






# NRC Non-Destructive Examination Research

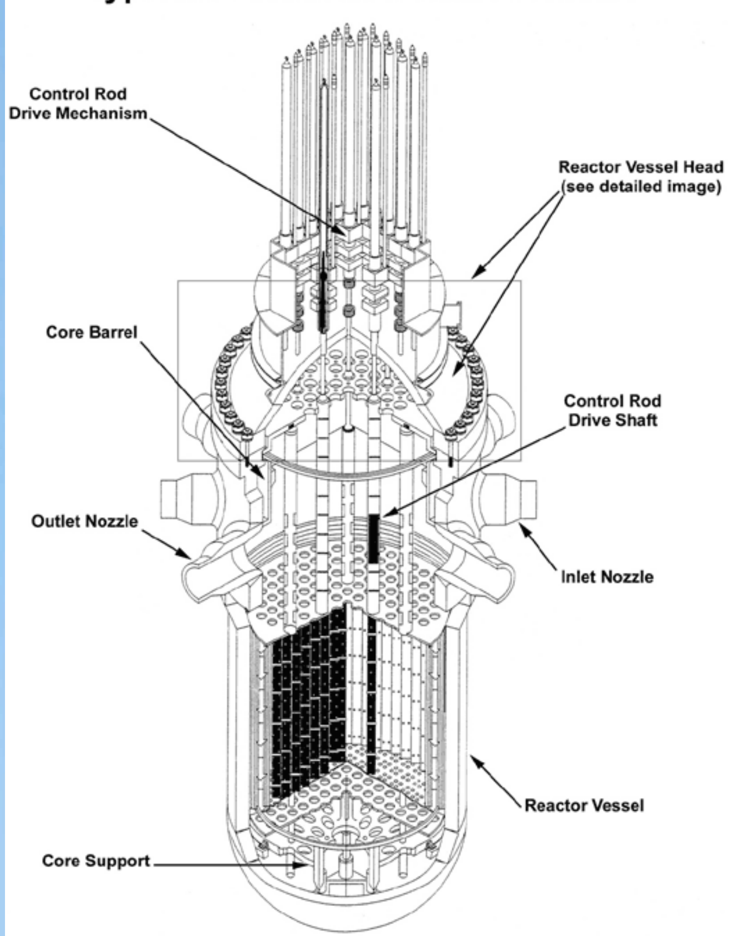

Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

Jeff Hixon

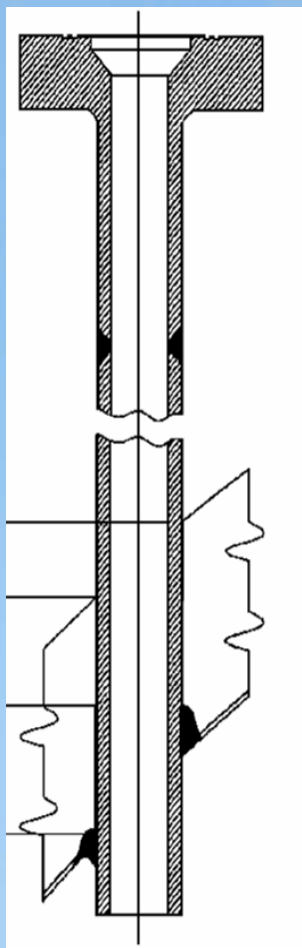

October 22, 2009

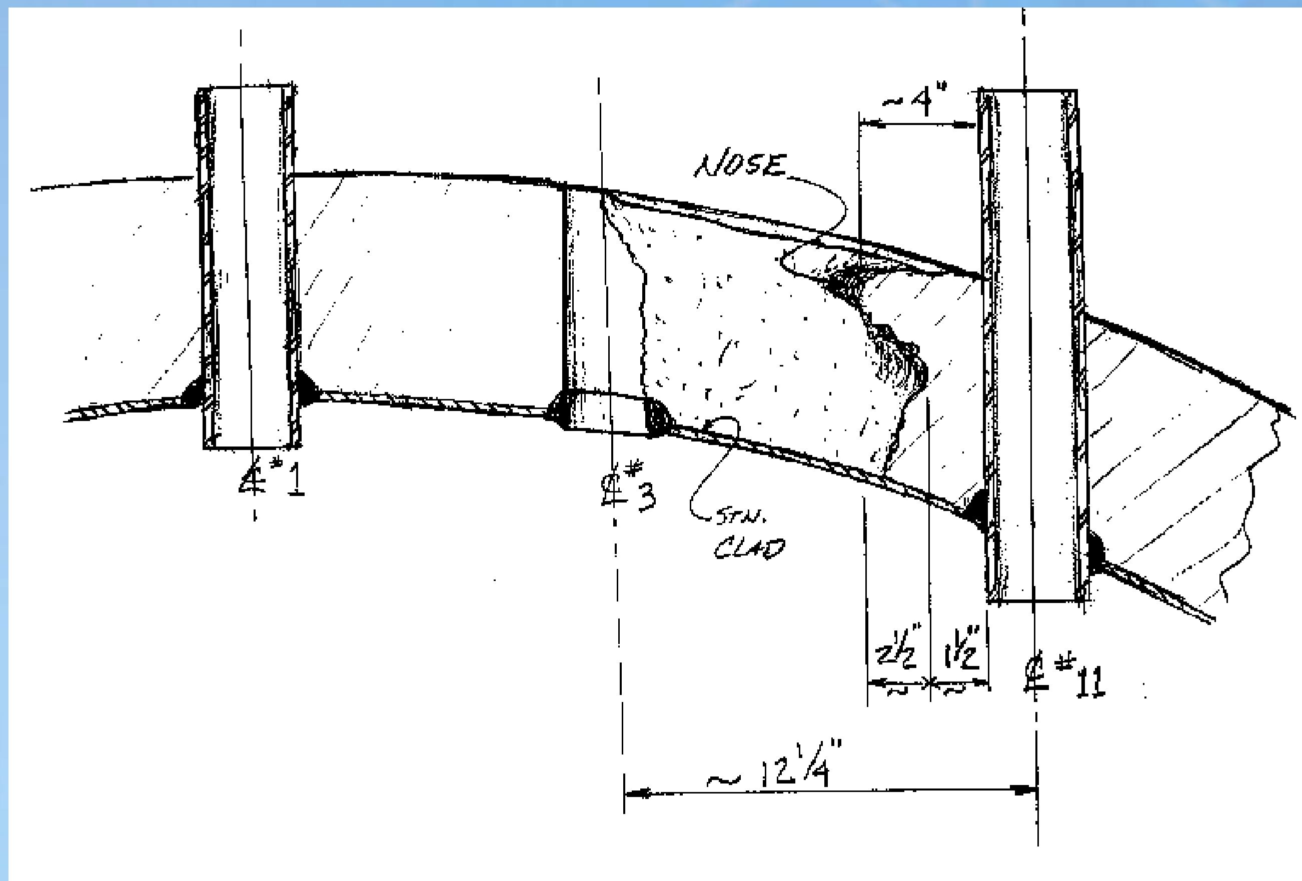
# Why NDE?

Typical Pressurized Water Reactor

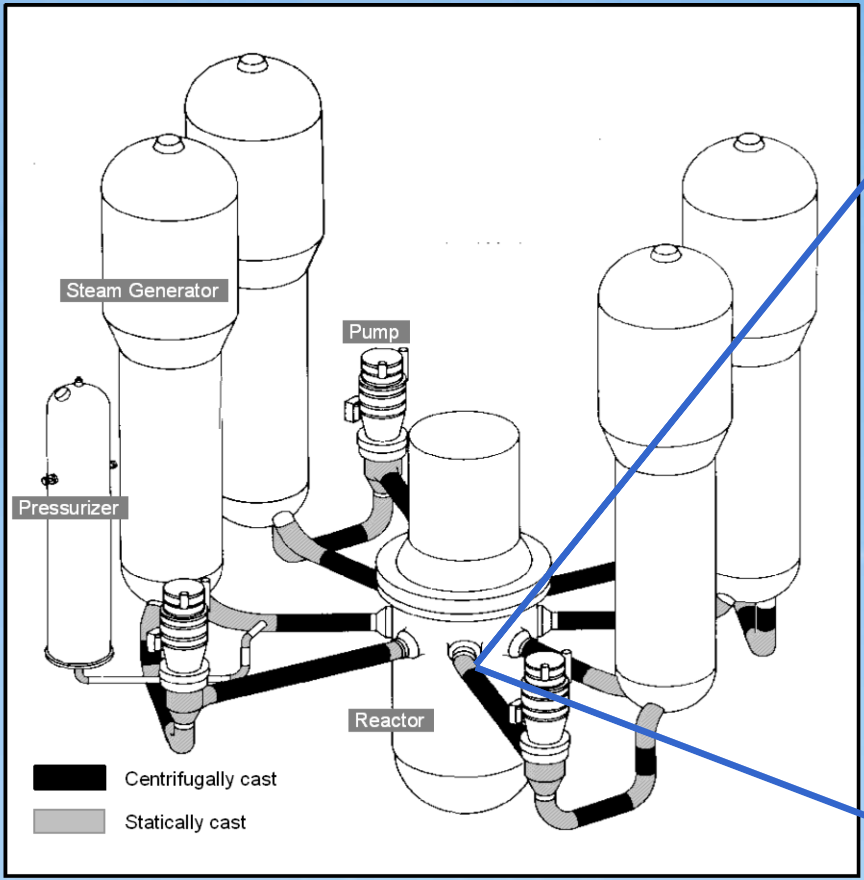


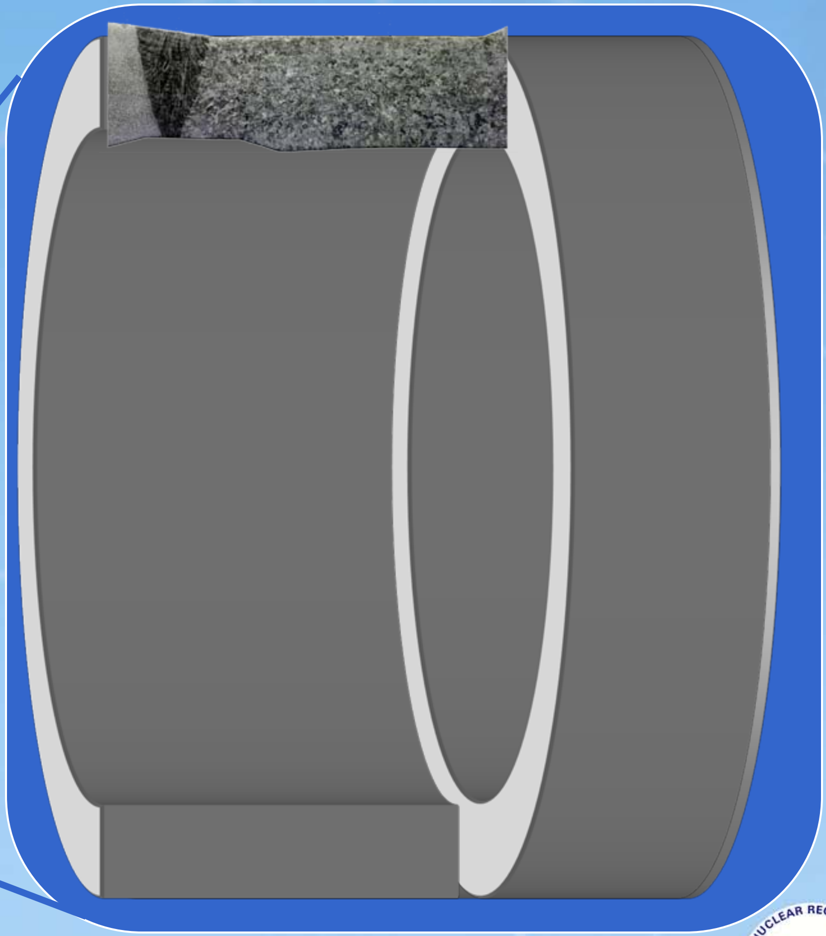

# Why NDE?





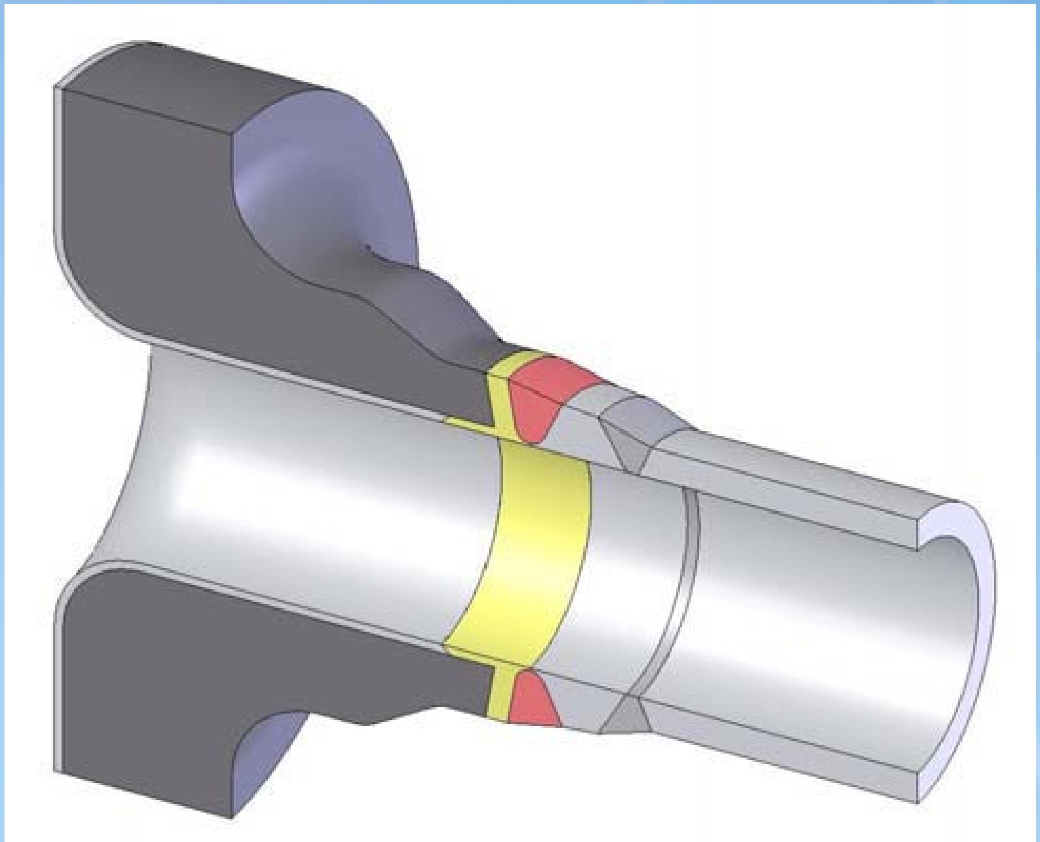
# Cast SS Piping Welds



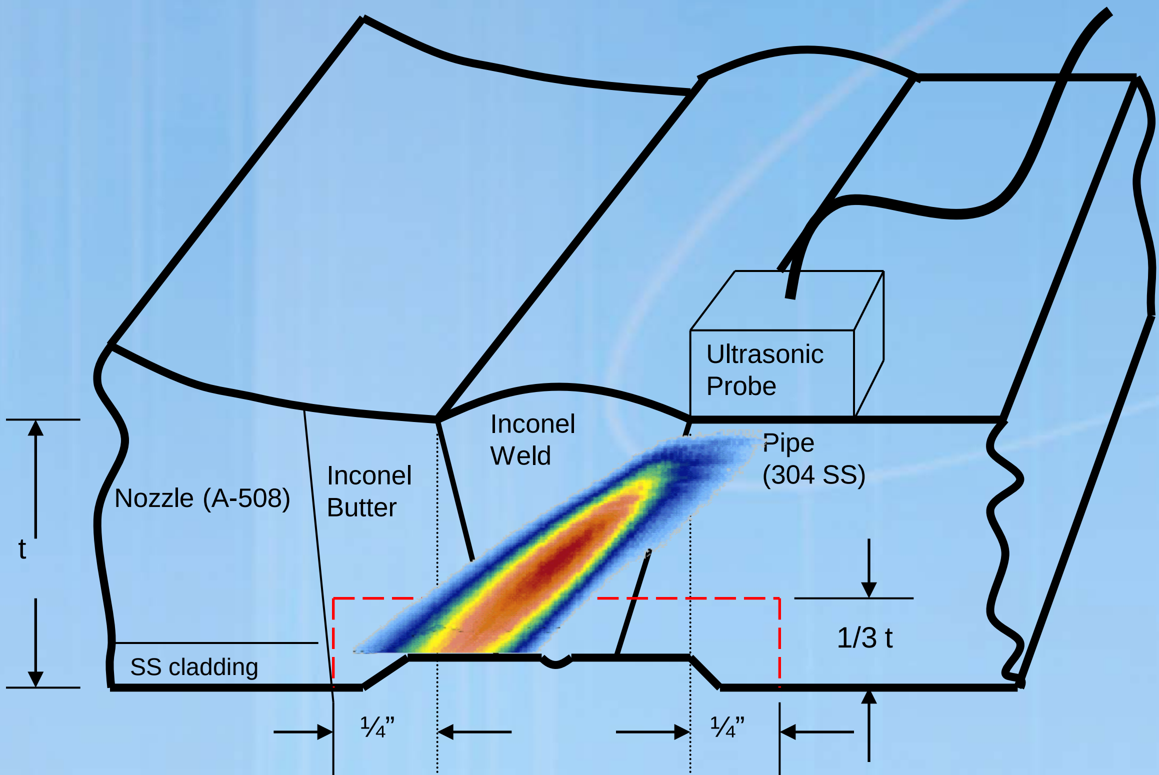
*Above illustration courtesy of A. Chockie, Chockie Group International, Inc.*

# Dissimilar Metal Welds



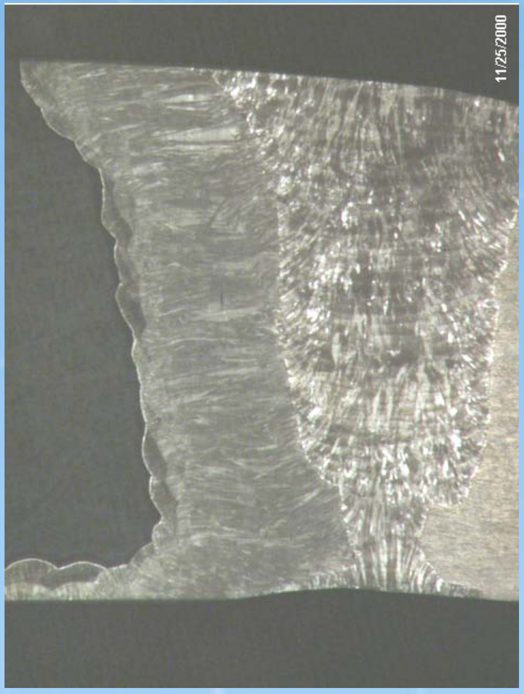
# NDE of Piping Welds

## Typical Geometrical Challenges

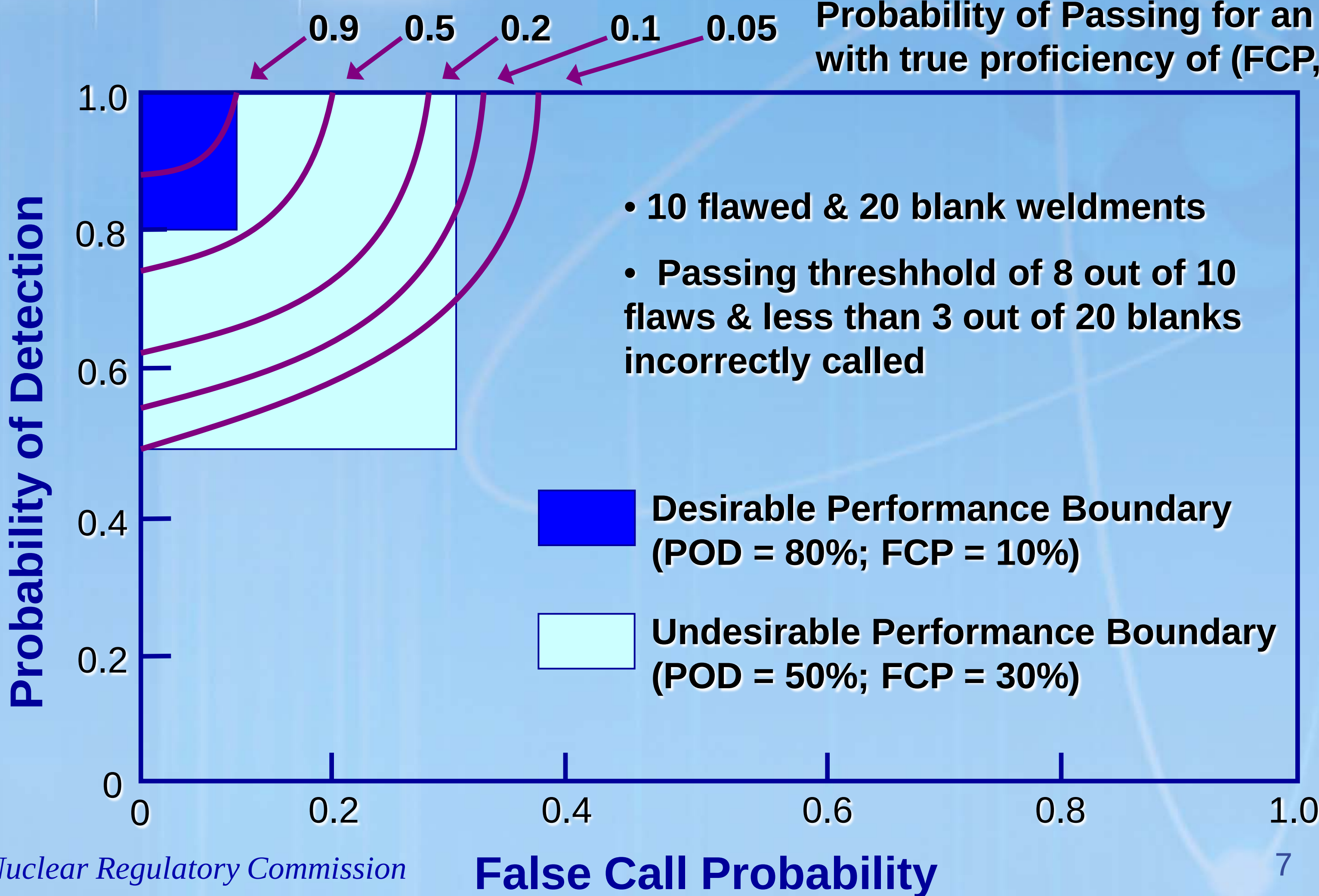



Typical Code Volume

## Typical Micro-structural Challenges



# NUREG/CR-4464, Performance Demonstration Tests for Detection of IGSCC

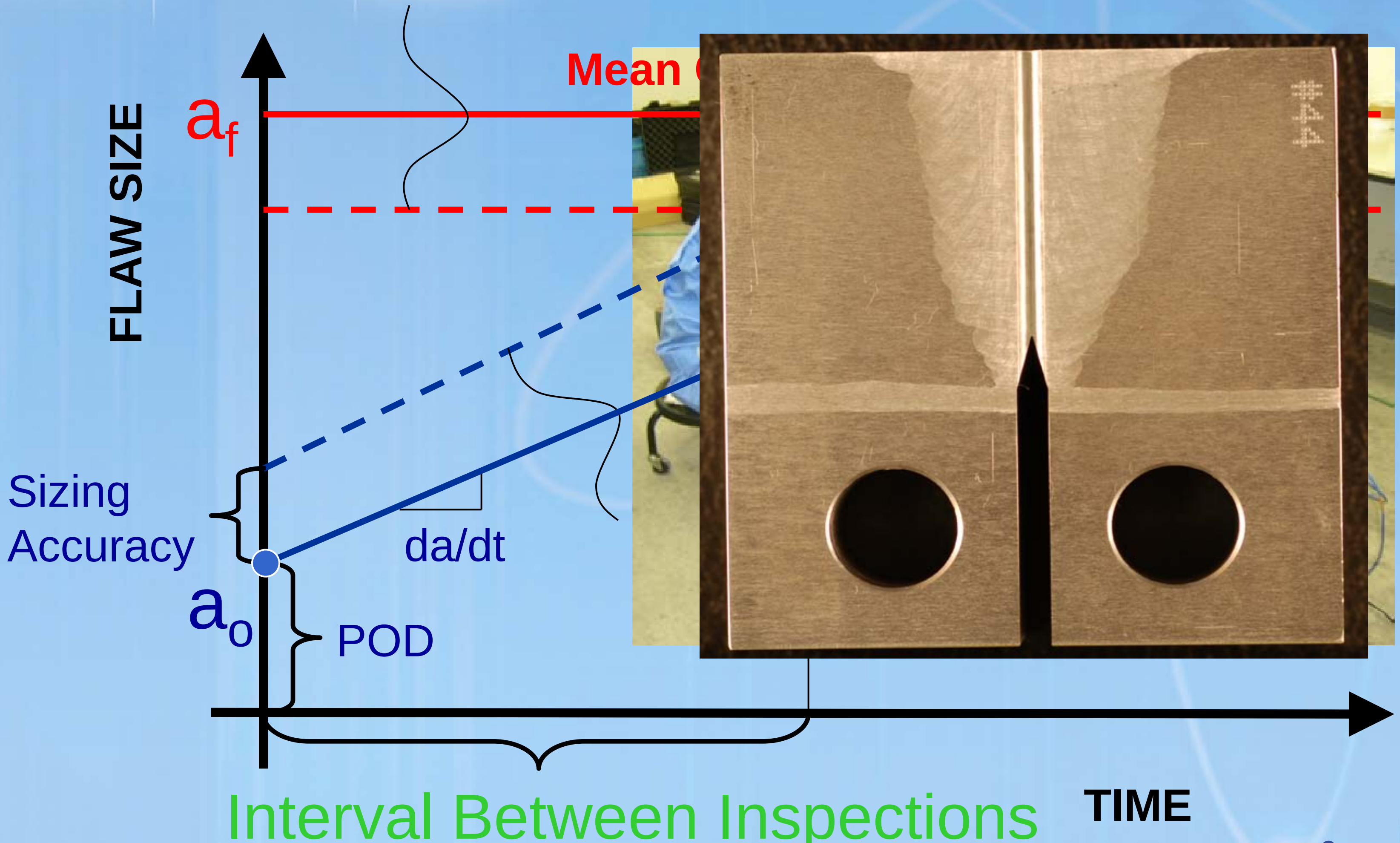




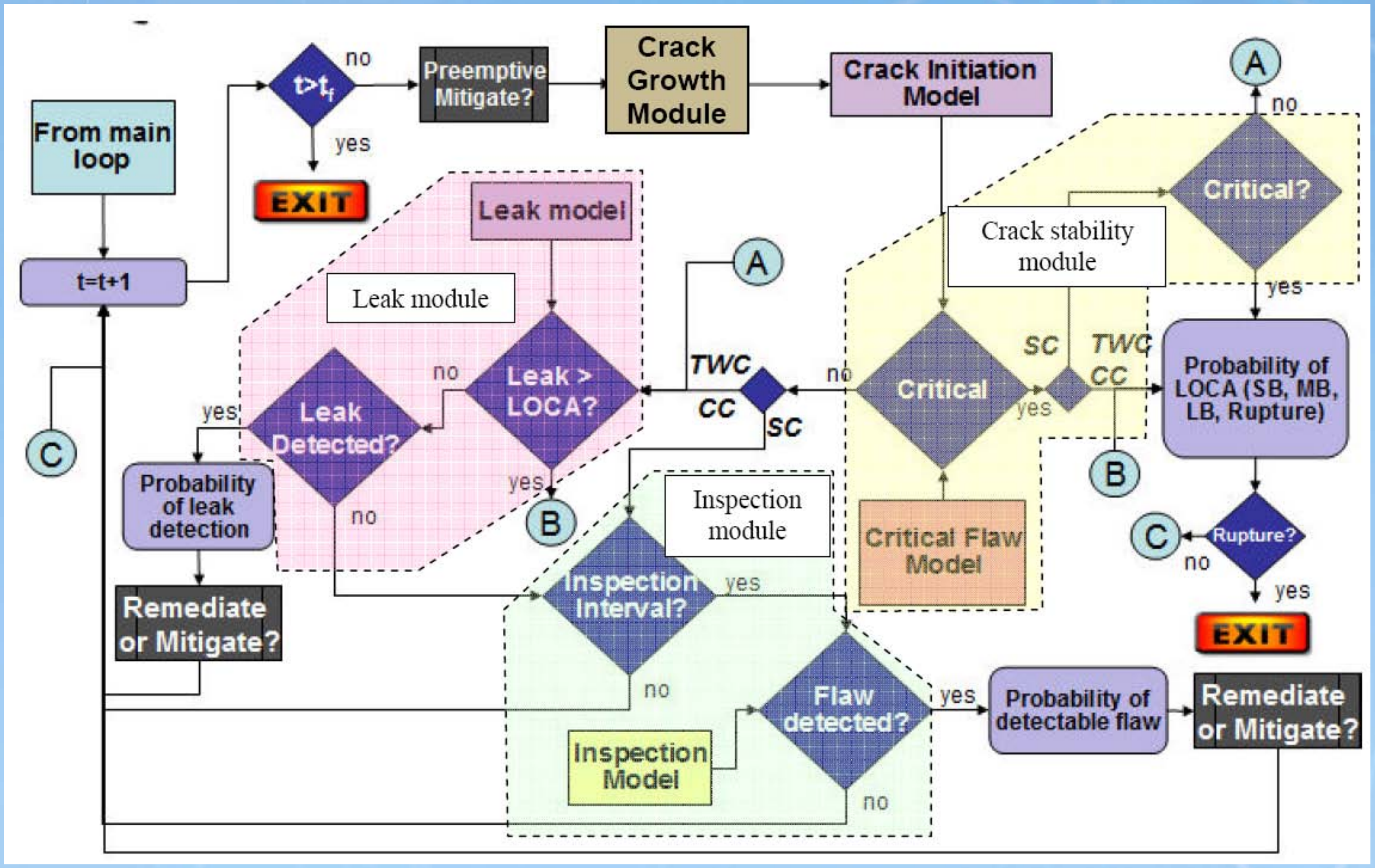
# Performance Demonstration

- NUREG/CR-4464, Performance Demonstration Tests for Detection of Intergranular Stress Corrosion Cracking
- NUREG/CR-4882, Qualification Process for Ultrasonic Testing in Nuclear Inservice Inspection Applications

# Structural Integrity Management

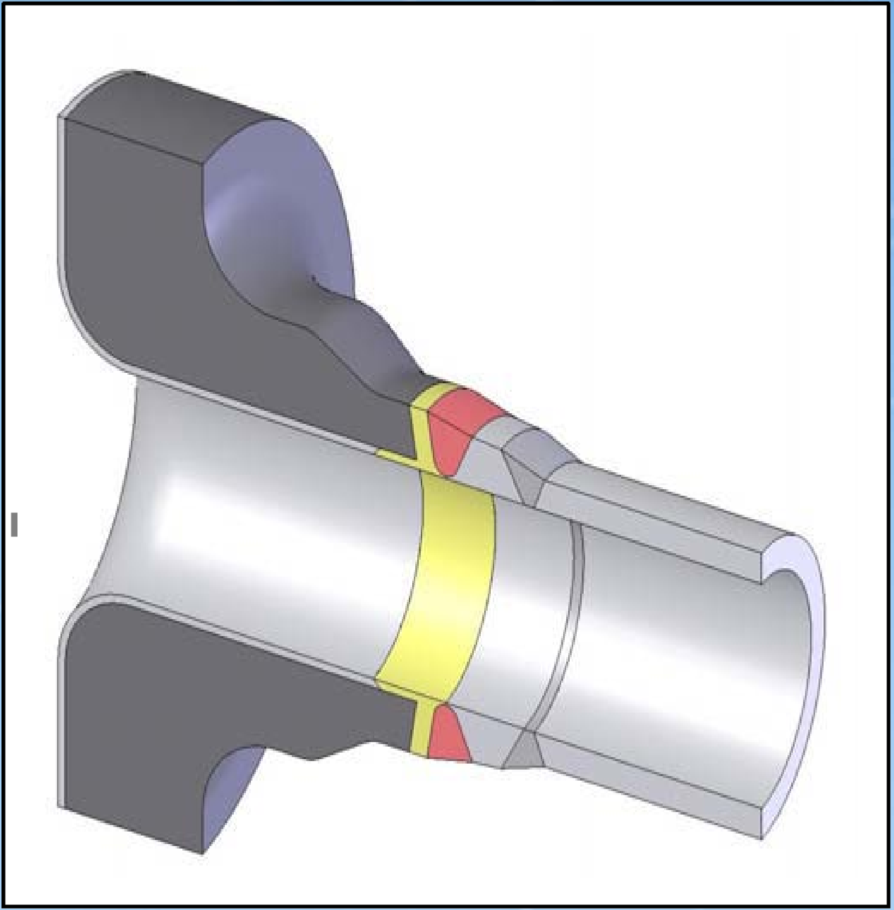


# Extremely Low Probability of Rupture (xLPR)



# EPRI-PDI POD for xLPR

- Reactor Pressure Vessel inlet/outlet nozzle
- Steam Generator inlet/outlet nozzle
- Pressurizer surge (hot leg and pressurizer connections)
- Circumferential defects only



*Above illustration courtesy of A. Chockie, Chockie Group International, Inc.*

ML0927900481



# EPRI-PDI POD for xLPR

| Category | Application | Diameter Range (in) | Thickness Range (in) | Inspection Surface |
|---|---|---|---|---|
| A | Pressurizer Surge | 12-14 | 1.2-2.3 | Outside |
| B1 | Reactor Vessel Nozzle | 27-31 | 2.5-3.0 | Inside |
| B2 | Steam Generator Nozzle | 27-31 | 5.0-5.2 | Outside |

ML0927900481

# EPRI-PDI POD for xLPR

- PDI was formed to implement performance demonstration requirements of ASME Code, Section XI, Appendix VIII and 10CFR50.55a
- Database of demonstrations since mid ’90s, world’s largest
- Every candidate (personnel and procedure demos) must examine a set of realistic mockups with flawed and unflawed grading units and meet applicable acceptance criteria to qualify
  - Detection
  - Sizing (length and depth)
  - False calls

ML0927900481

# EPRI-PDI POD for xLPR

ML0927900481

Definition of POD in this study:

- Conditional probability of detecting a flaw *during performance demonstration* given the existence of a flaw within the procedure scope
- Field Application Variables were not addressed

POD was developed from the PDI qualification program flaw detection results

- POD was calculated as function of flaw depth (% of wall thickness)
- Sizing uncertainty was not addressed
- Three categories of locations were selected based on configuration and examination procedure
- All original PDI data retained if needed for future use; truth state integrity preserved

# EPRI-PDI POD for xLPR

- Passed (P): data and POD from qualification attempts that met both the detection and false call criteria
- Failed (F): data and POD from qualification attempts that failed either the detection or false call criteria or both
- Passed + Failed (P+F): data and POD obtained by combining the P and F results
- False call: declaring a flaw detection in an unflawed grading unit

ML0927900481

# EPRI-PDI POD for xLPR

$$POD(x) = \frac{e^{\beta_1 + \beta_2 x}}{1 + e^{\beta_1 + \beta_2 x}}$$

- Fit the data with a POD model using binary regression (Hit/Miss analysis)
  - One-parameter logistic model for POD(x)
    - Independent variable: flaw depth, as % of thickness
  - Regression analysis produces maximum likelihood estimates for model coefficients $\beta_1$, $\beta_2$
- Result: six curves
  - Three categories (A, B1, B2)
  - Two cases (P and P+F)
- 95% upper and lower confidence bounds calculated for each curve

# EPRI-PDI POD for xLPR

Calculations performed with ‘R’ code (publicly available statistical analysis package)

- Similar to MIL-STD-1823 implementation of “R” but with improvements by P. Heasler (PNNL)
  - – Automated processing
    - Script (programming) provided by Heasler
  - – Was able to solve for confidence bounds when MIL-STD software failed
  - – Detailed output for documentation

ML0927900481

# EPRI-PDI POD for xLPR

- PDI Data available only for flaws ≥ ~10% T and ≤ ~90%T
  - ASME App VIII flaw distribution criteria (10 – 30%, 30 – 60%, 60 – 90%)
  - Curves were extrapolated to 10%T and 100%T to avoid disclosure of actual minimum and maximum flaw sizes in test sets
  - Extrapolation is over a relatively small span
- False calls were not considered relevant to POD calculation
  - False call performance is documented separately in the report
- Three alternative POD models were evaluated (all available within ‘R’ code)
  - Log likelihood
  - Bayesian (confidence bounds equivalent to log likelihood)
  - Wald (confidence bounds not accurate in small data sets or when POD near 1 or 0)
  - All three produced identical POD curves
- Confidence bound calculations are different
- **Log likelihood selected - confidence bounds calculation preferred**

ML0927900481

# EPRI-PDI POD for xLPR

## Flawed Grading Units Only

A: Surge line

B1:RPV Nozzles

B2:SG Nozzles

| Category | Detection Attempts | Detections | Average Detection Rate |
|---|---|---|---|
| A(P) | 1675 | 1582 | 94% |
| A(P+F) | 2358 | 2131 | 90% |
| B1(P) | 553 | 539 | 97% |
| B1(P+F) | 590 | 576 | 98% |
| B2(P) | 184 | 184 | 100% |
| B2(P+F) | 258 | 249 | 97% |



# EPRI-PDI POD for xLPR

## Unflawed Grading Units Only

A: Surge

B1: RPV

B2: SG

| Category | Attempts | False Calls | Average False Call Rate |
|---|---|---|---|
| A(P) | 5020 | 259 | 5% |
| A(P+F) | 7167 | 573 | 8% |
| B1(P) | 1467 | 34 | 2% |
| B1(P+F) | 1539 | 43 | 3% |
| B2(P) | 111 | 18 | 16% |
| B2(P+F) | 166 | 32 | 19% |



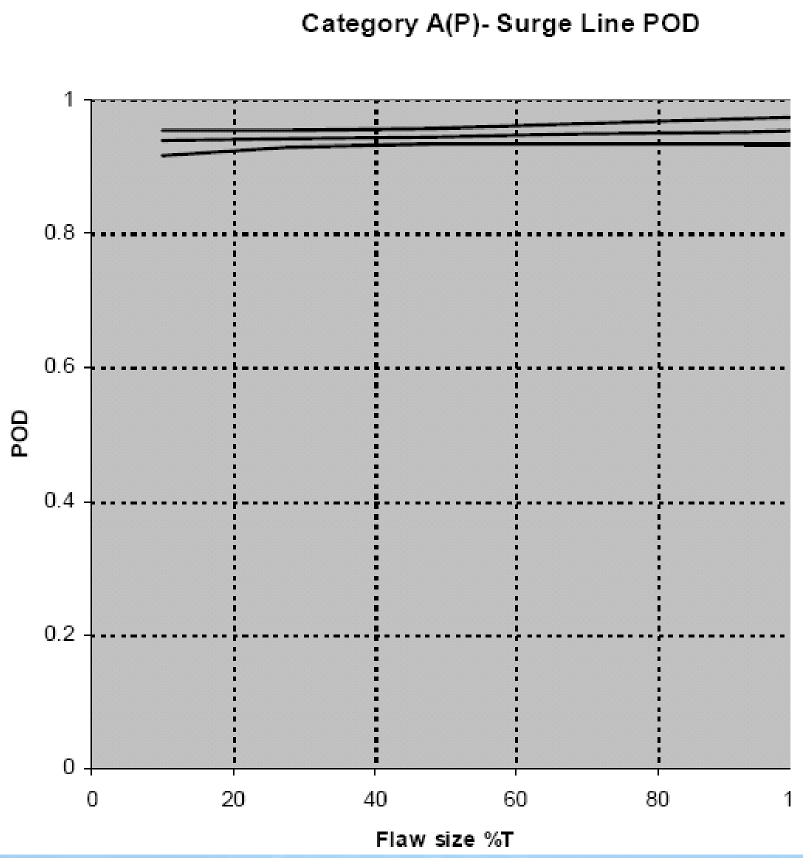
# EPRI-PDI POD for xLPR

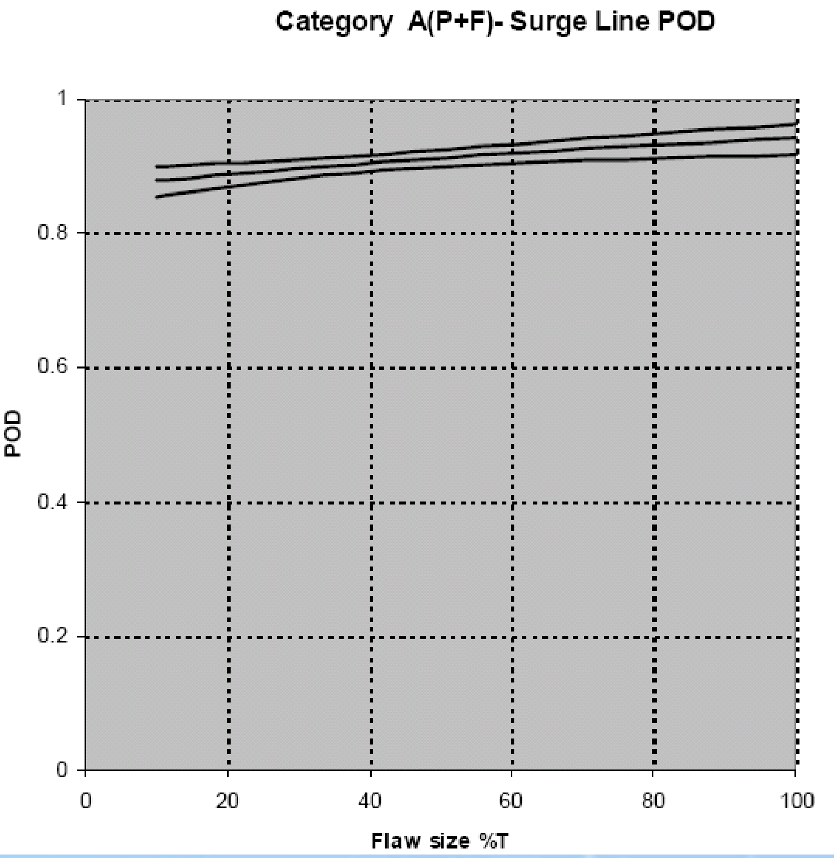
$$POD(x) = \frac{e^{\beta_1 + \beta_2 x}}{1 + e^{\beta_1 + \beta_2 x}}$$

| Case | $\beta_1$ | $\beta_2$ | Standard Error $\beta_1$ | Standard Error $\beta_2$ |
|---|---|---|---|---|
| A(P) | 2.7076 | 0.0031 | 0.2085 | 0.0045 |
| A(P+F) | 1.8789 | 0.0091 | 0.1348 | 0.0031 |
| B1(P) | 3.2440 | 0.0106 | 0.5490 | 0.0132 |
| B1(P+F) | 3.2996 | 0.0108 | 0.5493 | 0.0132 |
| B2(P) | 5.4089 | 0.0086 | 3.6423 | 0.0602 |
| B2(P+F) | 3.3148 | 0.0001 | 0.9516 | 0.0148 |

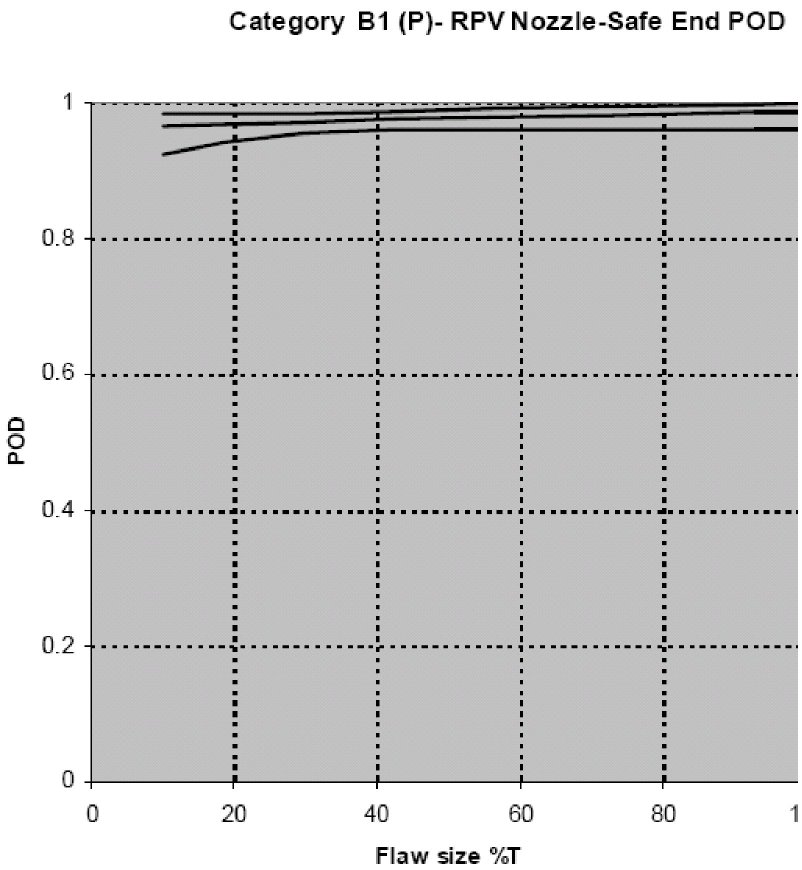
Flaw size is in units of %T

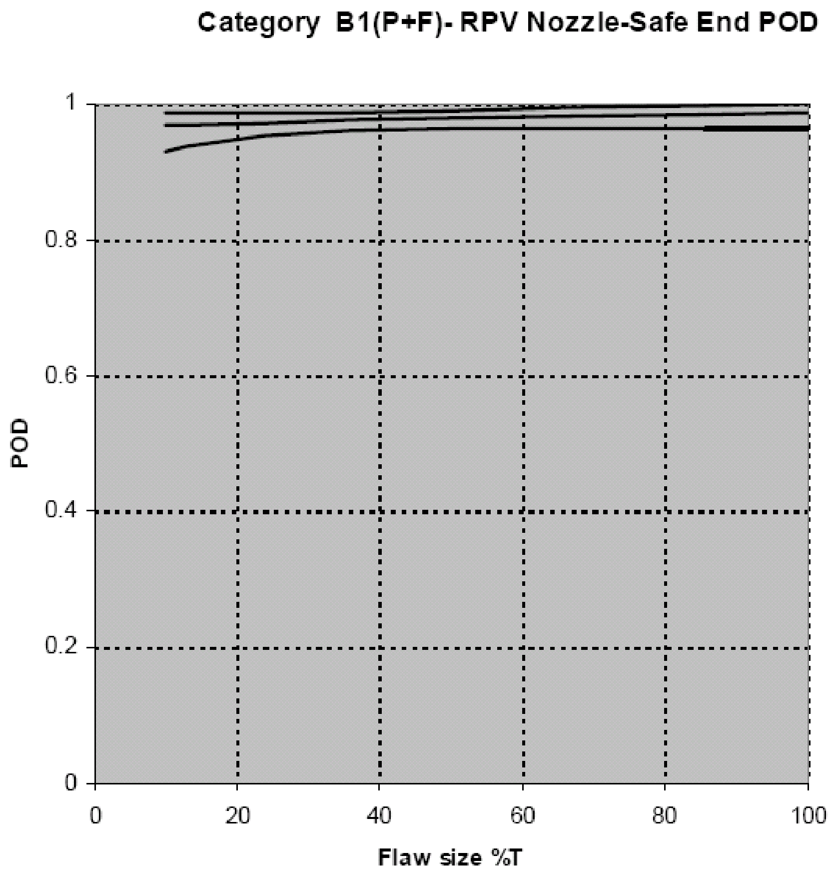
# EPRI-PDI POD for xLPR



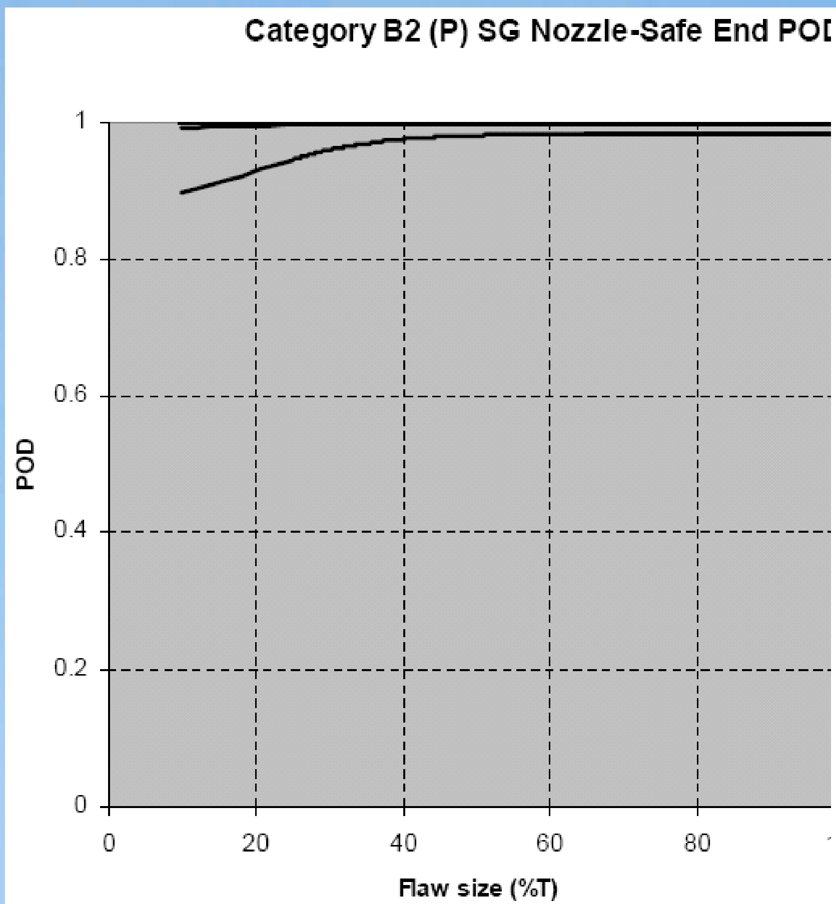



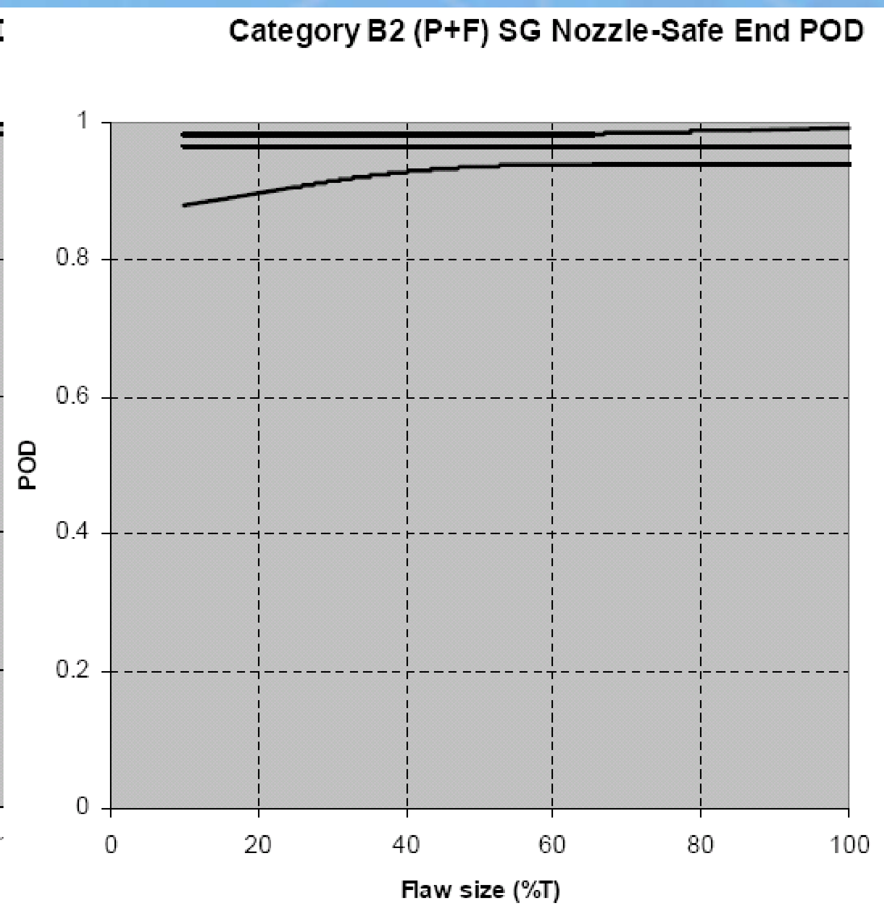
# EPRI-PDI POD for xLPR



# EPRI-PDI POD for xLPR



# Recent Publications

NUREG/CR-6982: Assessment of Noise Level for Eddy Current Inspection of Steam Generator Tubes

NUREG/CR-6933: Assessment of Crack Detection in Heavy-Walled Cast Stainless Steel Piping Welds Using Advanced Low-Frequency Ultrasonic Methods

NUREG/CR-6929: Assessment of Eddy Current Testing for the Detection of Cracks in Cast Stainless Steel Reactor Piping Components

NUREG/CR-6924: Non-destructive and Failure Evaluation of Tubing from a Retired Steam Generator