ELECTRIC POWER RESEARCH INSTITUTE

Technical Basis for Reexamination Interval for Alloy 690 PWR Reactor Vessel Top Head Penetration Nozzles (MRP-375)

Glenn White, Kevin Fuhr, Kyle Schmitt, and Amanda Olender
Dominion Engineering, Inc.

Paul Crooker
EPRI

ASME Code Week
February 9-14, 2014
San Diego, CA

Topics

- Background & Objectives
- Approach
  - Factor of Improvement Data
  - Probabilistic Modeling
- Report Summary
  - Table of Contents
  - Plant Service Experience
  - Laboratory Data
  - Deterministic Results
  - Probabilistic Results
  - Conclusions
- Recommended Inspection Regimes

Project Status

- Project initiated in February 2013
- Initial evaluation completed June 2013
- Final report (MRP-375) to be published February 2014
  - EPRI 3002002441
  - To be freely downloadable at www.epri.com
  - Intended to support ASME Code action
  - May be applied by individual licensees to support relief requests

Background

- ASME Technical Basis for Code Case N-729 (September 14, 2004):
  - Treatment of A690 heads in N-729 was intended to be conservative and subject to reassessment once "additional laboratory data and plant experience on the performance of Alloy 690 and Alloy 52/152 weld metals become available"
- Data are now available to support a technically based volumetric/surface reexamination interval using appropriate analytical tools
- Currently 65 PWRs are in operation in U.S.:
  - 40 with replacement Alloy 690 heads
  - 25 with original Alloy 600 heads (20 of which operate close to reactor cold-leg temperature)
- New plants to have heads with Alloy 690 nozzles

Objective

- Apply existing plant experience and laboratory data to develop a technically based alternative inspection regime for reactor vessel heads with Alloy 690 nozzles:
  - Develop an associated robust technical basis
  - Draft proposed changes to Code Case N-729

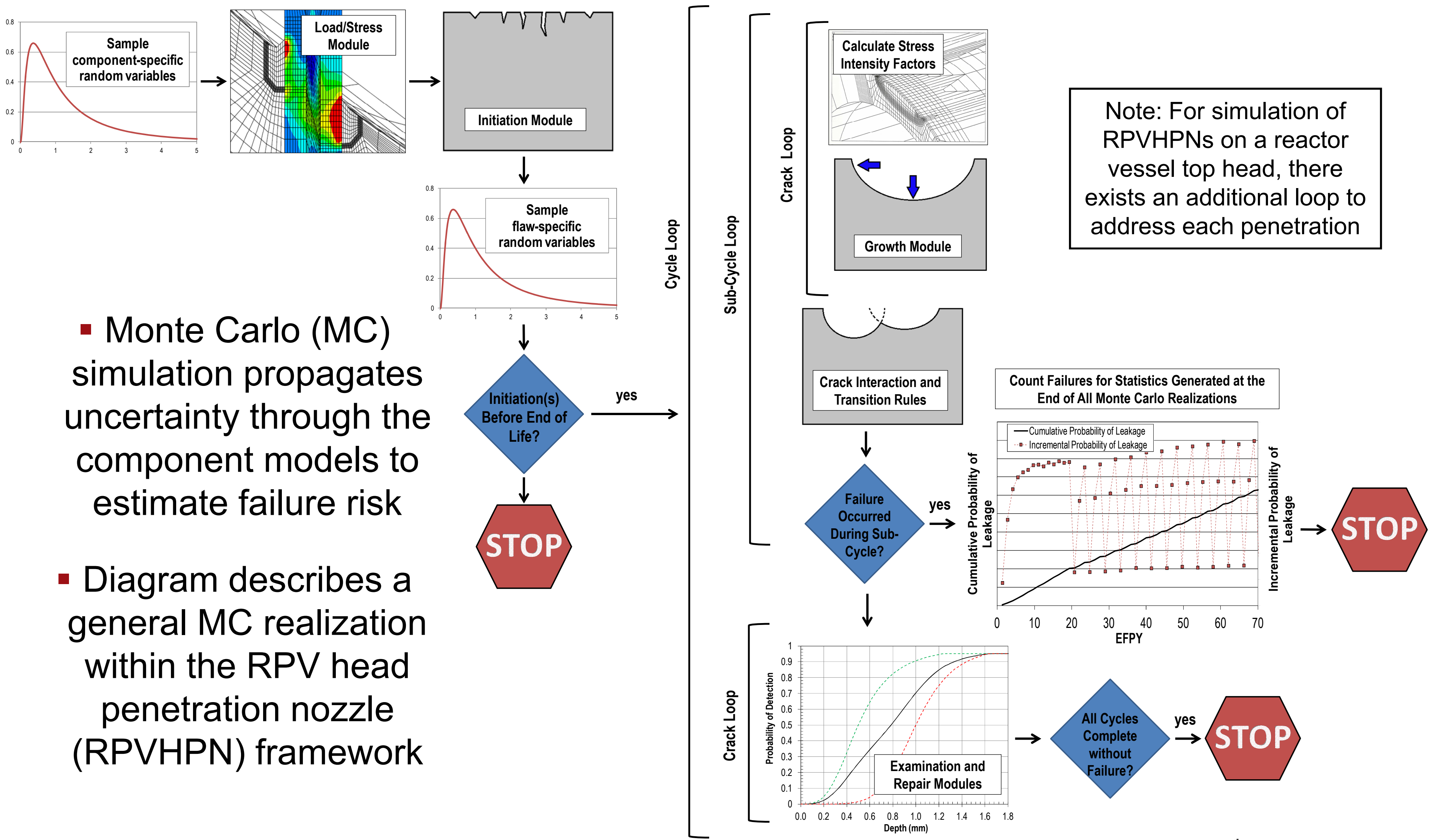
Approach

- Develop the technical basis through application of existing laboratory data and operating experience with Alloy 690 and its weld metals Alloys 52 and 152
- Perform deterministic and probabilistic calculations based on standard approaches for Alloy 600 heads, with conservatively small credit for improved PWSCC performance through factors of improvement (FOI) applied to crack growth rates and crack initiation times
  - Most cases include no credit for longer crack initiation times compared to Alloys 600/82/182 (i.e., initiation FOI = 1)
  - Conservatively small FOI values on crack growth rate justified by the latest set of laboratory crack growth rate data collected by the EPRI Expert Panel for PWSCC of Alloys 690/52/152
  - Applies the probabilistic model developed in MRP-335R1 (EPRI 3002000073) to assess the probability of through-wall cracking and nozzle ejection
  - Benchmark against probabilistic results of MRP-105, which is a key part of the technical basis for inspection requirements for RV heads with Alloy 600 nozzles
  - Assess results in terms of reduced risk versus Alloy 600 heads examined per N-729-1 and in terms of the MRP-105 type acceptance criteria

Approach (cont'd)

Description of Probabilistic Model

- Monte Carlo (MC) simulation propagates uncertainty through the component models to estimate failure risk
- Diagram describes a general MC realization within the RPV head penetration nozzle (RPVHPN) framework



Note: For simulation of RPVHPNs on a reactor vessel top head, there exists an additional loop to address each penetration

ELECTRIC POWER RESEARCH INSTITUTE

Approach (cont'd)

- Conservative application of data characterizing the PWSCC behavior of Alloys 690/52/152 supports:
  - Extension of the nominal 10-year interval for volumetric/surface examinations
  - Sample volumetric/surface examination schedule for pair of "sister heads"
  - "Sister heads" are defined as having a similar or identical design, same material supplier, and same head fabricator
  - "Sister head" approach is analogous to that taken in Paragraph IWL-2421 of ASME Section XI for inspection of unbonded post-tensioning systems of concrete containments
- Maintain the schedule of direct visual examinations (VEs) for leakage per N-729-1 as a conservatism
  - This VE schedule is the same as for Alloy 600 heads with EDY < 8 and no flaws unacceptable for continued service previously detected

Technical Basis Table of Contents

- Section 1. Introduction
  - Background, Objective, Scope, Approach, Report Structure
- Section 2. Plant Experience with Alloys 690/52/152
  - SG Tubing, SG Tube-End Welds, SG Tube Plugs, Instrumentation Nozzles and Heater Sleeves, Replacement Top Heads, Implications
- Section 3. Factors of Improvement (FOI) for Alloys 690/52/152
  - Material Conditions of Concern, Assessments of Laboratory Data, EPRI Database of PWSCC CGRs for Alloys 690/52/152, Conclusions Regarding FOIs
- Section 4. Deterministic and Probabilistic PWSCC Evaluations
  - Deterministic Crack Growth Calculations, Probabilistic Modeling
- Section 5. Conclusions
  - Implications of Plant and Laboratory Data, Alternative Volumetric/Surface Reexamination Intervals, Modeling Conservatisms

Technical Basis Table of Contents (cont'd)

- Section 6. References
- Appendix A. Description of Probabilistic PWSCC Model
  - Introduction, Framework, Spatial Discretization of Flaws, Flaw Initiation, Loads and Stress Intensity Factors, Treatment of Flaw Growth Rate, Inspection and Detection, Nozzle Leakage and Ejection Criteria
- Appendix B. Inputs and Results of Probabilistic PWSCC Model
  - Modeling Assumptions and Simplifications, Description of Model Inputs, Base Case Results, Inspection Timing Sensitivity Results, FOI Sensitivity Results, Model Sensitivity Results, Convergence Test Results, Benchmarking Results

Conservative FOI Approach

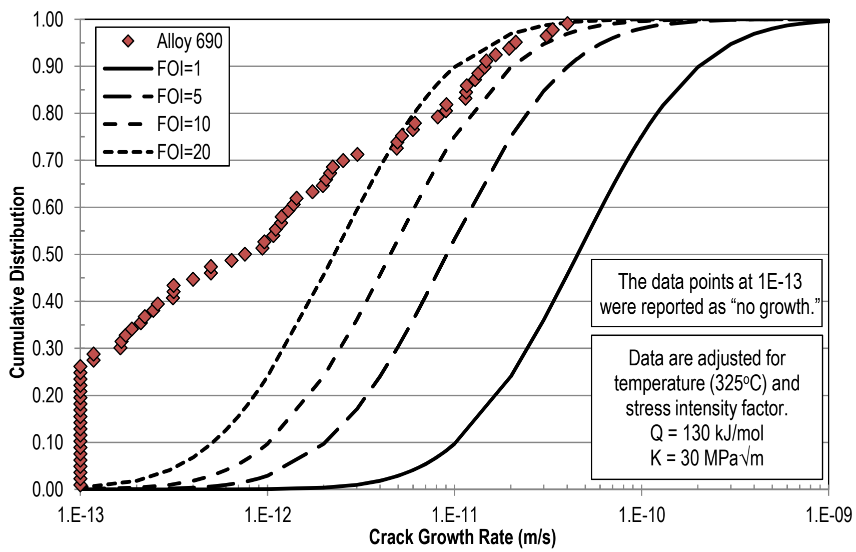
- Much of the available laboratory data indicate a factor of improvement for Alloys 690/52/152 versus the performance of Alloys 600/182 (for equivalent temperature and stress conditions) on the order of 100 in terms of the crack growth rate. Moreover, existing laboratory and plant data demonstrate a factor of improvement in excess of 20 in terms of the time to PWSCC initiation.
- This much reduced susceptibility to PWSCC initiation and growth supports elimination of all volumetric examinations (as well as visual examinations for evidence of leakage) throughout the plant service period.
- However, since work is still ongoing to determine the performance of Alloys 690/52/152 in PWR replacement head applications, the determination of inspection intervals for reactor vessel heads with Alloy 690 nozzles was based on conservatively smaller factors of improvement. This conservative approach provides for continued monitoring of the status of the U.S. fleet of replacement heads.

Plant Service Experience

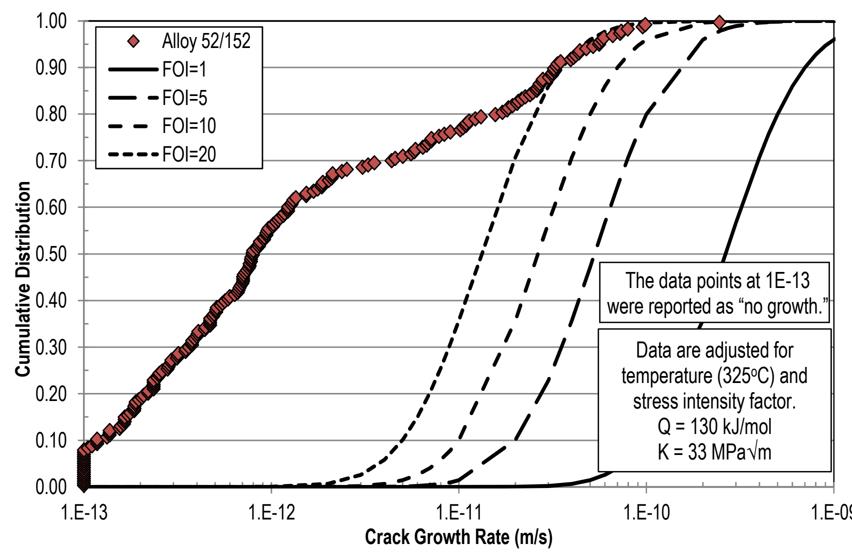
- No reports of corrosion-induced flaws initiating in Alloy 690 SG tubing, SG tube end welds, SG tube plugs, instrumentation nozzles, pressurizer heater sleeves, and replacement top head penetration nozzles
  - 24 years of service in some cases
- The wide range of plant experience with Alloys 690, 52, and 152 clearly demonstrates a substantial improvement in PWSCC resistance versus that for Alloys 600, 82, and 182
- Depending on the application, a factor of improvement in time to detectable PWSCC of at least 5 to 20 is apparent, with the value increasing as additional service time with the replacement materials is accumulated

Laboratory Data Regarding FOI

- Reported data reviewed to determine FOI values for Alloy 690 versus Alloy 600 and Alloys 52/152 versus Alloy 182
  - FOI values for initiation are generally minimum values given general lack of initiation of Alloys 690/52/152 observed under conditions representative of plant components
  - EPRI Alloy 690 Expert Panel CGR database compiles available data



Empirical Cumulative Distribution Function of Alloy 690 Data with <10% Cold Work from the 2013 EPRI CGR Database, Shown with Variations on the MRP-55-Based Curve



Empirical Cumulative Distribution Function of Alloy 52/152 Data from the 2013 EPRI CGR Database, Shown with Variations on MRP-115-Based Curve

FOIs Applied in Technical Basis Calculations

- Assumed FOI values:
  - The technical basis calculations apply growth FOIs varying from 10 to 20 for Alloy 690 base metal and from 5 to 10 for Alloy 52/152 weld metal and Alloy 690 HAZ material. The lower assumed growth FOI values for the weld metal and HAZ material reflect the general concern for potentially elevated crack growth rates in the weld metal and base metal HAZ in comparison to that for bulk base metal. It is noted that the currently available laboratory data for Alloy 690 HAZ material do not show a substantially elevated crack growth rate in comparison to that for Alloy 690 bulk base metal.
  - The technical basis calculations investigating the nuclear safety concern of nozzle ejection do not take any credit for an improved resistance to PWSCC initiation of the Alloy 690 RPVHPNs (i.e., an initiation FOI of 1 is assumed). Additional cases apply a conservatively small initiation FOI of 5 for the purpose of investigating the benefit of the improved performance of Alloys 690/52/152 for the probability of leakage due to through-wall PWSCC.
- Based on the work presented in Sections 2 and 3 of MRP-375, there is high confidence that the actual FOI values for Alloy 690 RPVHPNs are substantially greater than the values assumed in the inspection technical basis calculations. In the future, the situation may be re-assessed and excess conservatism removed from the technical basis for inspection.

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Summary of Deterministic Results

- Deterministic calculations performed support extension of Alloy 690 volumetric/surface inspection interval to 20 years and beyond
  - Performed calculations and adjusted existing Alloy 600 deterministic calculations to 613°F (323°C) and Alloy 690 using FOIs
- Part-depth cracks growing with a modest FOI (of 20 for ID flaws in the wrought material and of 10 for OD flaws assumed to grow through more susceptible material) take at least 20 years to grow through-wall at 613°F
- Through-wall circumferential cracks growing with an FOI of 20 at 613°F (323°C) take at least 120 years to grow to a circumferential extent where NSC and nozzle ejection becomes a possibility

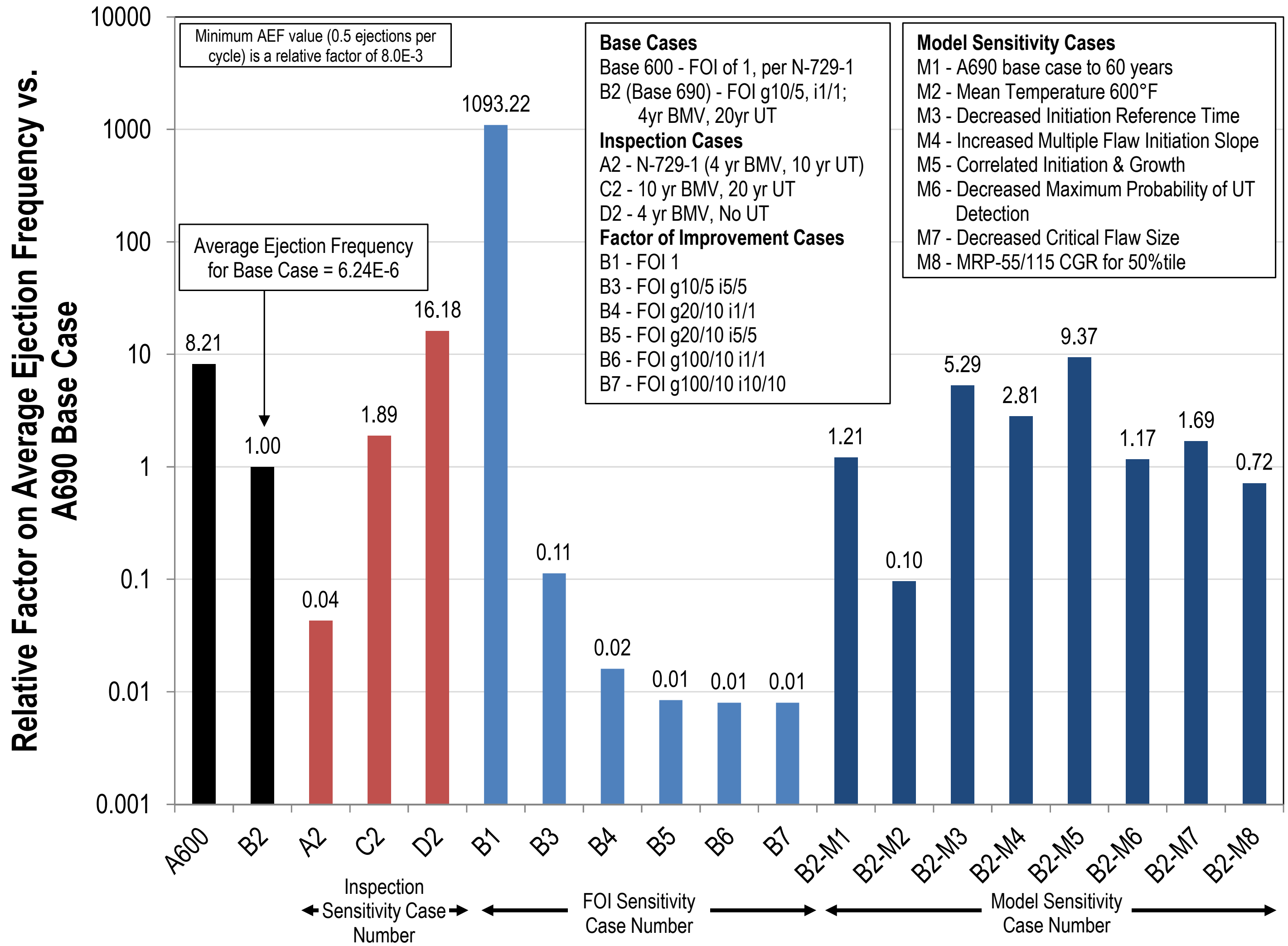
Summary of Probabilistic Results

Form of Results

- Probabilistic modeling of Alloys 690/52/152 by using a deterministic "factor of improvement" (FOI) over Alloys 600/82/182 crack growth rates
- No credit taken for improved initiation performance in results below
- Results compared against an Alloy 600 case (613°F) using N-729-1 inspection intervals
- Results presented as number of penetrations for which an event was modeled divided by number of heads simulated (each Monte Carlo realization simulates one top head)
  - E.g., average leakage frequency is number of penetrations that leaked divided by the number of realizations, averaged over time

Summary of Results (1st A690 Base Case)

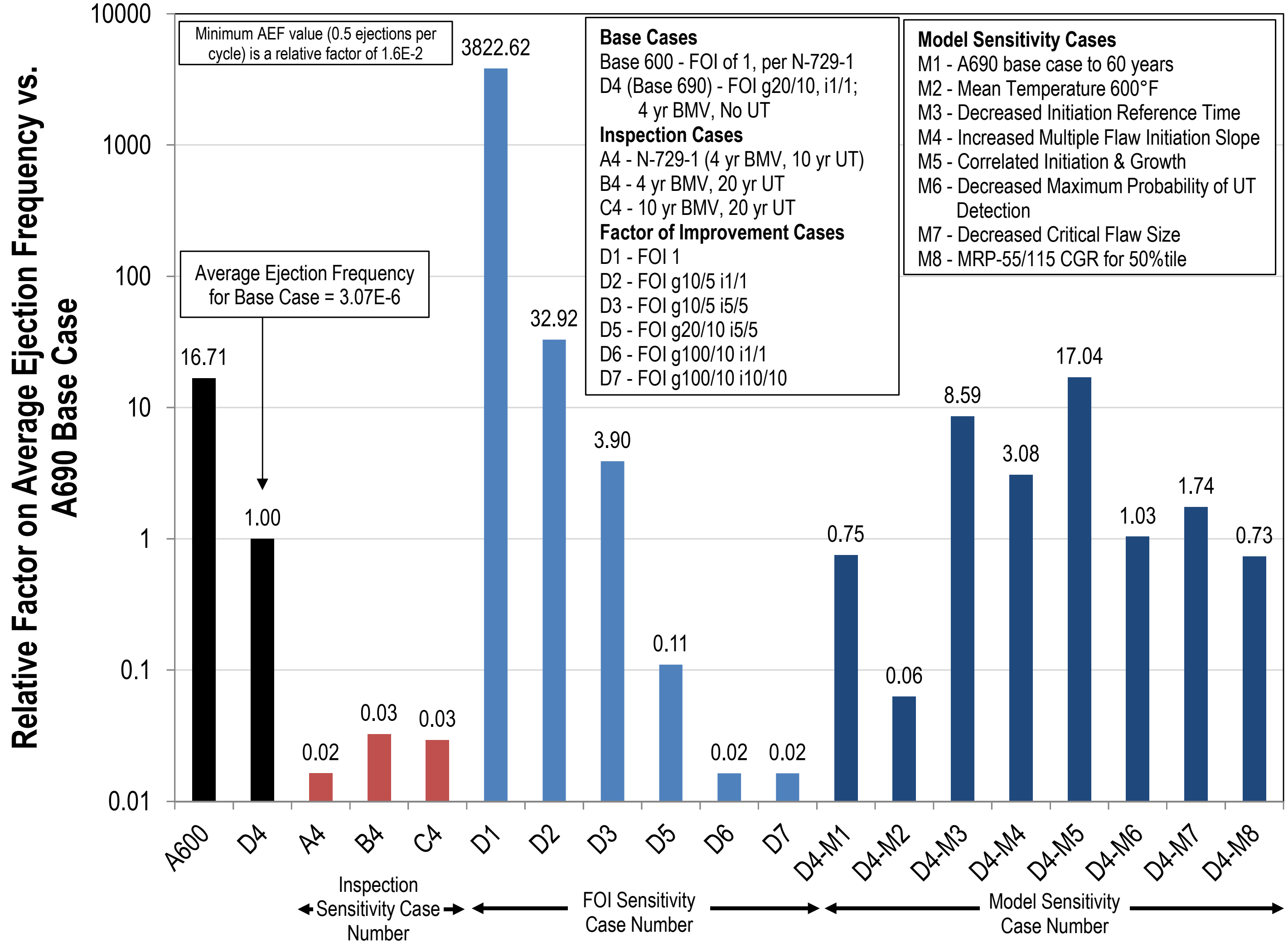
Incremental Frequency of Ejection – FOI of 10 on wrought, 5 on weld and HAZ material; UT inspection after 20 years



EPRI ELECTRIC POWER RESEARCH INSTITUTE

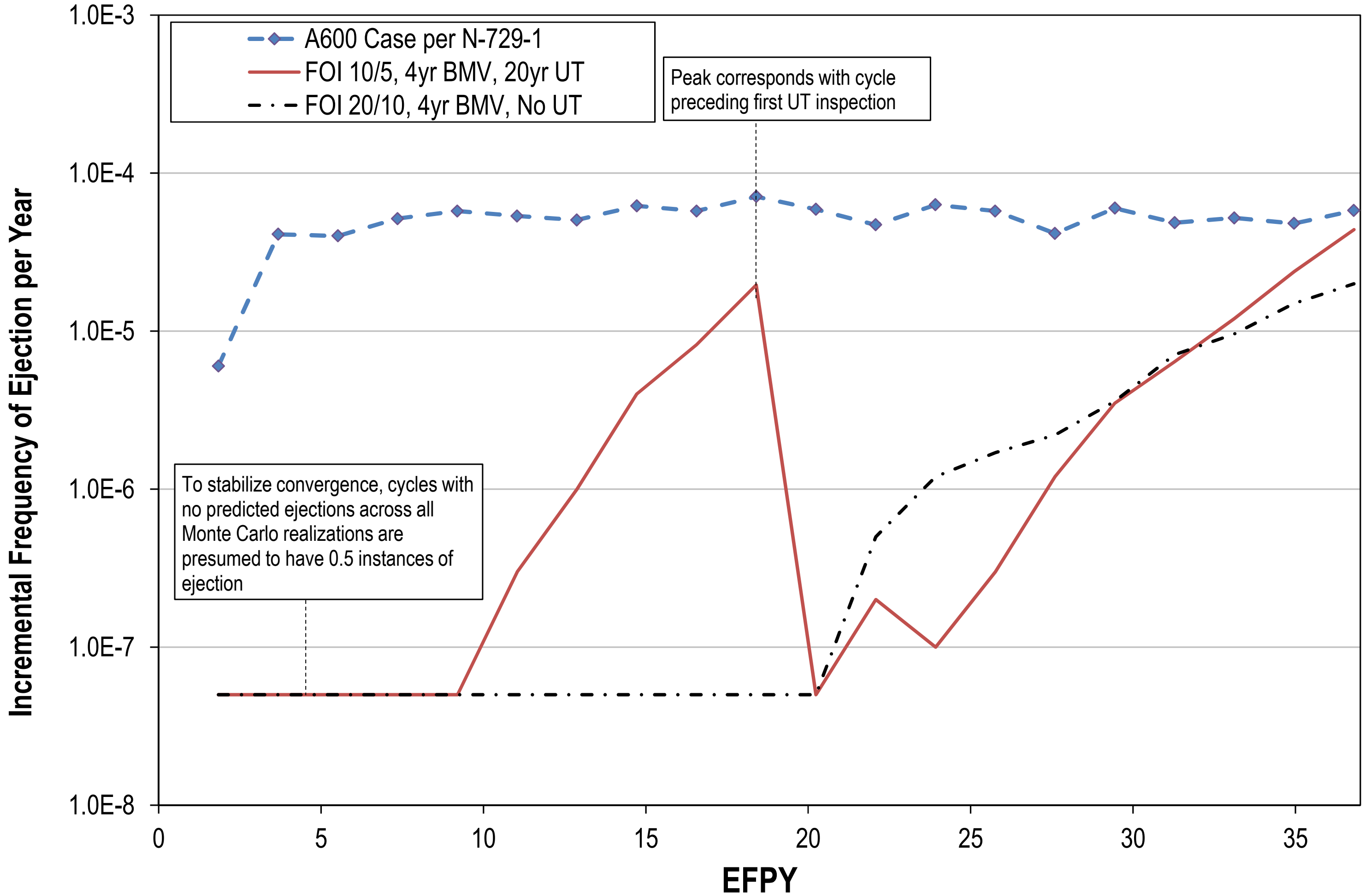
Summary of Results (2nd A690 Base Case)

Incremental Frequency of Ejection – FOI of 20 on wrought, 10 on weld and HAZ material; UT inspection after 40 years (effectively no UT)



Summary of Probabilistic Results (cont'd)

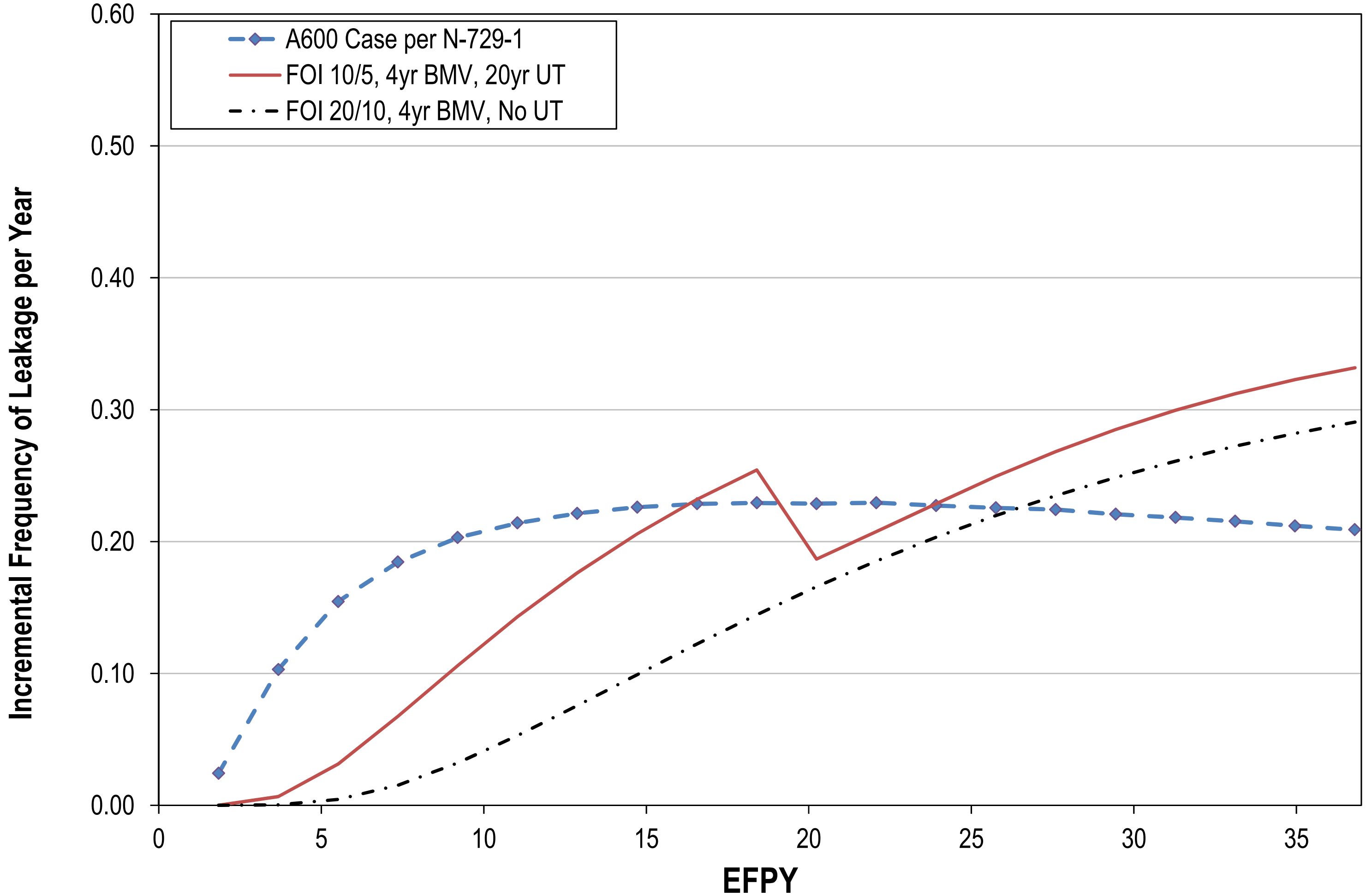
Incremental Ejection Frequency (IEF) for Base Probabilistic Cases



IEF is the number of penetration ejections modeled to occur per year divided by the number of Monte Carlo realizations and depicts the risk over time. FOIs above are applied only to growth and are indicated as "**FOI** wrought/weld&HAZ".

Summary of Probabilistic Results (cont'd)

Incremental Frequency of Leakage (ILF) for Base Probabilistic Cases



ELECTRIC POWER RESEARCH INSTITUTE

Summary of Probabilistic Results (cont'd)

- Ran range of inspection regimes, growth & initiation FOIs, model sensitivity, convergence, and benchmarking cases
  - For an FOI of 10 on base metal and 5 on HAZ & weld (10/5), average ejection frequency is 6.2E-6 per year after 40 years with UT every 20 years (8.2x lower than for A600 per N-729-1)
  - For an FOI of 20/10, average ejection frequency is 3.1E-6 per year after 40 years with no UT exam (17x lower than A600 per N-729-1)
  - For Alloy 600 case per N-729-1, average ejection frequency is 5.1E-5 per year after 40 years
  - For an FOI of 100/10, no ejections are predicted after 40 years without any UT inspections
- Taking credit for improved resistance to initiation decreases leakage frequencies by roughly the same factor (e.g., FOI of 5 on initiation reduces leakage frequency by factor of ~7)

Summary of Conclusions

- Taking conservatively small credit for reduced CGR of Alloy 690 (FOIs of 5 to 20) supports extending volumetric/surface reexamination interval to 40 years on basis of the nuclear safety concern of nozzle ejection
  - Effect on nuclear safety is acceptably small
  - Safety risk is substantially reduced compared to Alloy 600
- Taking conservatively small credit for improved resistance to initiation results in a low probability of leakage
- Taking more realistic credit for improved resistance to initiation results in a very low probability of leakage
- As discussed in Section 5.2.3 of the report, the existing visual exam (VE) interval of no more than 5 calendar years supplements the volumetric/surface exam requirement and conservatively addresses the potential concern for boric acid corrosion

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Recommendations for Alternative N-729-1 Inspections

<u>Volumetric/Surface Reexamination Interval</u>

- Extension of the nominal 10-year interval (one Section XI interval) to two intervals (nominally 20 years)
- Options for sample examination schedule for pair of "sister heads":
  - Option 1: Perform volumetric/surface examination of one sister head nominally every 15 calendar years, alternating between the heads
  - Option 2: Perform volumetric/surface examination of one sister head nominally every 20 calendar years, alternating between the heads
  - Option 3: Nominal 20-year interval for 1st sister head, and nominal 40-year interval for 2nd sister head
  - Predicated on no PWSCC being detected in either sister

<u>Direct Visual Examinations (VEs) for Leakage</u>

- Maintain the schedule of VEs per N-729-1 as a conservatism

Together…Shaping the Future of Electricity