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Covariance of Limit Defining Pairs (CLDP)

A Novel Approach to Establishing Detection Sensitivity for Structural Health Monitoring Data

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Probability of Detection (POD)

- USAF-funded effort partially devoted to POD statistics for SHM
  - MIL-HDBK-1823A lays out traditional statistical analysis for NDI methods
  - Key metric is $a_{90/95}$ – smallest flaw w/90% probability & 95% confidence
  - Suggest at least 60 independent specimens are tested; 1 point per test

- Traditional POD approaches are challenging for SHM
  - For NDI, specimens are cracked, then inspector manually inspects each
  - SHM sensors are permanently installed, disposable after each test
  - 60+ unique tests generally impractical for SHM due to sensor expense

- Leveraging benefits of SHM
  - As opposed to NDI, after installation additional data points are “free”
  - However MH1823A only allows 1 point per test due to data independence
  - Must develop efficient statistical approach that accounts for dependance

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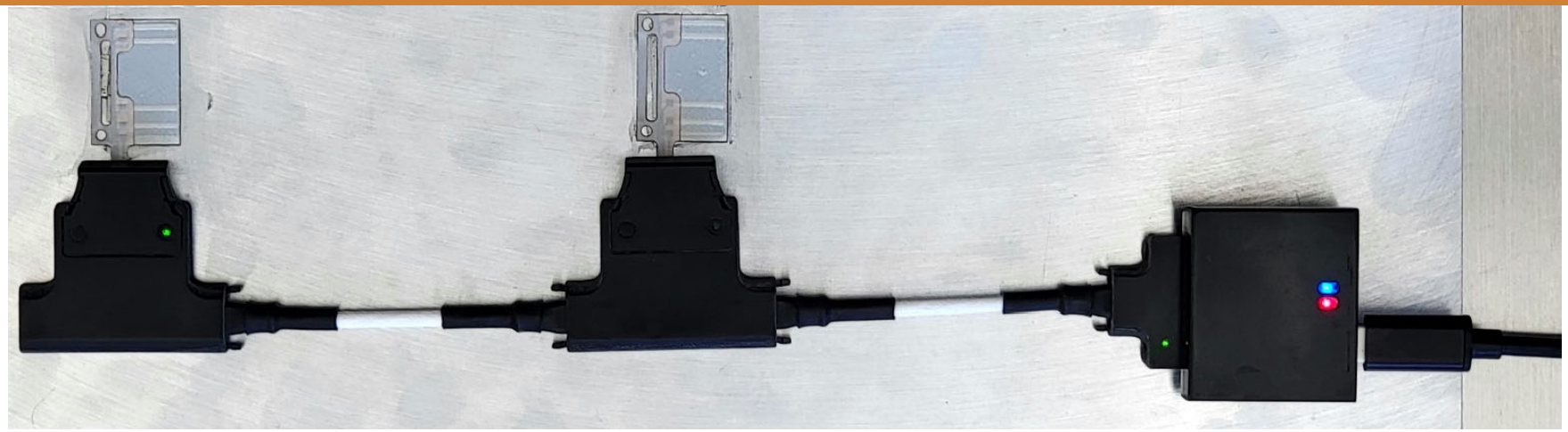
Witness Integrity Sensor Platform (WISP)



- **Architecture for facilitating condition-based maintenance (CBM)**
  - Miniature (~10 cm^2) & lightweight (~10 g) distributed acquisition
  - Completely passive electronics except when transferring data
  - Options to integrate/retrofit without any ties into asset power/data
- **WISP hardware compatible with a wide variety of sensors**
  - Standard COTS sensors for strain, temperature, humidity, etc.
  - Advanced nanoengineered sensors
    - Fatigue crack gauge
    - Corrosive & erosive potential gauges

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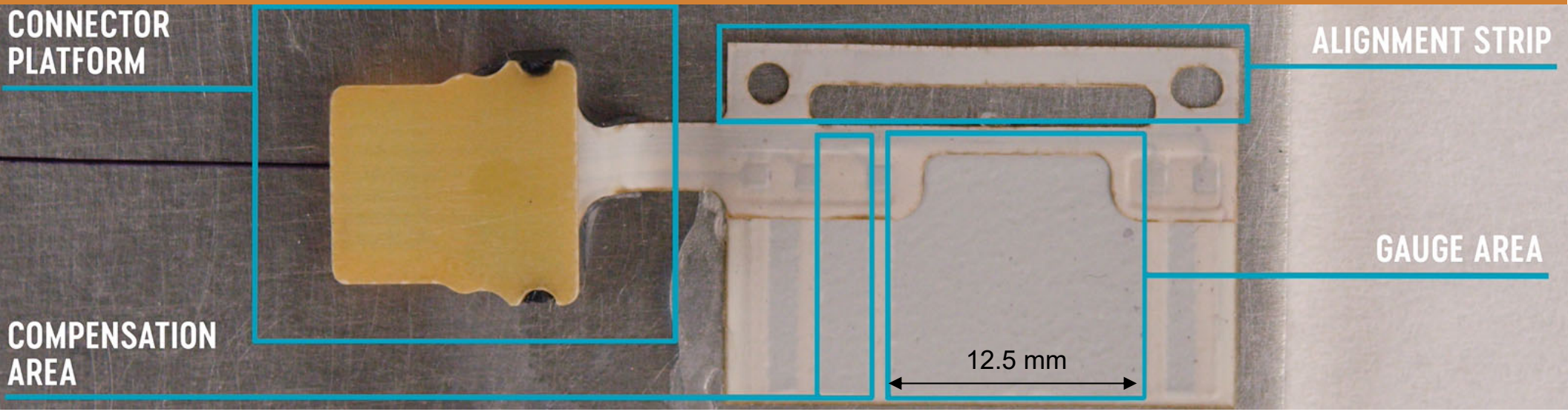
WISP Fatigue Crack Gauge



- Crack gauge physical characteristics
  - Form-factor: 12.5 mm square gauge area (not a limitation), ~200 µm thick
  - Mass: ~10 mg/cm^2, can be installed with a bend radius up to 5mm
  - Built-in self-calibration & self-compensation element
- Crack detection mechanism
  - Laminated CNT assembly bonds to structure with Loctite 415 (30 sec cure)
  - CNT network electrical resistance changes proportional to crack length
  - Completely passive sensor, crack “encoded” even when no power applied

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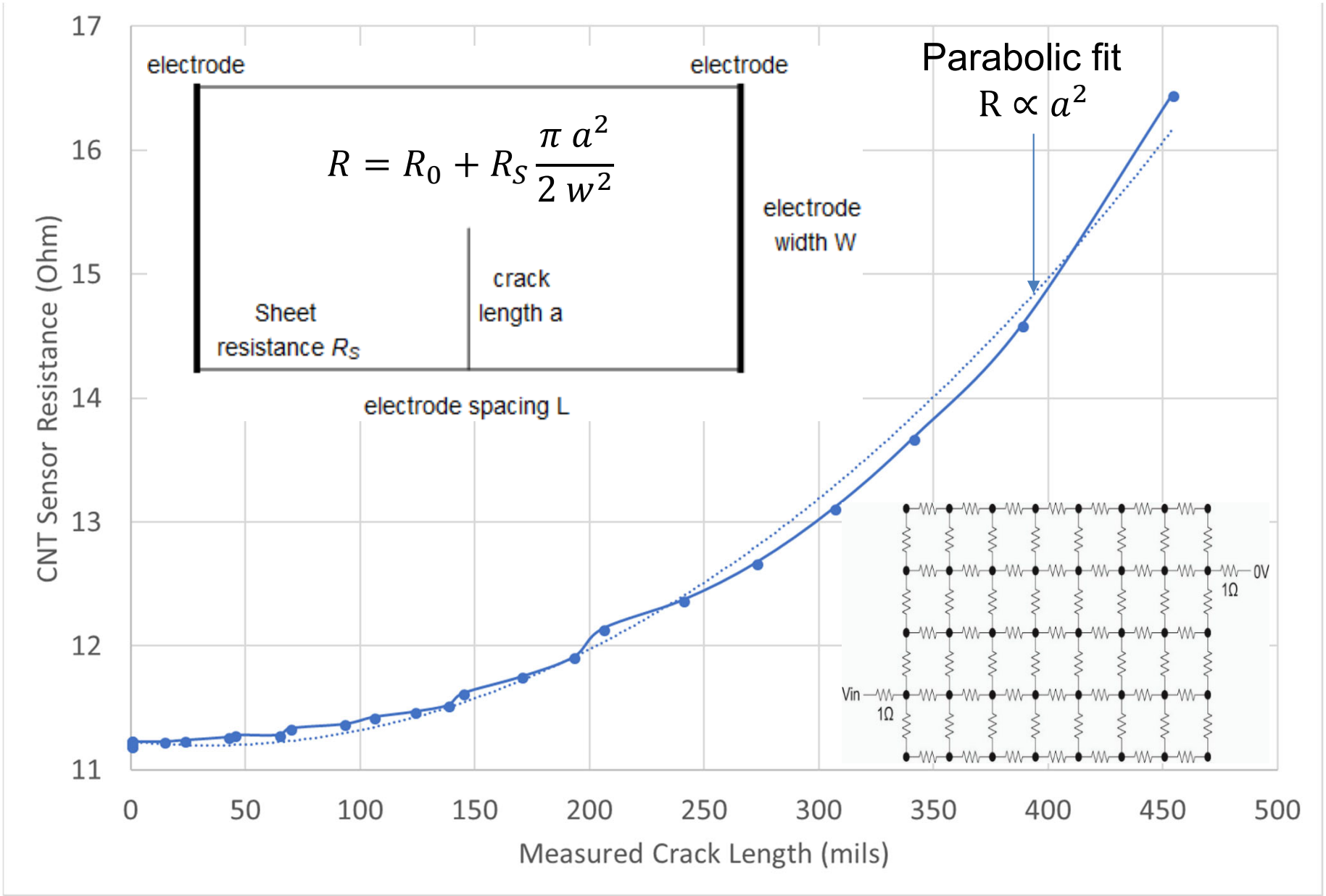
WISP Crack Gauge Resistance vs Measured Crack



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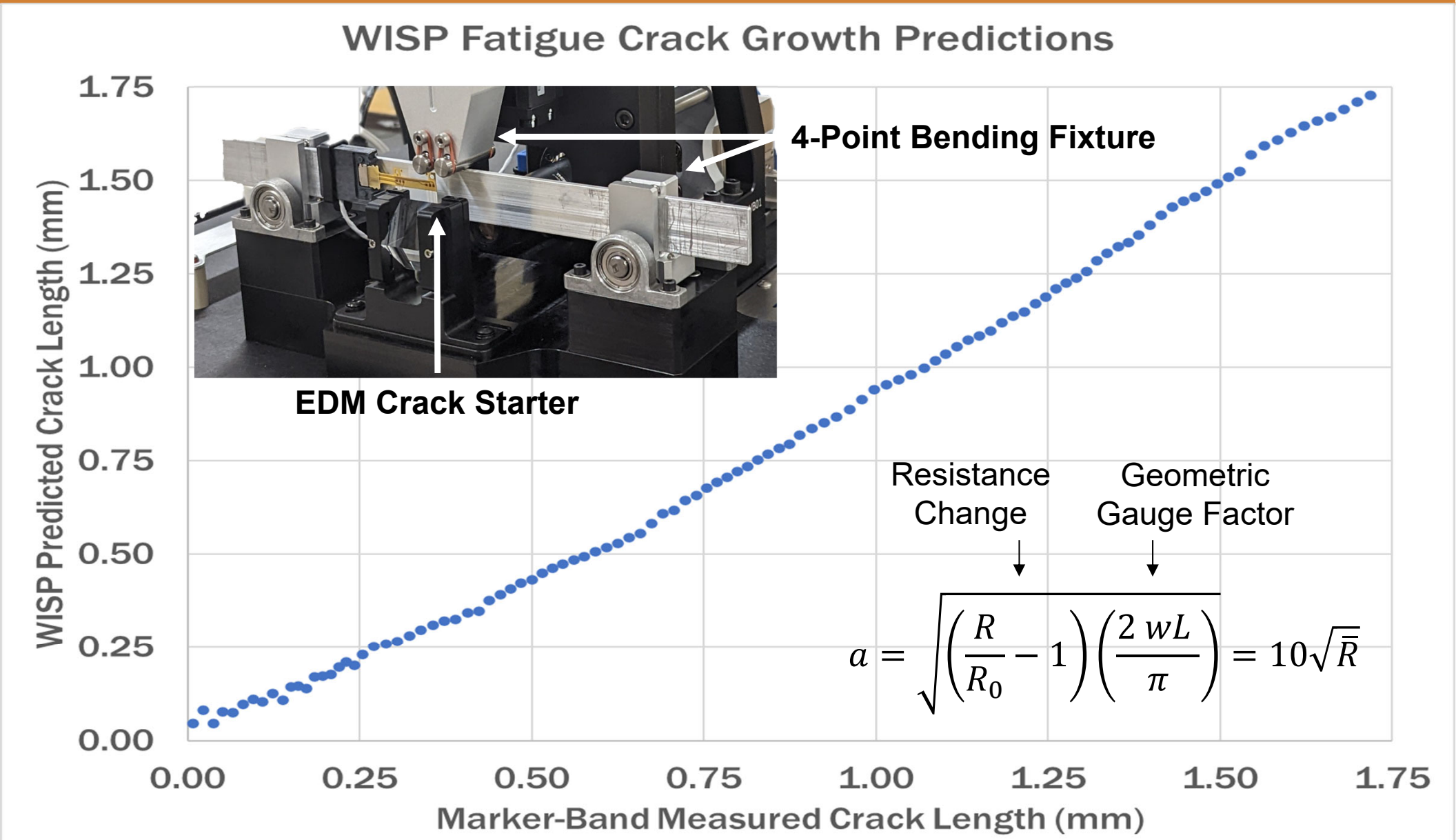
WISP Crack Gauge Detection Sensitivity Study



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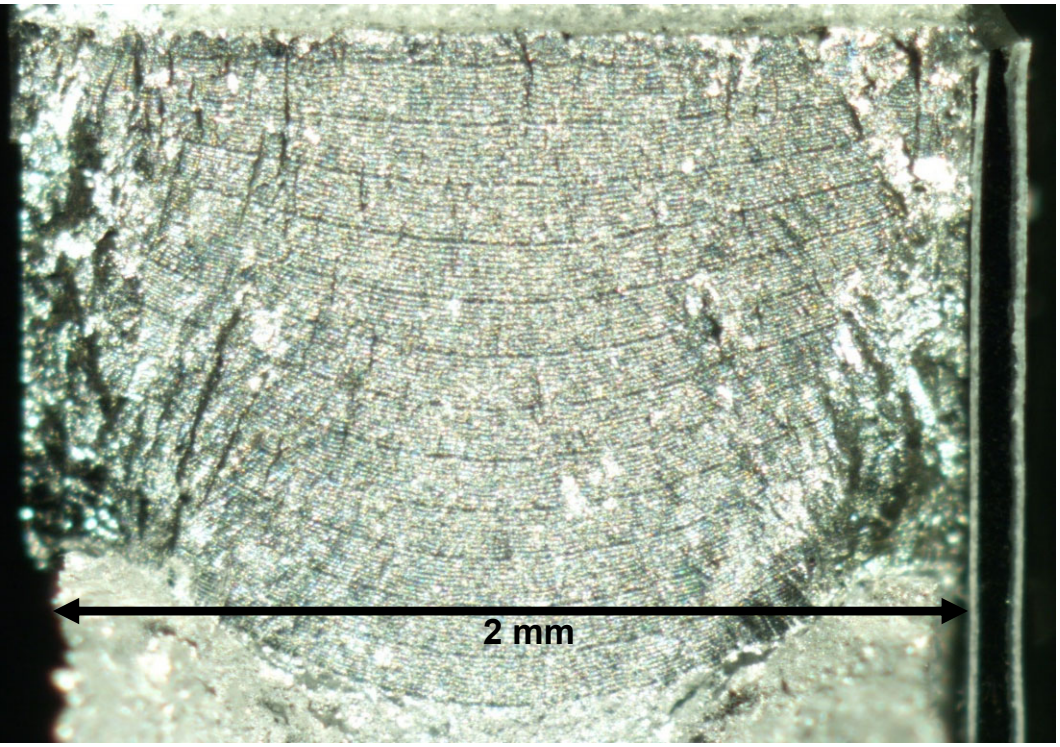
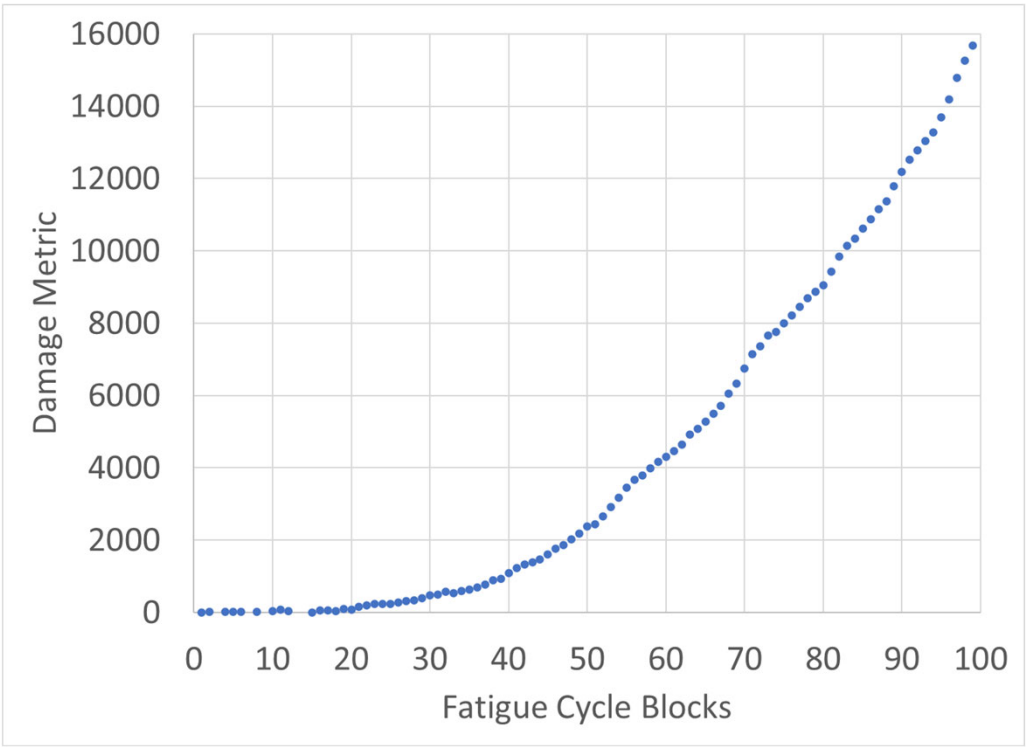
WISP Crack Gauge Detection Sensitivity Results

Marker Bands used for Truth Data



Damage Metric at each Marker Band



- 60 specimens instrumented & tested through 10,000 cycles
- 100 WISP points collected corresponding to marker band lines
- $[(R/R_0)-1]*10^6$ damage metric for statistical analysis (REM)
- Offset crack length value used (only portion beneath gauge area)

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Traditional Hit/Miss Analysis

- Traditional Hit/Miss analysis from MH1823A initially used
  - Uses binary response of WISP signal above/below threshold value
  - Logistic regression model fit to data to plot POD vs crack length
  - Confidence intervals calculated using Firth's Method

- MH1823A only allows for 1 data point per specimen
  - Code written to extract 1 random point per specimen to calculate POD stats
  - Code iterated 1000 times to generate mean/stdev on POD stats
  - Illustrates traditional approach can be poorly behaved , luck-of-the-draw

	a_{90} (mm)				$a_{90/95}$ (mm)			
#	Mean	StDev	Min	Max	Mean	StDev	Min	Max
60	0.23	0.05	0.08	0.41	0.45	0.10	0.24	1.25

- Subsequently investigated performance with fewer specimens
  - Code written to randomly select specimen subset of size n
  - Code iterated 1000 times to generate mean/stdev on POD stats for size n

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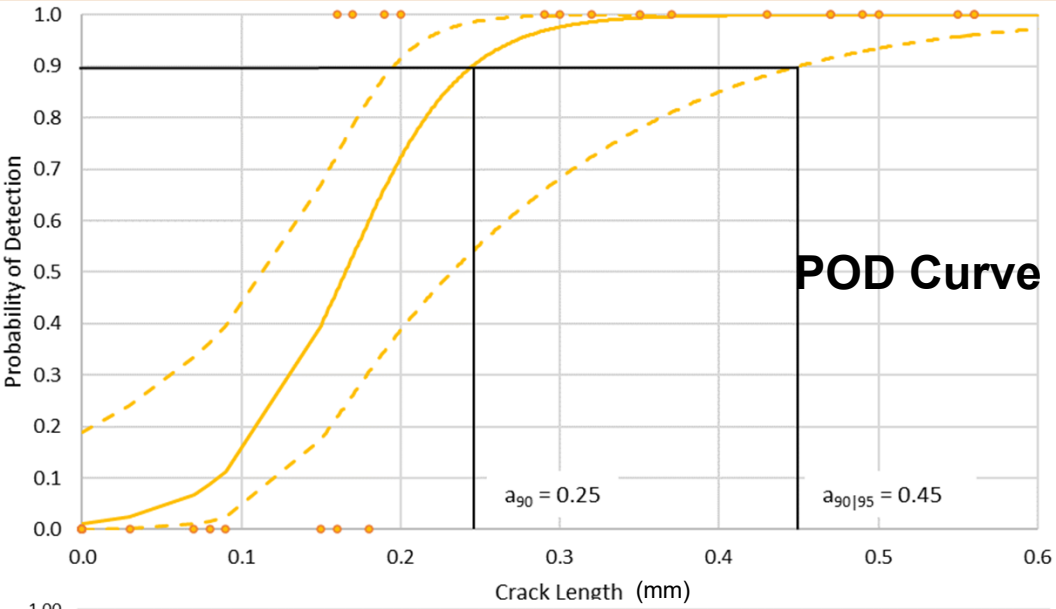
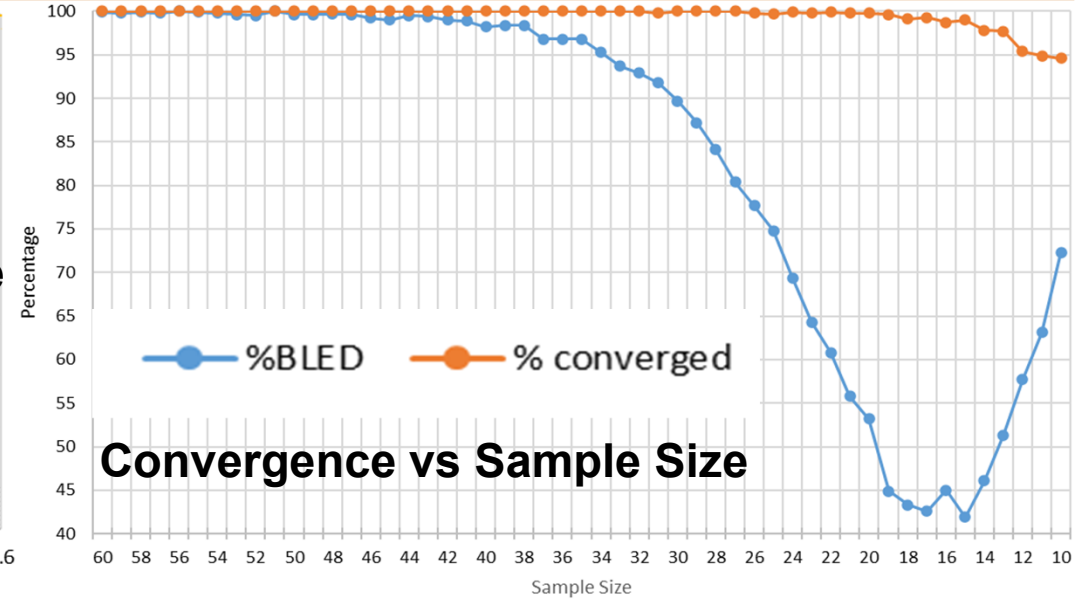
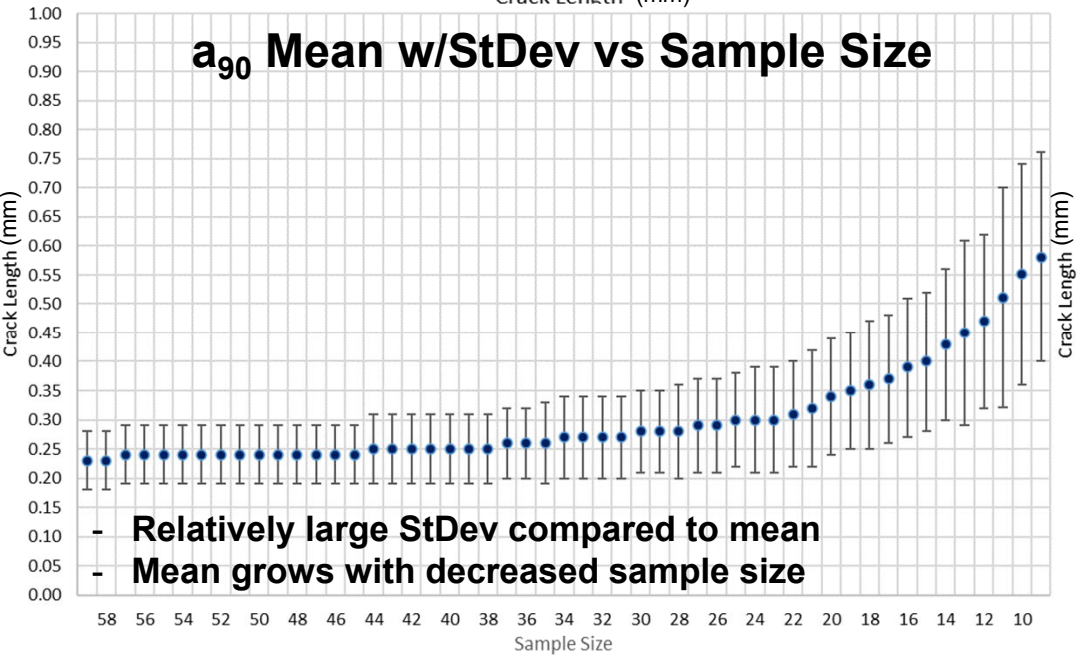
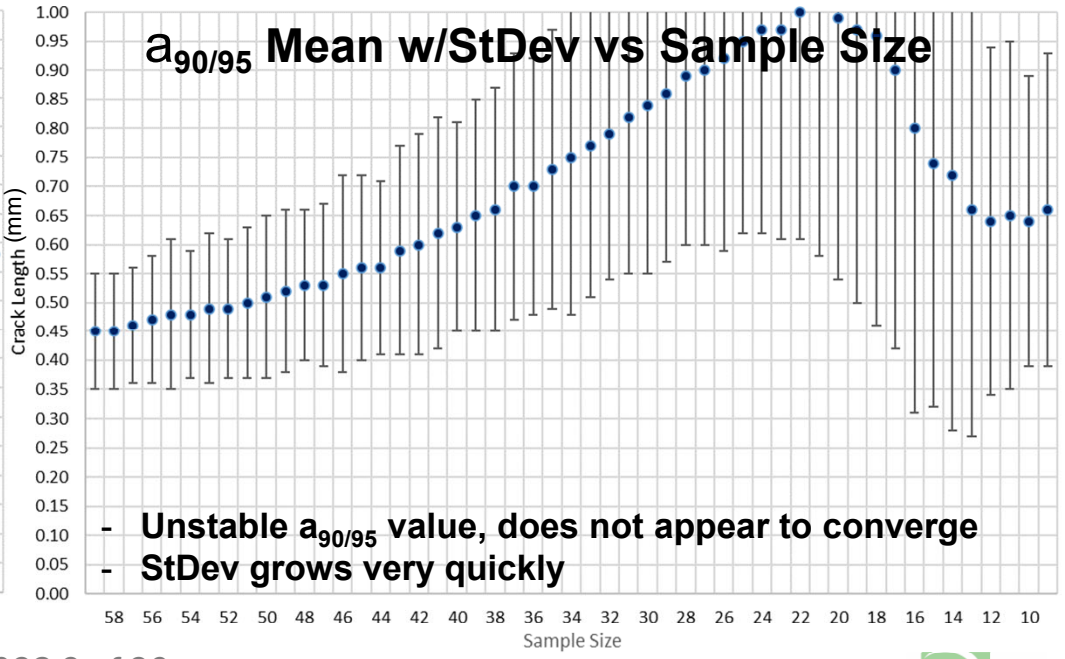
Traditional Hit/Miss Results (1000 iterations)









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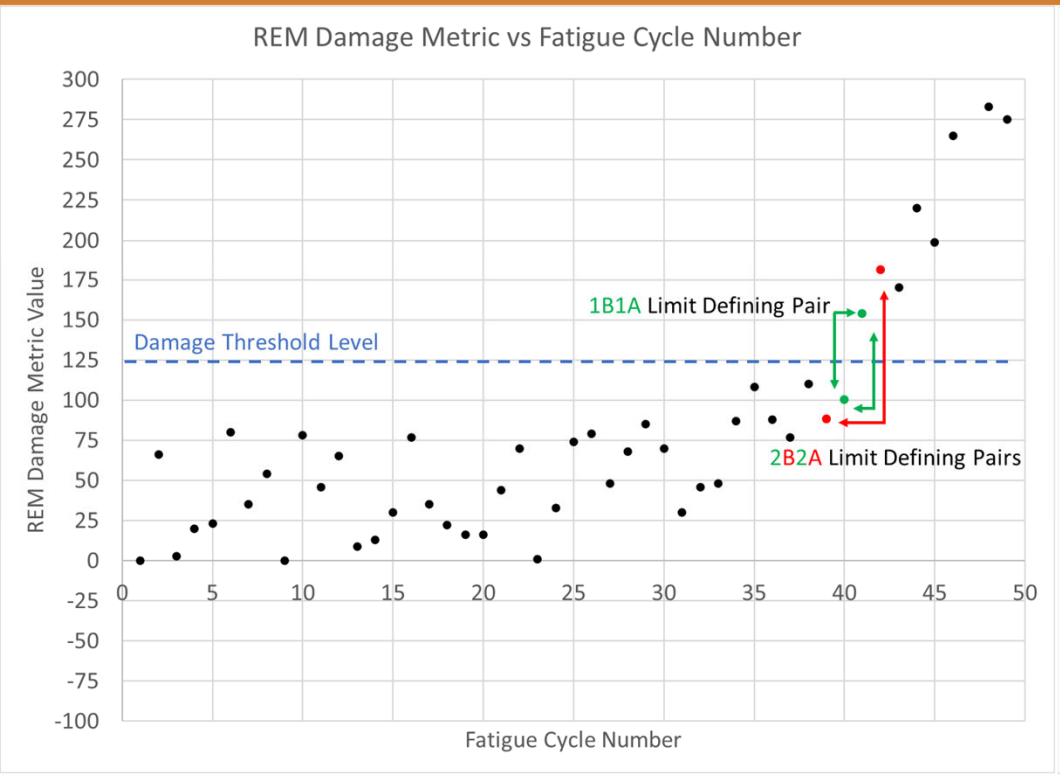
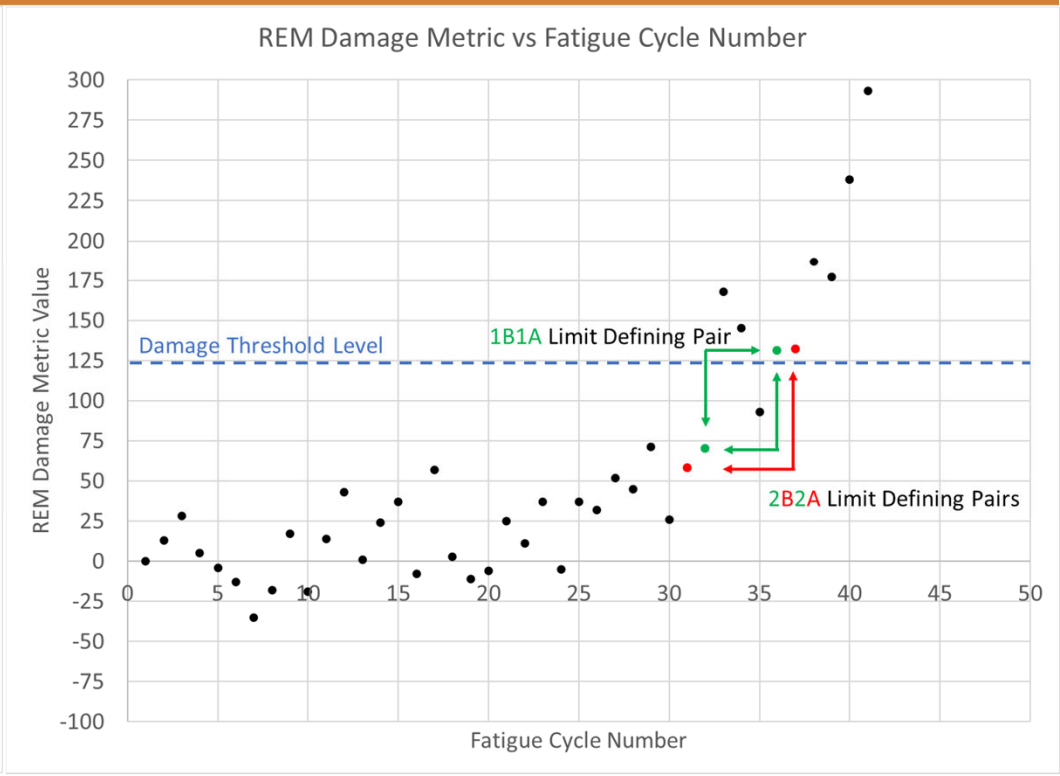
CLDP Modified Hit/Miss Analysis





- Covariance of Limit Defining Pairs (CLDP)
  - Methodology for consistent selection of samples used in statistical analysis
    - Largest "miss" such that all smaller flaws never detected for that specimen
    - Smallest "hit" such that all larger flaws always detected for that specimen
    - Hit/Miss analysis using 1 (1B1A) or 2 (2B2A) pairs from each specimen
  - Covariance term added into hit/miss analysis to account for dependance

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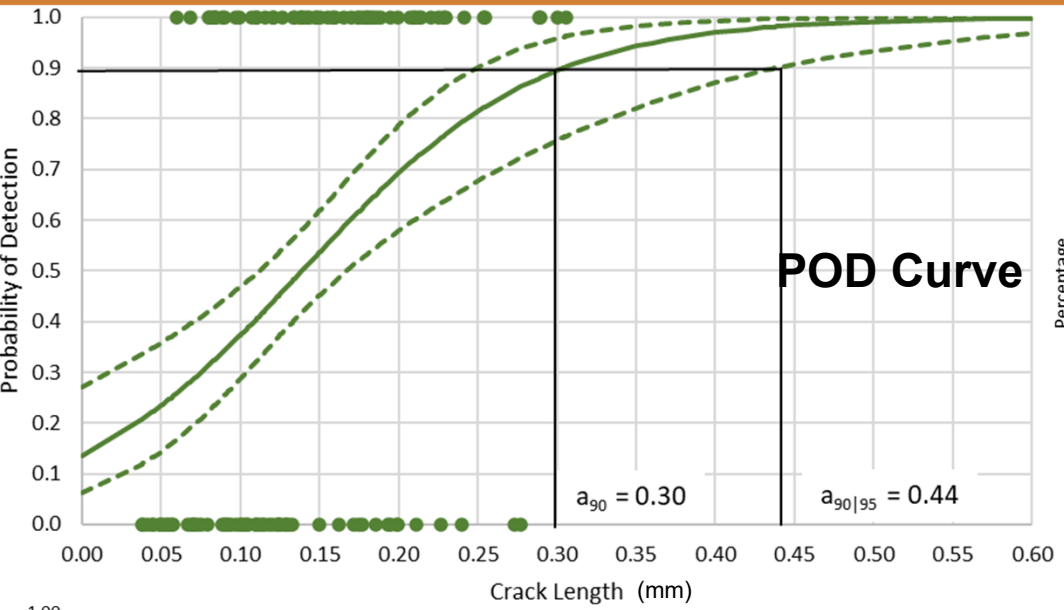
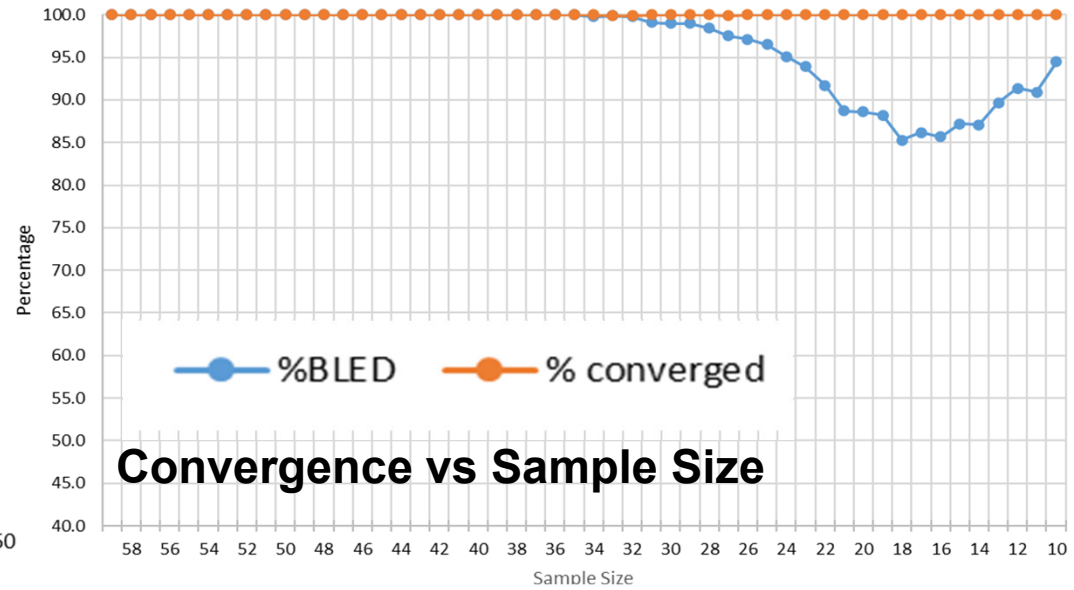
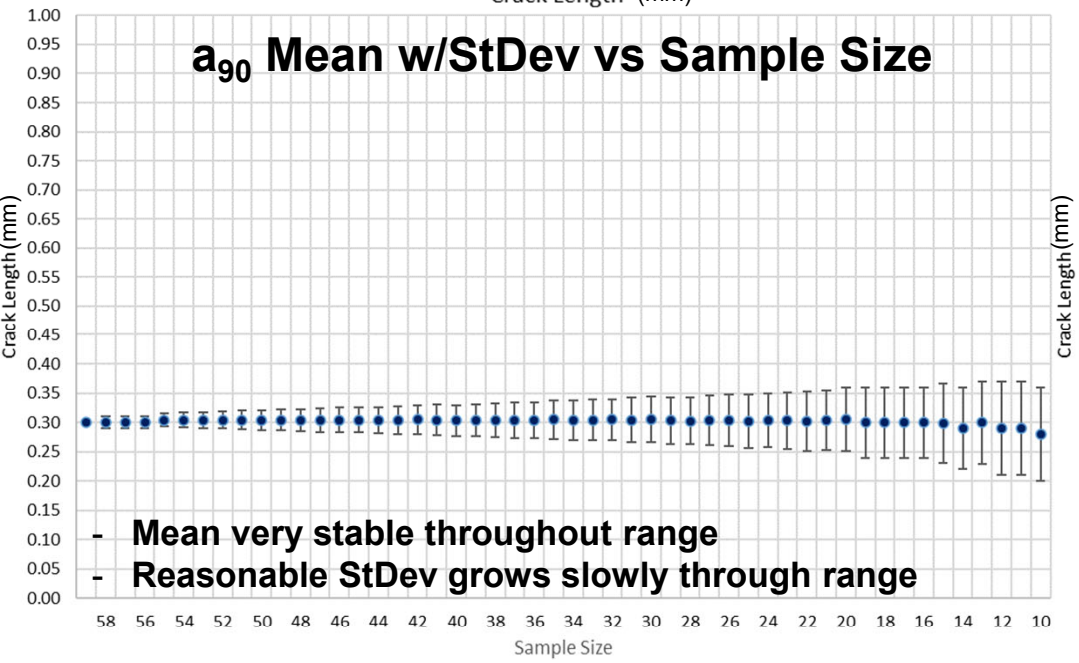
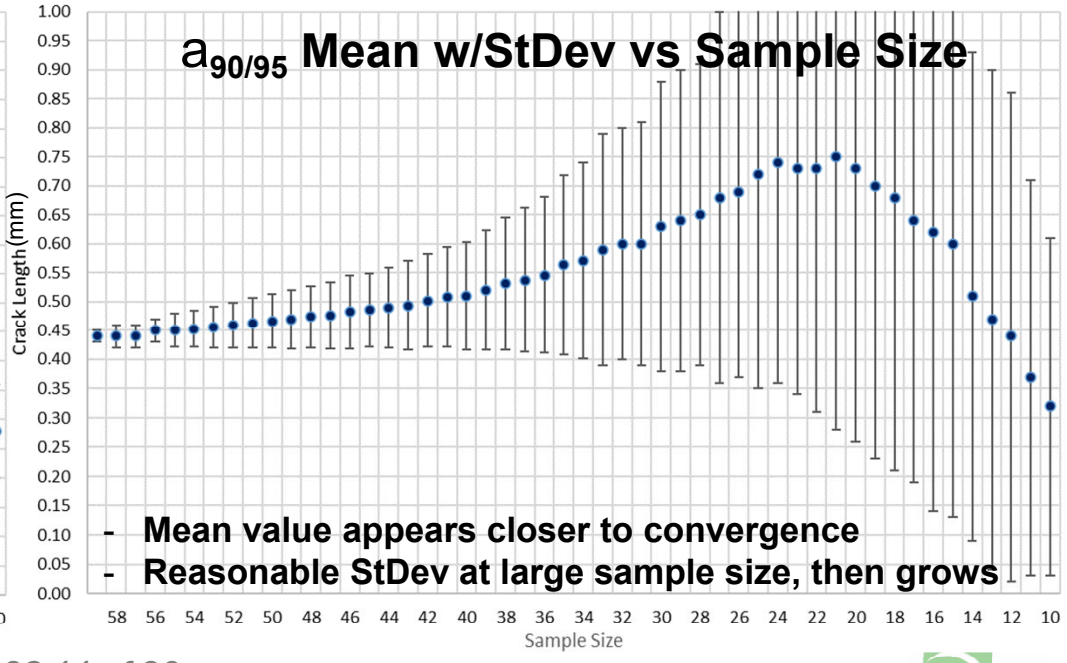
CLDP 1B1A Analysis Results (1000 iterations)









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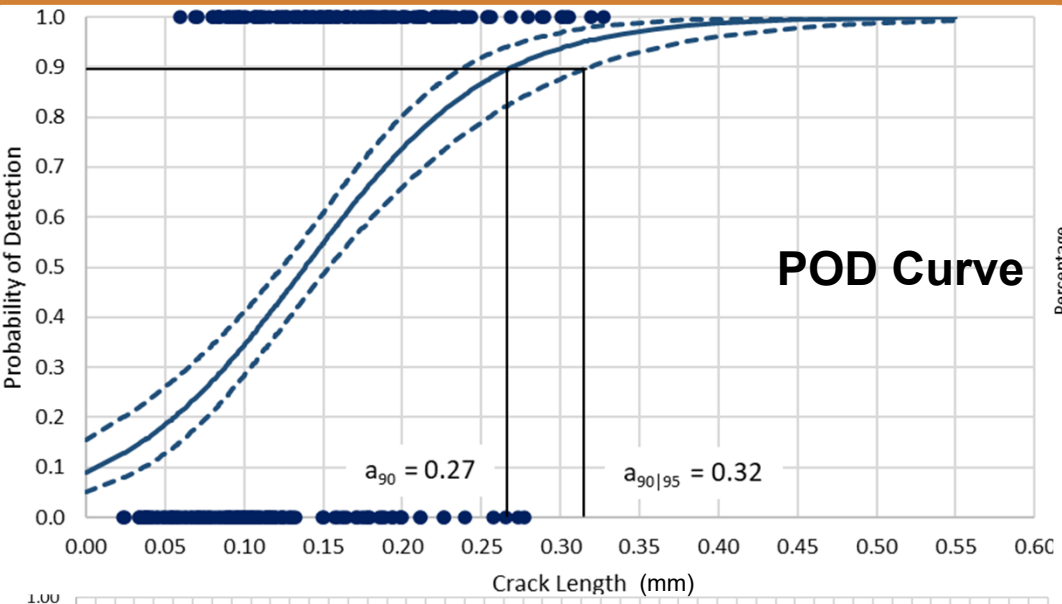
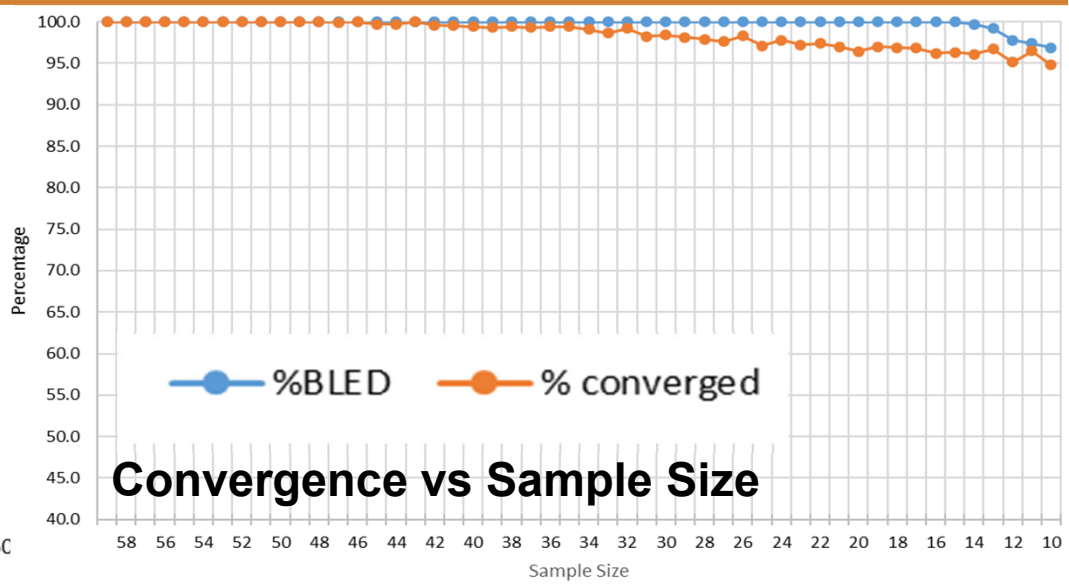
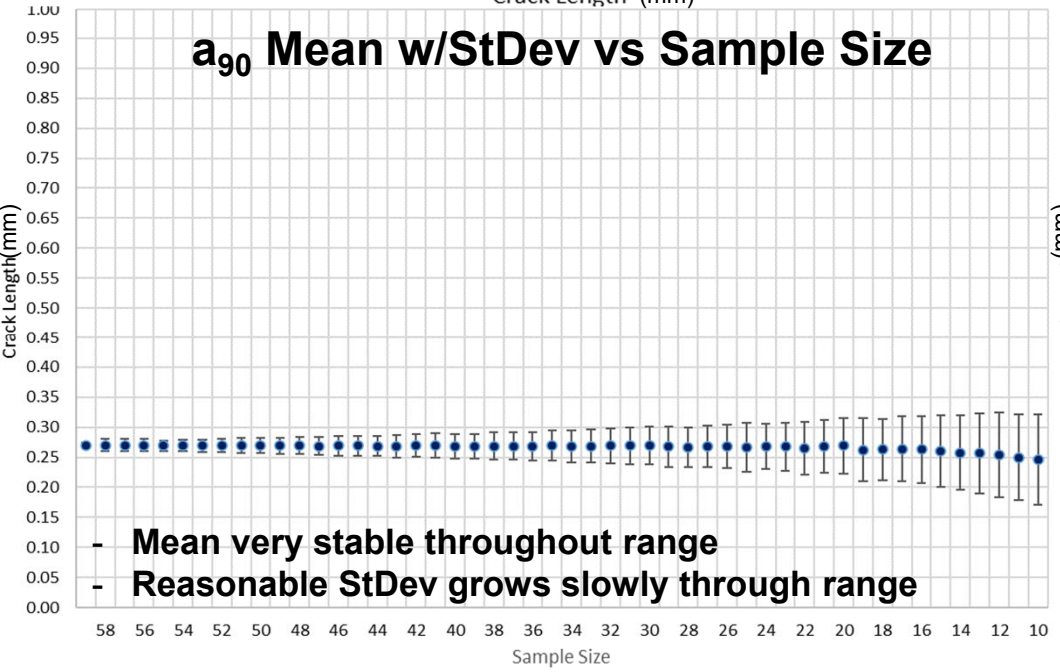
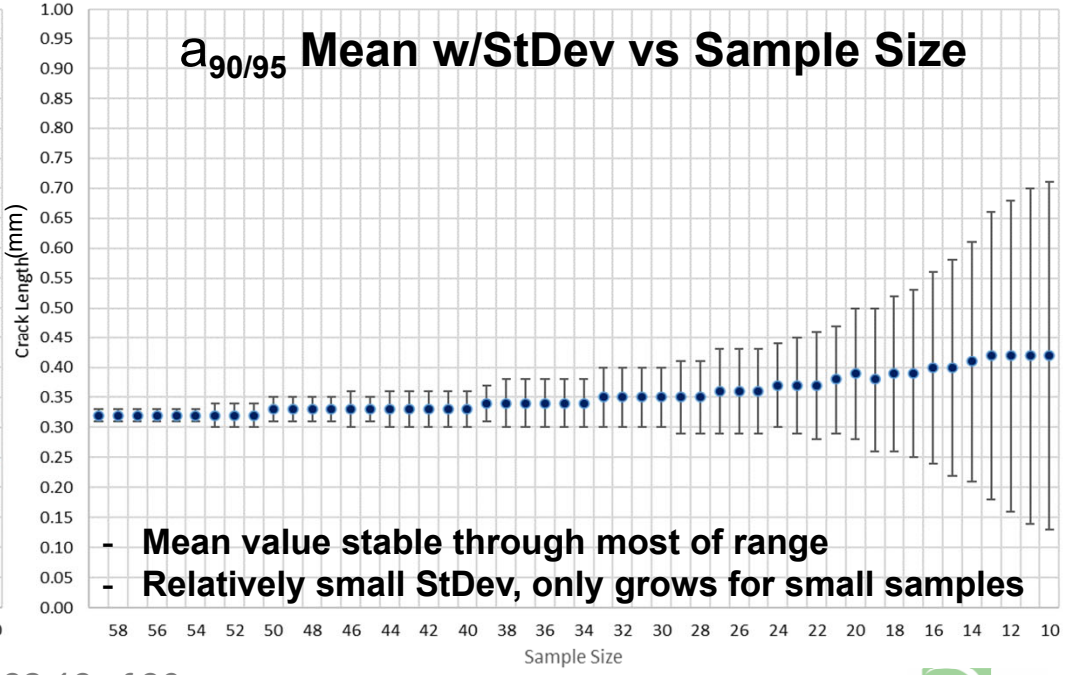
CLDP 2B2A Analysis Results (1000 iterations)









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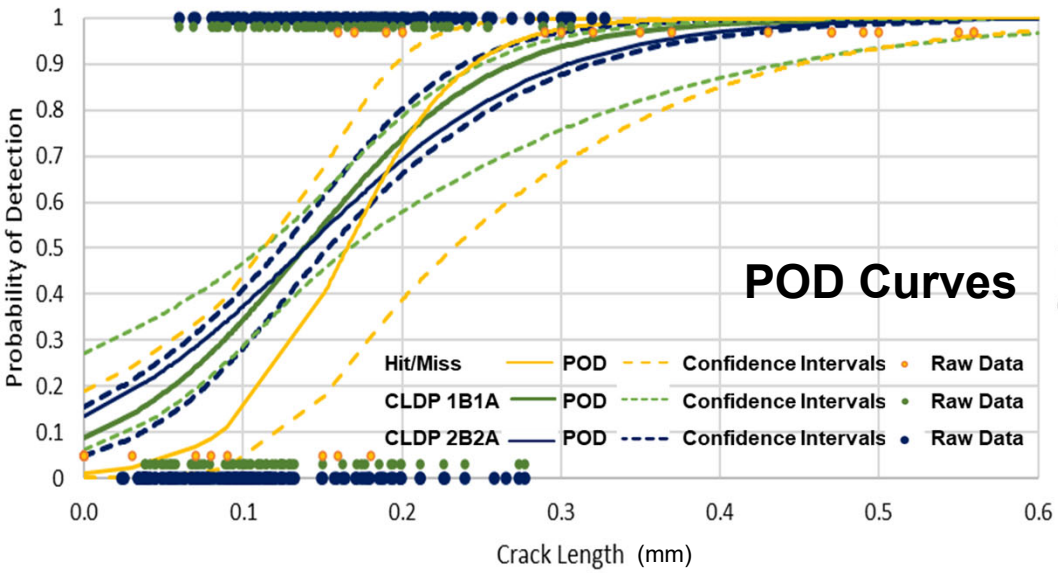
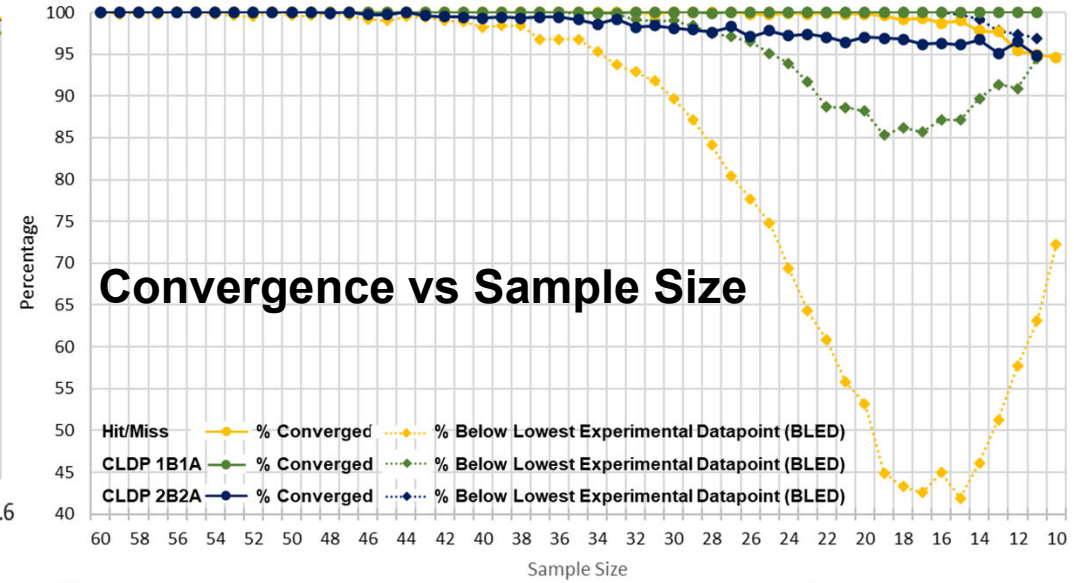
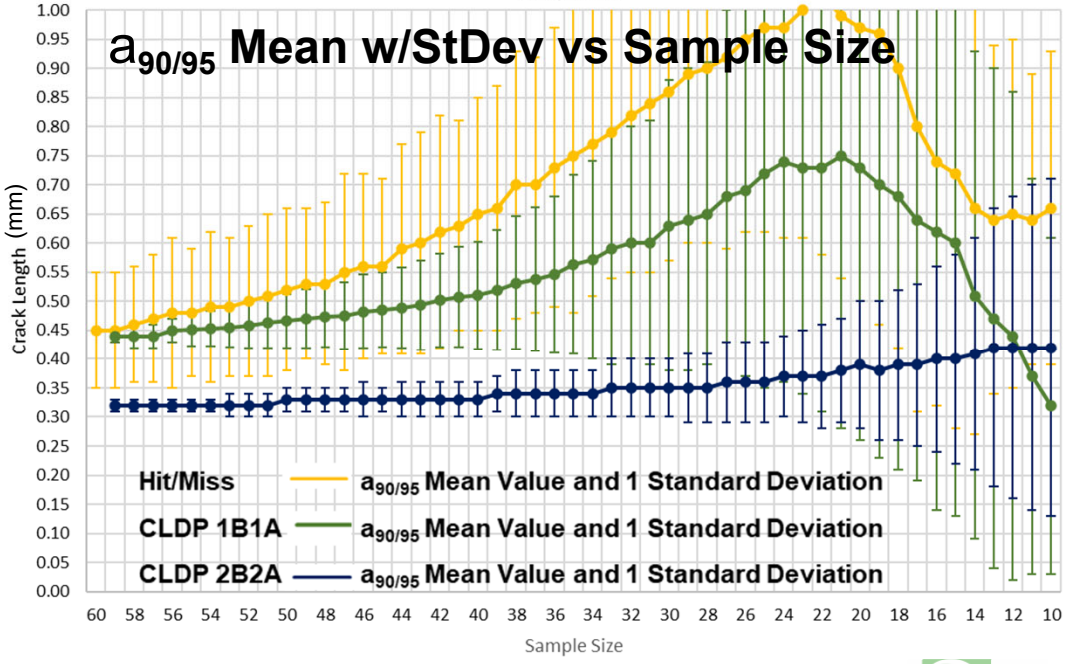
Comparison of All Analyses





- All 3 POD curves are similar
  - CPLD improves confidence bound
  - Tighter & more reasonable shape
- CLDP 2B2A has >95% convergence @ 10 samples
- CLDP 2B2A is only approach with stable $a_{90/95}$ throughout



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Efficiency of CLDP Approach

- Traditionally points distributed amongst desired detection range
  - Includes points with large obvious flaws with 100% detection
  - Includes points with very small flaws with 0% detection
  - Includes false positives where sensor “hits” due to noise, adds to variability
- CLDP is more efficient than traditional sample selection
  - All points are taken right at threshold value to maximize value to regression
  - Implicit that earlier data is 0% & later data is 100% POD, no false positives
  - Valid but impractical for NDI because quantity of manual inspection
- Comparison of results demonstrates validity of CLDP
  - Similar values for all POD stats, but CLDP has much less variability
  - CLDP mean & StDev much more stable for fewer specimen subsets
  - CLDP also improves convergence when using few specimens

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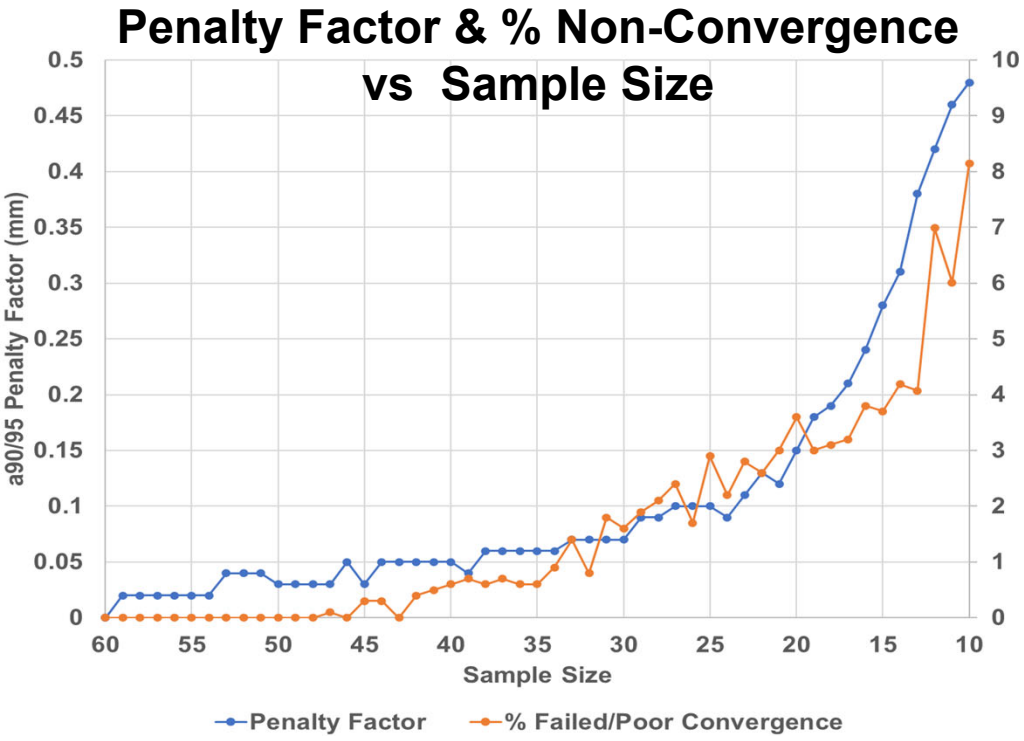
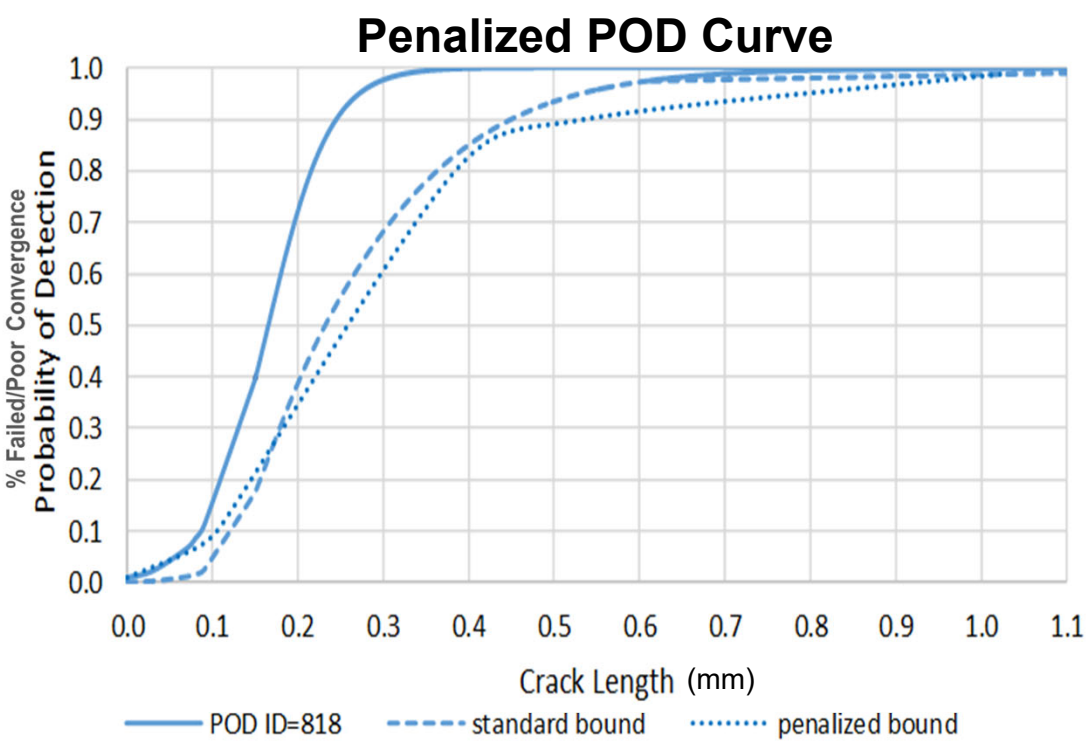
Testing Fewer Physical Specimens with CLDP





- CLDP analysis performed for full 60 specimen of new SHM sensor
  - Generate table of POD stats for simulated reduced datasets
  - Penalty factor calculated to be applied when using reduced dataset later

    $(2\sigma\ a_{90/95}$ reduced dataset) + ($a_{90/95}$ full dataset) - (mean $a_{90/95}$ reduced dataset)
  - Can generate penalized POD curve by fitting penalized $a_{X/95}$ values
  - Must also consider potential for non-convergence, fix with additional tests

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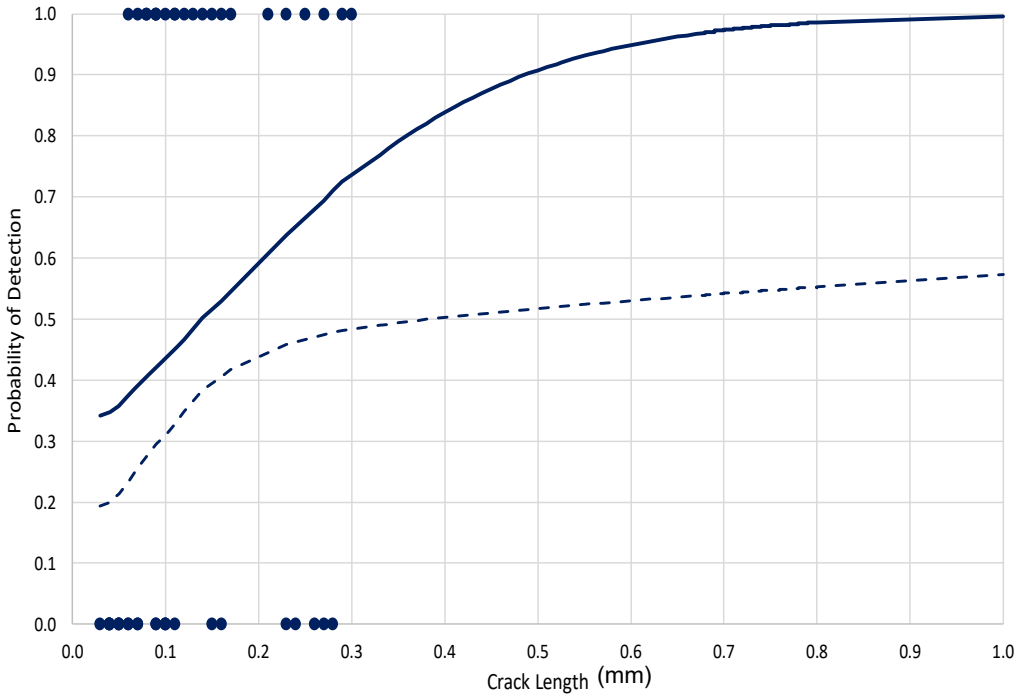
Resolving Non-Convergent Cases

- Upper confidence bound considered “non-convergent” when value beyond tested data
- Usually occurs when substantial overlap of hit/miss points
- 35 of 1000 were non-convergent for 20-specimen subset (3.5%)
- Can collect additional pairs to fix



CLDP 2B2A Analysis	a_{90}				$a_{90/95}$			
	Mean	StDev	Min	Max	Mean	StDev	Min	Max
60-specimen results	0.27	-	-	-	0.32	-	-	-
20-specimen subset, non-convergent datapoints removed	0.27	0.05	0.11	0.40	0.39	0.11	0.15	1.00
20 iterations of non-convergent case, 1 new LDP, 3 converge	0.25	0.01	0.24	0.27	0.33	0.02	0.32	0.36
20 iterations of non-convergent case, 2 new LDP, 11 converge	0.24	0.01	0.23	0.24	0.31	0.03	0.25	0.36
20 iterations of non-convergent case, 5 new LDP, 16 converge	0.25	0.02	0.22	0.28	0.32	0.04	0.25	0.37
20 iterations of non-convergent case, 20 new LDP, 19 converge	0.24	0.03	0.17	0.28	0.30	0.05	0.19	0.37

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Summary

- Sought alternative means for evaluating POD of SHM methods
  - Minimize necessary physical experiments, maintain statistical equivalence
  - Minimize & appropriately account for dependent data
- Focus on WISP fatigue crack gauge
  - Lightweight CNT-based sensor not susceptible to corrosion or fatigue
  - Hot-spot sensor: failure critical or known flaw locations
- CLDP approach provides efficient account of detection capability
  - More SHM data collected, only use most valuable points for analysis
  - Conventional hit/miss analysis, include covariance term for dependence
  - Demonstrated validity of CLDP approach using 60 WISP FCG experiments
  - Proposed methodology for further reducing experiments with penalty factor

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Overall AFWERX Program

- Design of Experiment (DOE)
  - Included temperature, strain, humidity, pressure, ageing, fatigue, hardware
  - Demonstrated that compensation method eliminates all external variables
- Detection sensitivity study
  - MIL-HDBK-1823A +CLDP
- Airworthiness testing (MIL-STD-810)
  - -65°C to 125°C temperature testing
  - shock/vibration/acceleration up to 20g
  - Chemical contamination exposure
- Flight testing on F-15 (Aug–Dec 2023)
  - Survived 30x 8g maneuvers!

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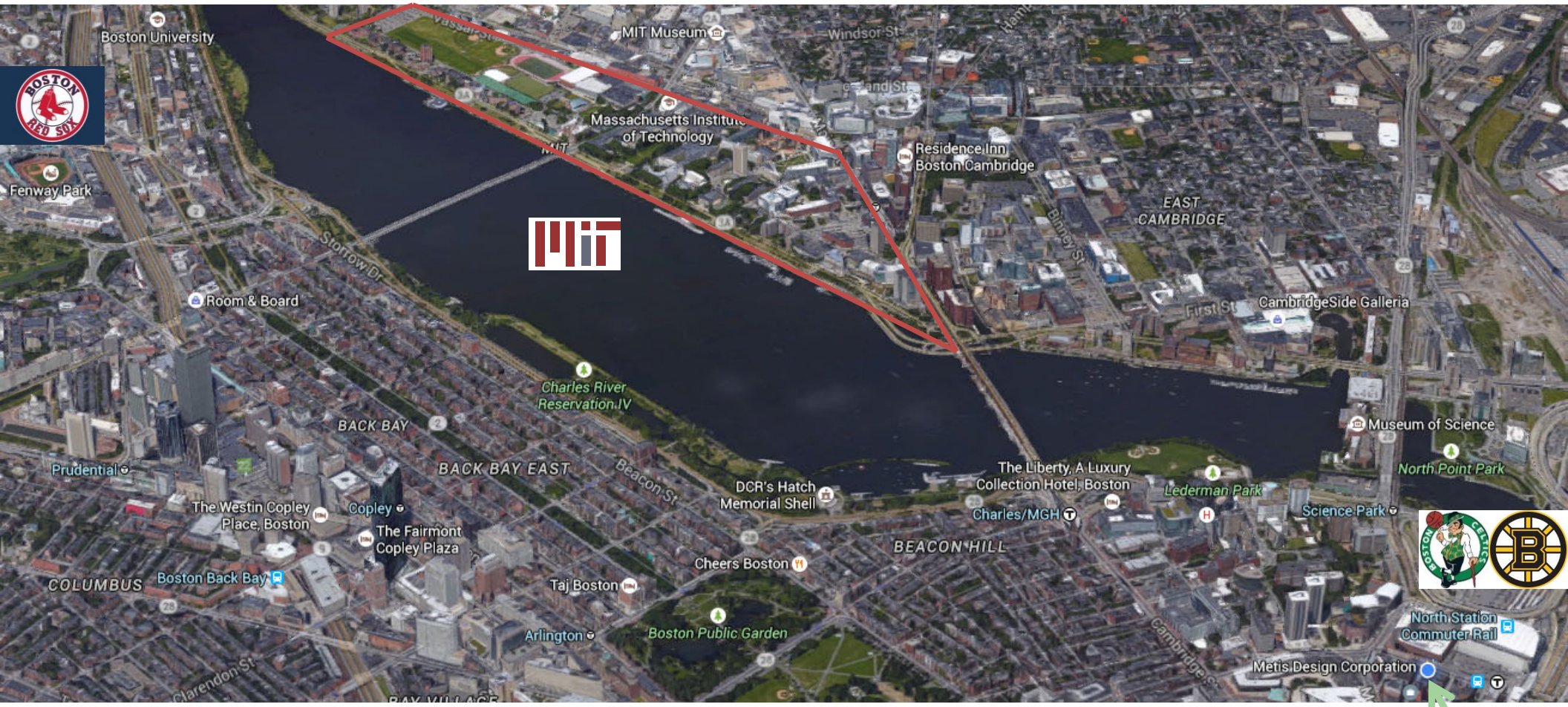

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