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Analysis of Empirical Probability of Detection Data for Dissimilar Metal Welds

RYAN M. MEYER[1], AIMEE E. HOLMES[1], BRUCE LIN[2]

[1]Pacific Northwest National Laboratory
[2]US Nuclear Regulatory Commission

NRC-Industry NDE Technical Information Exchange Meetings
Rockville, MD
January 15-17, 2019

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Outline

- eXtremely Low Probability of Rupture (xLPR) Probabilistic Fracture Mechanics Code
- What is Probability of Detection (POD)?
- xLPR In-Service Inspection POD Model
- Sources of Empirical Data for POD Estimation
- False Call Probability (FCP)
- Presentation of Results
- Discussion and Conclusions

Background - What is xLPR?

- Motivation - assist users of the probabilistic fracture mechanics code called eXtremely Low Probability of Rupture (xLPR)
- xLPR is a modular-based probabilistic computational tool capable of determining probability of leakage and rupture for reactor coolant piping
- One of the modules in xLPR is the in-service inspection (ISI) module which models the probability of detection (POD) and sizing performance of nondestructive examination (NDE) performed during ISI
- Developed under a cooperative agreement between US NRC Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI)

What is Probability of Detection (POD)?

- POD is the de facto metric used in quantifying the performance of an inspection for detecting structural defects (usually cracks). POD reflects the stochastic nature of detection and has a value often expressed as a percentage (range from 0% to 100%) or fraction (range from 0 to 1). It is usually represented as a function of flaw size in this context.

- The ideal POD curve is a step function with perfect (POD = 1) detection of all flaws of a>0 and no detection (POD = 0) of flaws of a=0 (or a ≤ pre-defined minimum flaw size).

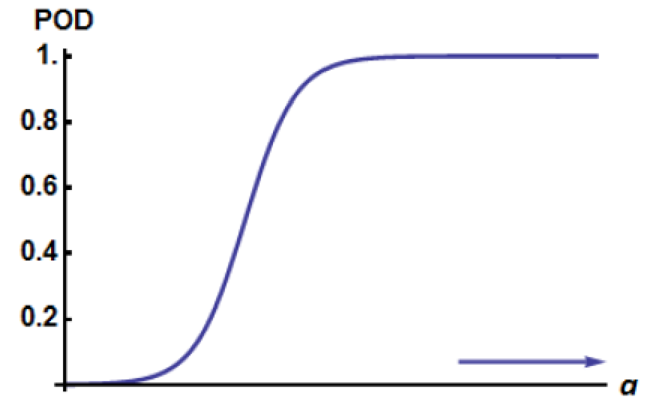
Representation of POD

- The logistic function is often used for creating a continuous POD response from discrete binary (hit/miss) NDE response data

- Creates a mathematical expression of POD as a function of flaw variable (most often, flaw depth)

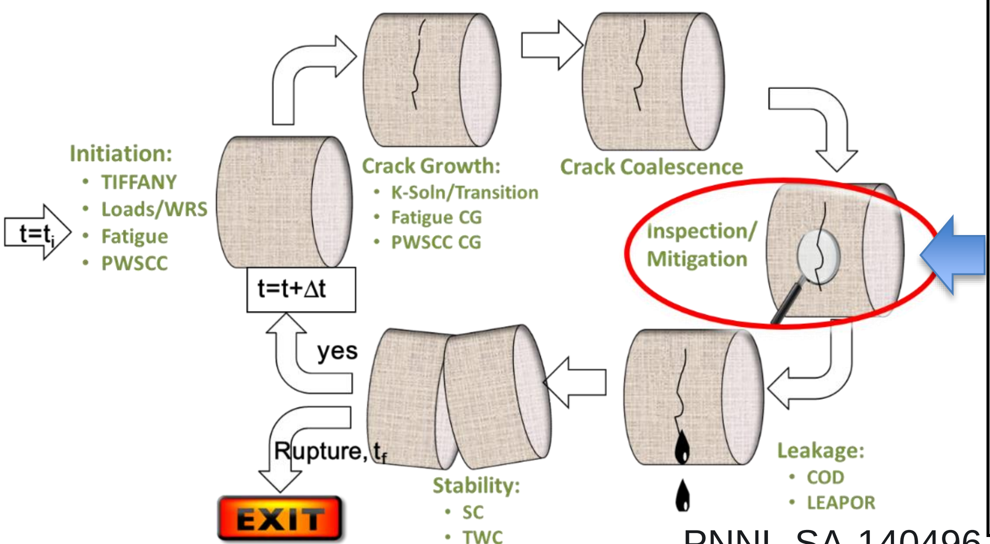
- The parameters, β_1 and β_2 , are determined using maximum likelihood estimation (MLE). Uncertainties in model parameters are represented by standard deviations in the parameters, σ_{β_1} and σ_{β_2}, and the covariance $\rho_{\beta_1\beta_2}$

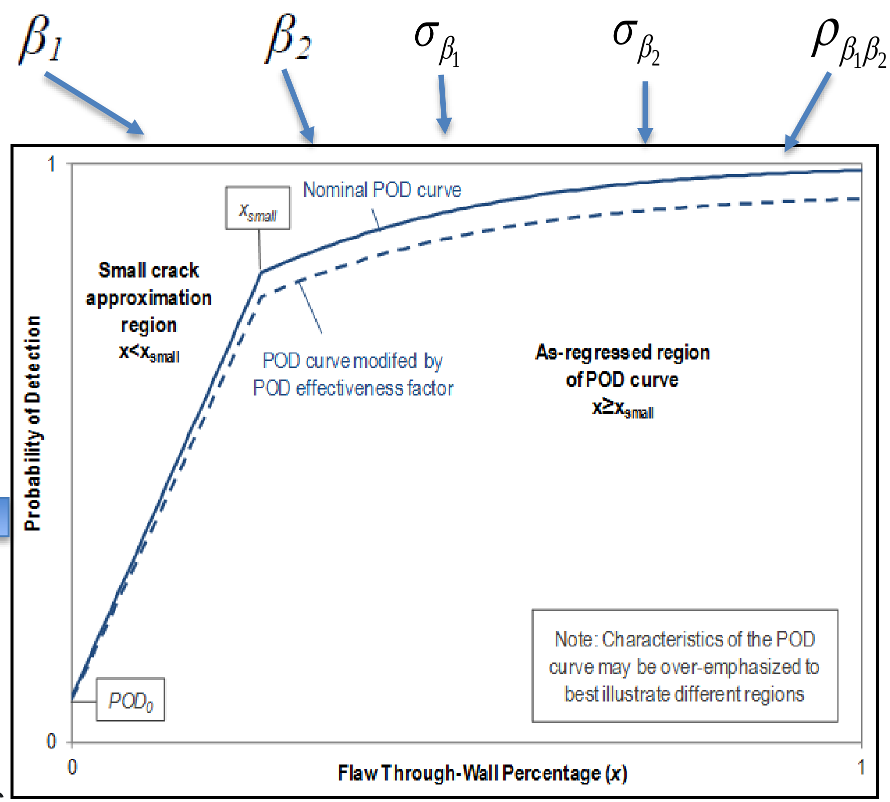
$$\mathrm{POD}(a) = \frac{1}{1+\exp(-\beta_1 - \beta_2 a)} = \frac{\exp(\beta_1 + \beta_2 a)}{1+\exp(\beta_1 + \beta_2 a)}$$



xLPR In-Service Inspection POD Model

- In xLPR, POD can be defined piecewise over the flaw size variable and can be expressed as a combination of a logistic function above a certain flaw size and simpler expression below a certain flaw size
- This model of POD is based on analysis of EPRI PDI data which included no flaws < 10% TW





Sources of Empirical NDE Performance Data

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- **Program for Inspection of Nickel Alloy Components (PINC)**
  - Blind round-robin test on specimens containing simulated PWSCC cracks to determine the detection and sizing performance capabilities of various NDE techniques
  - Participants organized by the United States, Japan, Sweden, Finland, and South Korea
  - The PINC final report NUREG/CR-7019 (available at www.nrc.gov) [ML17159A466]

- **Program to Assess the Reliability of Emerging Nondestructive Techniques (PARENT)**
  - Open testing was conducted to evaluate the performance of emerging/novel NDE techniques
  - Blind testing was conducted to quantitatively evaluate the performance of commercially used NDE techniques
  - PARENT final reports NUREG/CRs 7235 (Blind) & 7236 (Open) (available at www.nrc.gov) [Blind - ML17159A466; Open - ML17223A700]

- **EPRI Performance Demonstration Initiative (PDI)**
  - Developed from EPRI Performance Demonstration Initiative data
  - POD analysis of PDI data is summarized in EPRI report: 3002010988 [MRP-262 Rev. 3]

Sources of Empirical NDE Performance Data - Considerations

- **PINC AND PARENT**
  - Smaller sample sizes (30 to 183 attempts)
  - Both UT and ECT procedures
  - Most, but not all, procedures qualified
  - Data collected over limited time period (< 2 years)
  - For some scenarios, flaw sizes < 10% TW included in sample
  - False call data utilized in POD Analysis
  - Lower pressure – test outcome will not affect qualification status

- **EPRI PDI**
  - Largest source of NDE performance data (288 to 1675 attempts)
  - Only includes UT performance data
  - All qualified procedures
  - Database built over period of ~20 years
  - No flaws < 10% TW
  - False call data not utilized in POD Analysis
  - High pressure – passing qualification is necessary to perform job function

Scope of Test Blocks

SBDMW = Small Bore Dissimilar Metal Weld
LBDMW = Large Bore Dissimilar Metal Weld

PINC - SBDMW

PARENT - SBDMW

PARENT - LBDMW

	PDI			PINC	PARENT	
	Pressurizer Surge (Category A)	Reactor Pressure Vessel (Category B1)	Steam Generator Nozzle (Category B2)	SBDMW	SBDMW	LBDMW
Outer Diameter (mm)	305–356	686–787	685–787	386–390	289 and 815	852–895
Wall Thickness (mm)	30–58	64–76	127–132	42–46	35 and 39.5	68–78
Access	OD	ID	OD	OD and ID	OD	OD and ID
ID = inner diameter; OD = outer diameter						

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Sample Sizes

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		PDI			PINC	PARENT	
		Pressurizer Surge (Category A)	Reactor Pressure Vessel (Category B1)	Steam Generator Nozzle (Category B2)	SBDMW	SBDMW	LBDMW
OD	Axial	611[A]	---	---	100	45	45
	Circumferential	1675[A]	---	184[B]	150	183	50
ID	Axial	---	288[A]	---	30	---	34
	Circumferential	---	553[A]	---	45	---	38

[A]Table 6-1 in MRP 262 Rev. 3
[B]Table G-2 in MRP 262 Rev. 3

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Flaw Size Ranges

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		PDI			PINC	PARENT	
		Pressurizer Surge (Category A)	Reactor Pressure Vessel (Category B1)	Steam Generator Nozzle (Category B2)	SBDMW	SBDMW	LBDMW
OD	Axial	10% - 100%*			11% - 71%	11% - 74%	1% - 36%
	Circumferential				10% - 83%	3% - 72%	
ID	Axial				11% - 71%	---	
	Circumferential				10% - 83%	---	

*Flaw size distribution in PDI meets the requirements of ASME Boiler and Pressure Vessel Code Section XI, Appendix VIII, Supplement 10

Flaw Depth (% Wall Thickness)	Minimum Number of Flaws
10–30%	20%
31–60%	20%
61–100%	20%

At least 75% of the flaws shall be in the range of 10% to 60% of wall thickness.

False Call Probability (FCP)

- False Call Probability (FCP) – the likelihood that an inspection will provide an indication of detection when no structural defect is present

- In PINC and PARENT, FCP is a data point obtained by converting the observed false call rate (FCR) where FCR is the # of false calls observed per length of inspected material

$$FCR = \frac{\#\ of\ False\ Calls}{Length\ of\ Material\ Inspected}$$

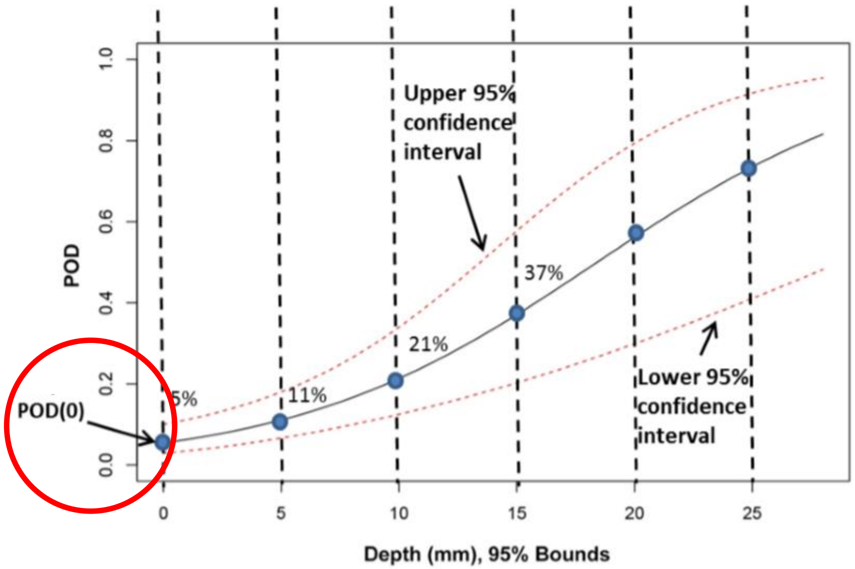
- Assuming that false calls are randomly distributed, FCP can be calculated from FCR

$$FCP = 1 - \exp\left(-FCR\left(L_{gu} + L_{fc}\right)\right)$$

$$L_{gu} = Length\ of\ blank\ grading\ unit$$
$$L_{fc} = Length\ of\ false\ call$$

POD(a=0)

- POD(a = 0) is the value of POD curve fit at a = 0
- Similar concept to FCP, but not exactly the same
- POD(0) is influenced by FCP and data for a > 0



$$POD(a=0) = \frac{\exp(\beta_1 + \beta_2 * 0)}{1 + \exp(\beta_1 + \beta_2 * 0)} = \frac{\exp(\beta_1)}{1 + \exp(\beta_1)}$$

$\beta_1 \ll 0$	$POD(0) \rightarrow 0$
$\beta_1 = -2.20$	$POD(0) = 0.1$
$\beta_1 = 0$	$POD(0) = 0.5$
$\beta_1 = 2.20$	$POD(0) = 0.9$
$\beta_1 \gg 0$	$POD(0) \rightarrow 1$

Small Bore Dissimilar Metal Weld (SBDMW) Outer Diameter (OD) Access - Procedures

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PINC procedures

Team	Techniques	Data Collection	Procedure ID
13	PAUT	Automated	PAUT.13
22	UT	Automated	UT.22
28	UT	Automated	UT.28
30	UT	Manual	UT.30
39	PAUT	Automated	PAUT.39
48	UT	Manual	UT.48
63	UT	Automated	UT.63
66	UT and PAUT	Manual+Encoded	UT.PAUT.66
72	PAUT	Automated	UT.72
82	UT and TOFD	Automated	UT.TOFD.82
UT = conventional UT, PAUT = phased array UT, TOFD = time-of-flight diffraction UT			

PARENT procedures

Team	Techniques	Data Collection	Procedure ID
25	UT	Automated	UT.25
115	PAUT	Manual	PAUT.115
128	PAUT	Automated	PAUT.128
117	UT and TOFD	Automated	UT.TOFD.117
108	UT	Manual	UT.108
108	PAUT	Manual	PAUT.108.1
134	UT	Manual	UT.134.2
126	UT	Manual	UT.126
126	PAUT	Manual	PAUT.126.1
UT = conventional UT, PAUT = phased array UT, TOFD = time-of-flight diffraction UT			

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Small Bore Dissimilar Metal Weld (SBDMW) Outer Diameter (OD) Access - Results

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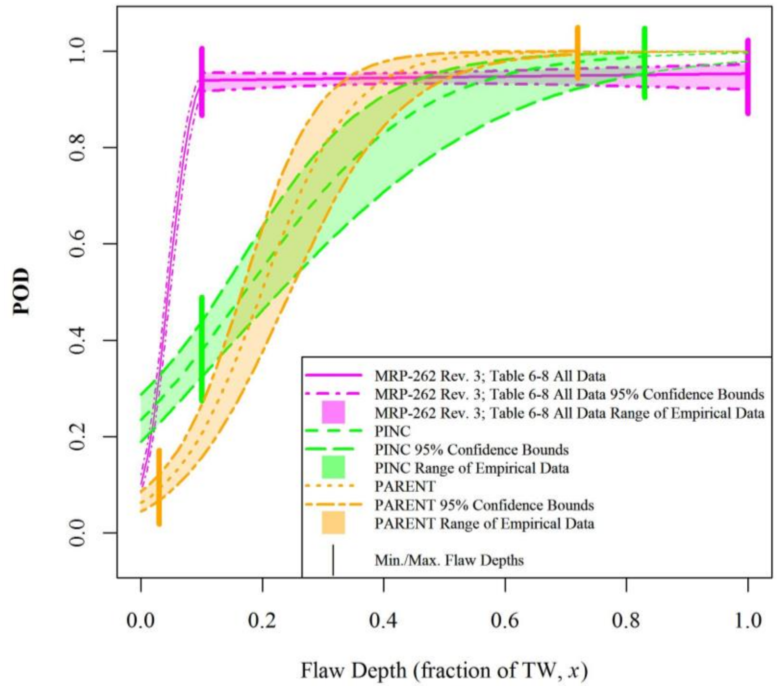
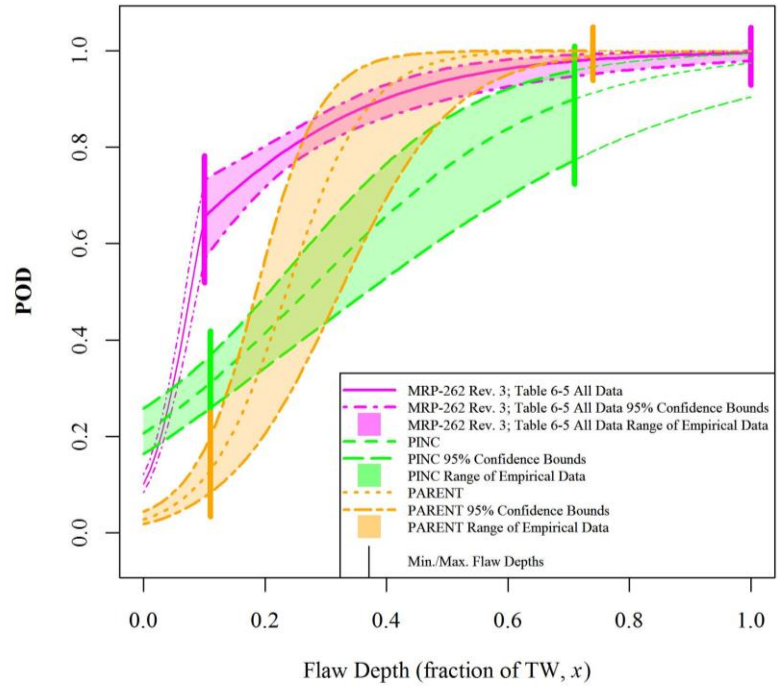
Circumferential Flaws



Axial Flaws



Shading below "Min" flaw size to indicate that empirically derived false call data is used in the logistic curve fit for PINC and PARENT

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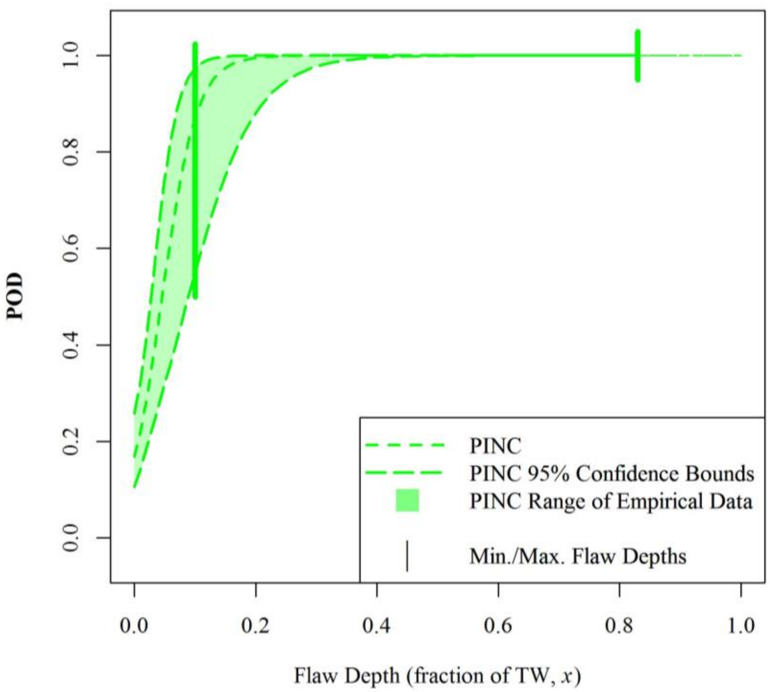
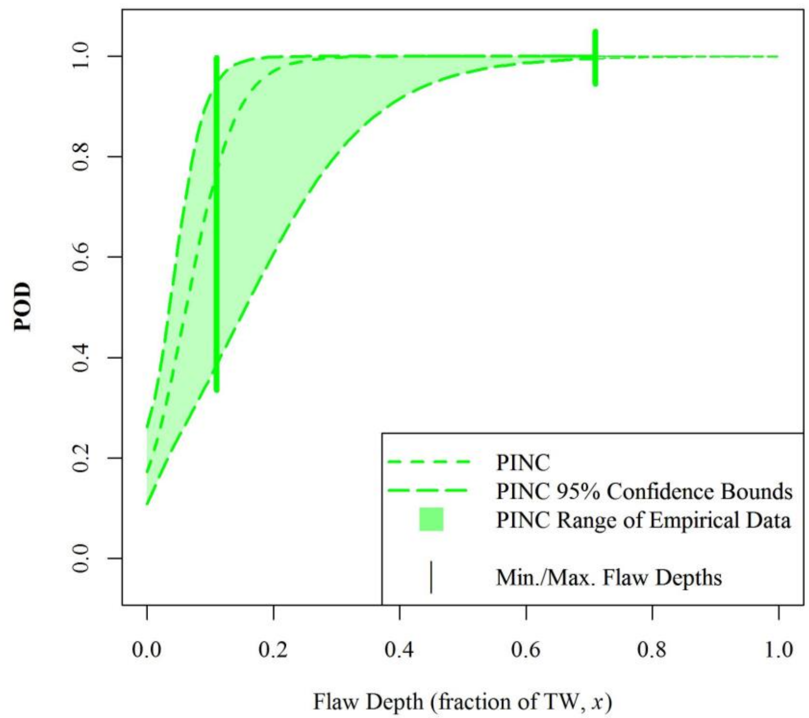
Small Bore Dissimilar Metal Weld (SBDMW) Inner Diameter (ID) Access - Results

Circumferential Flaws



Axial Flaws



Team	Techniques	Data Collection	Procedure ID
38	ECT	Manual+Encoded	ECT.38
70	ECT	Manual+Encoded	ECT.70
96	ECT	Automated	ECT.96
ECT = eddy current testing			

Large Bore Dissimilar Metal Weld (LBDMW) Inner Diameter (ID) Access - <u>Results</u>

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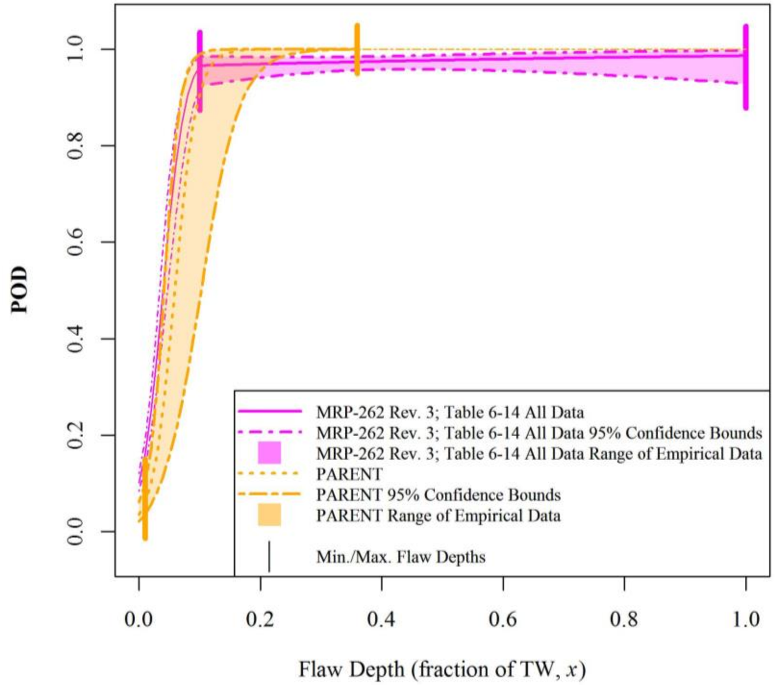
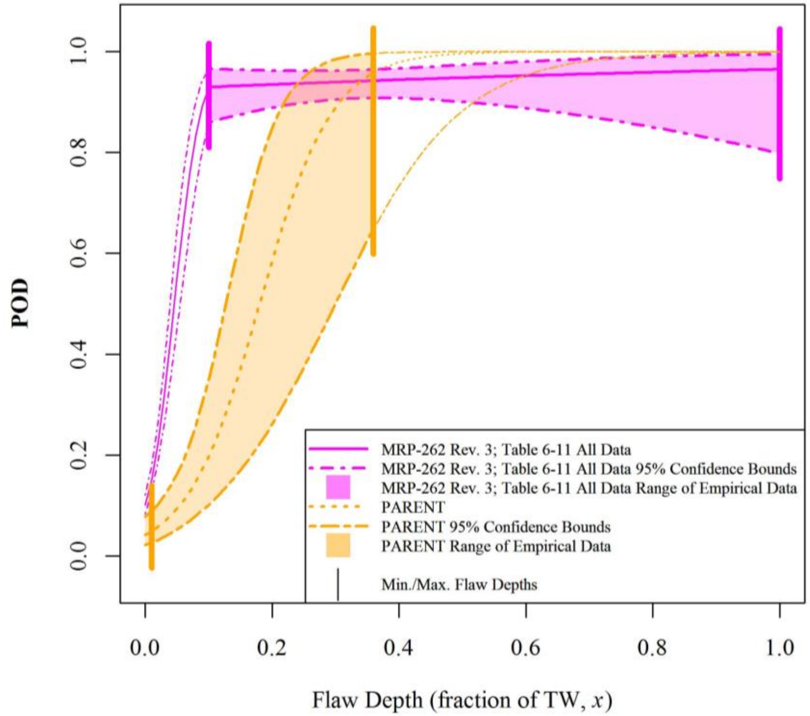
Circumferential Flaws



Axial Flaws

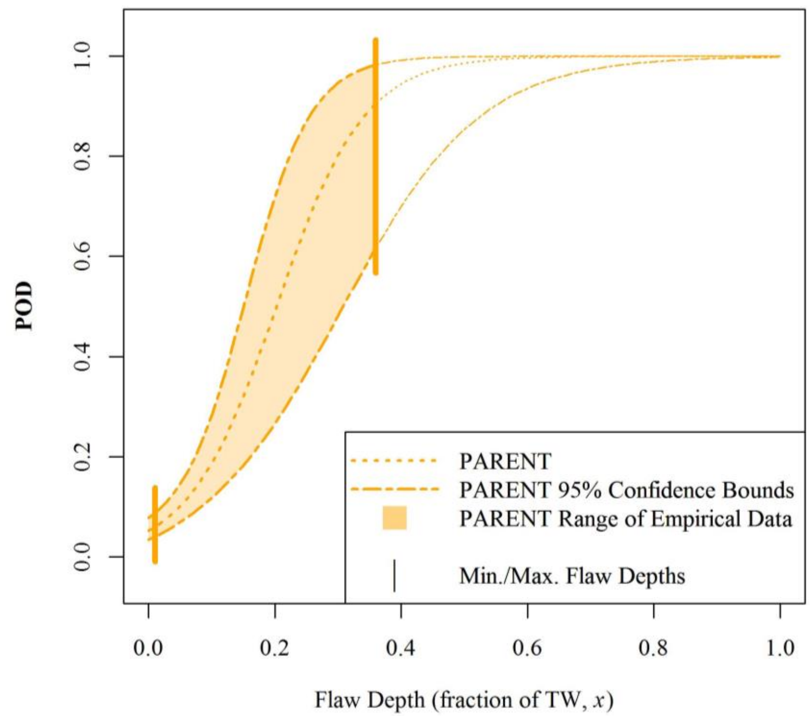


Team	Techniques	Data Collection	Procedure ID
101	ECT, UT, and TOFD	Automated	UT.TOFD.ECT.101
144	ECT and UT	Automated	UT.ECT.144
113	UT and PAUT	Automated	UT.PAUT.113
135	ECT	Manual+Encoded	ECT.135
UT = conventional UT, TOFD = time-of-flight diffraction UT, ECT = eddy current testing, PAUT = phased array UT			

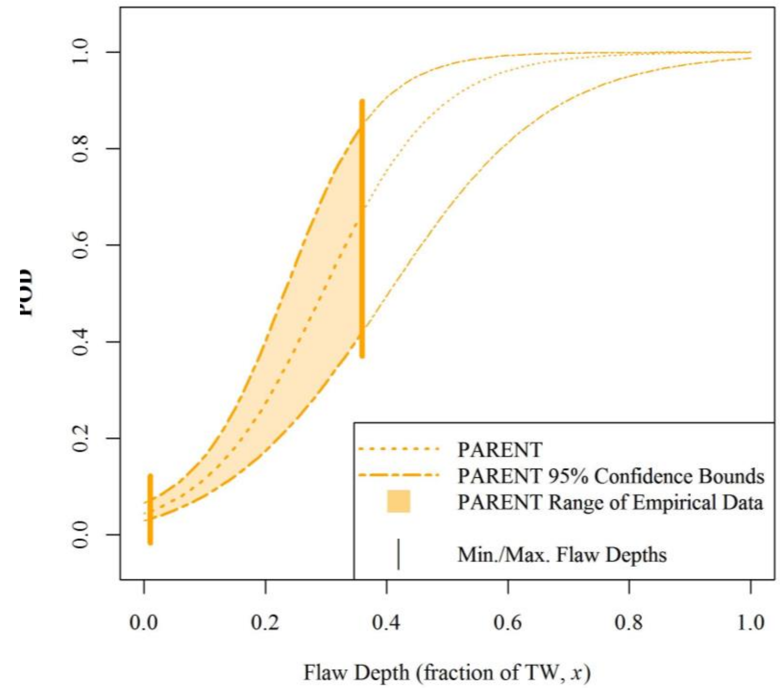
PNNL-SA-140496

Large Bore Dissimilar Metal Weld (LBDMW) Outer Diameter (OD) Access - Results

Circumferential Flaws



Axial Flaws



Team	Techniques	Data Collection	Procedure ID
108	UT	Manual	UT.108
108	PAUT	Manual	PAUT.108.1
134	UT	Manual	UT.134.2
126	UT	Manual	UT.126
126	PAUT	Manual+Encoded	PAUT.126.1
UT = conventional UT, PAUT = phased array UT			

Summary of Model Parameters

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Category	Flaw Orientation	Data Source	β_1	β_2	σ_{β_1}	σ_{β_2}	$\rho_{\beta_1\beta_2}$	Min. Flaw Depth, x	Max. Flaw Depth, x
SBDMW (OD Access)	Circumferential	PDI – Category A (MRP-262 Rev. 3; Table 6-8)	2.71	0.31	0.21	0.45	−0.86	0.10	1.00
		PINC	−1.18	6.9	0.14	1.0	−0.49	0.10	0.83
		PARENT	−2.71	13.7	0.18	1.5	−0.48	0.03	0.72
SBDMW (OD Access)	Axial	PDI – Category A (MRP-262 Rev. 3; Table 6-5)	0.12	5.24	0.27	1.02	−0.91	0.10	1.00
		PINC	−1.34	4.99	0.15	0.77	−0.46	0.11	0.71
		PARENT	−3.56	15.1	0.23	2.3	−0.43	0.11	0.74
SBDMW (ID Access)	Circumferential	PINC	-1.6	35.1	0.28	8.9	−0.23	0.10	0.83
SBDMW (ID Access)	Axial	PINC	-1.57	25.4	0.27	8.0	−0.24	0.11	0.71
LBDMW (ID Access)	Circumferential	PDI – Category B2 (MRP-262 Rev. 3; Table 6-14)	3.24	1.06	0.55	1.32	−0.87	0.10	1.00
		PARENT	−3.31	56	0.29	13	−0.33	0.01	0.36
LBDMW (ID Access)	Axial	PDI – Category B1 (MRP-262 Rev. 3; Table 6-11)	2.50	0.82	0.51	1.40	−0.87	0.10	1.00
		PARENT	−3.14	17.4	0.35	3.9	−0.40	0.01	0.36
LBDMW (OD Access)	Circumferential	PARENT	−2.91	14.3	0.22	2.7	−0.37	0.01	0.36
LBDMW (OD Access)	Axial	PARENT	−3.08	10.5	0.22	1.6	−0.46	0.01	0.36

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Some Sources of Variation Among Studies

- Flaw size distribution and manufacturing technique for flaws…
- Test format and objectives
  - PDI intent is to determine if performance is “good enough,” not meant to fully characterize performance
  - PARENT and PINC results more likely to represent performance that is possible
- Period of time for data collection
  - PINC and PARENT data each collected over 1-2 year time frame
  - PDI data accumulated over 20 years (estimated performance represents an average over this period)
- Variation in the procedures/techniques represented in each dataset and the relative distribution of procedures (e.g. # of PAUT and # of UT procedures)
- Variation in how data analysis is performed (i.e. how is false call data utilized?)

Conclusions/Recommendations

- Empirically derived POD data from PINC, PARENT, and PDI studies are excellent resources for basing POD inputs to xLPR code

- Sensitivity analyses can be useful to estimate importance of accurate knowledge of POD for small flaw sizes where large variability exists

- Treatment of POD at 0 TW size may have a significant influence on POD, especially for smaller flaw sizes

- A standardized set of guidelines for performing POD analysis would be useful to facilitating comparison of POD results from different data sets

Questions?

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