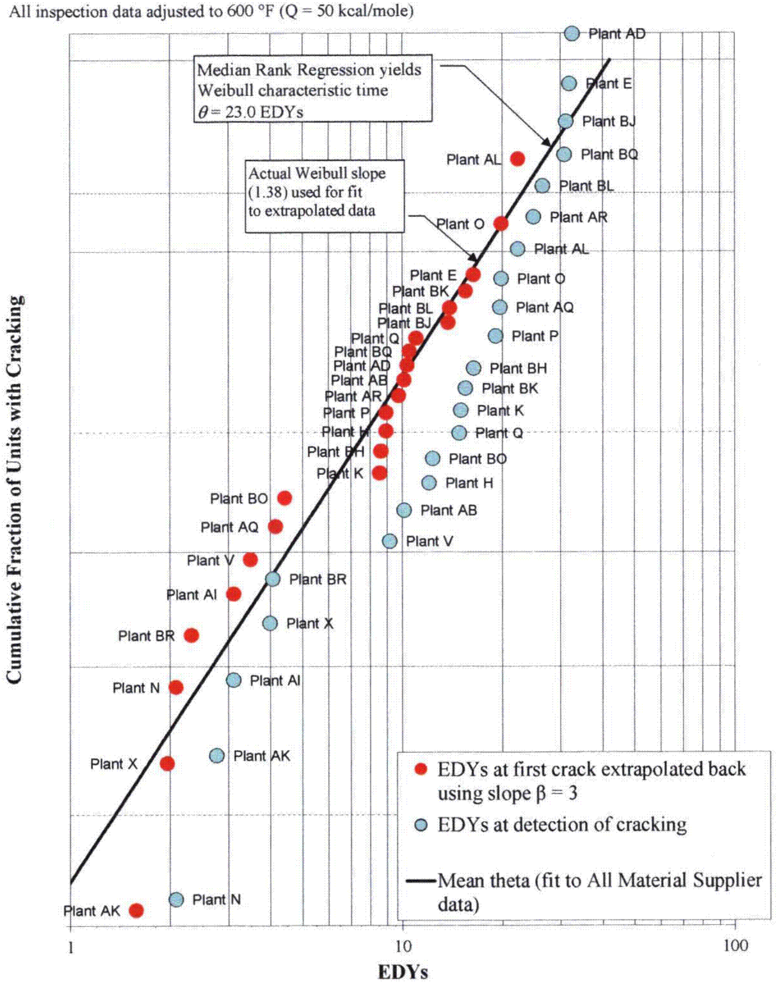

Figure A-3
2014 Update – All Materials, B&W + 8°F,
NDE: 63 Heads; 23 w/cracks

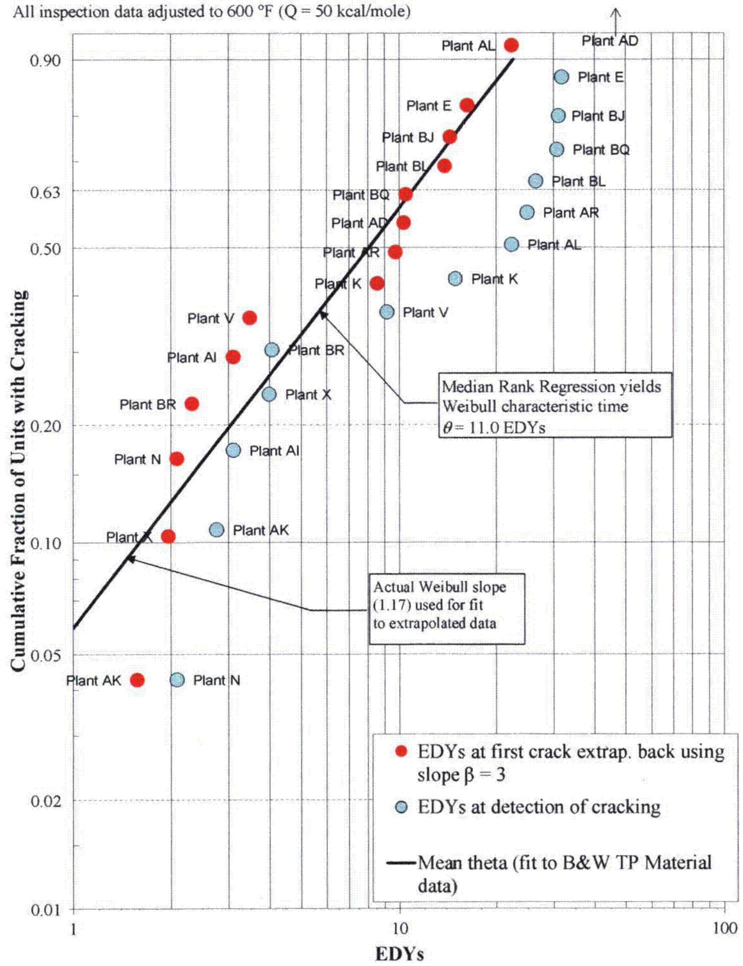

Figure A-4
2014 Update – B&WTP Materials, B&W + 8°F,
NDE: 16 Heads; 14 w/cracks

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