DETECTION SENSITIVITY ANALYSIS OF A NOVEL FATIGUE CRACK GAUGE

Comparing Traditional MIL-HDBK-1823A Probability of Detection Assessment with Alternative Statistically Equivalent Approaches

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NDT 22 SHM · MPIG NONDESTRUCTIVE TESTING FORUM

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Executive Summary

- AFWERX funded program to qualify novel sensor for aircraft CBM
  - WISP nanoengineered fatigue crack gauge
  - Approaches to optimize data needed for detection sensitivity assessment

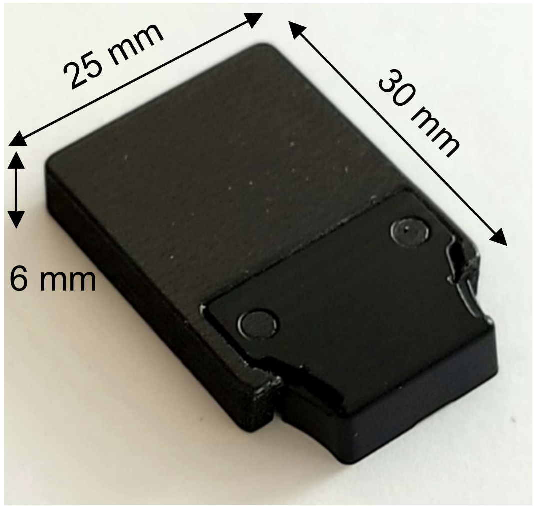
- Main tasks of program
  - Evaluate airworthiness of sensor & hardware (MIL-STD-810/DO-160)
  - Design of Experiment (DOE) to characterize variables of interest
  - Assess detection sensitivity for measuring fatigue cracks (MIL-HDBK-1823)
  - Flight testing on a fighter jet

- Probability of Detection (POD) deep-dive
  - Explore variability in traditional POD model using all independent data
  - Investigate alternative approaches that reduce quantity of physical tests

Witness Integrity Sensor Platform (WISP)

WISP Solo w/Crack Gauge

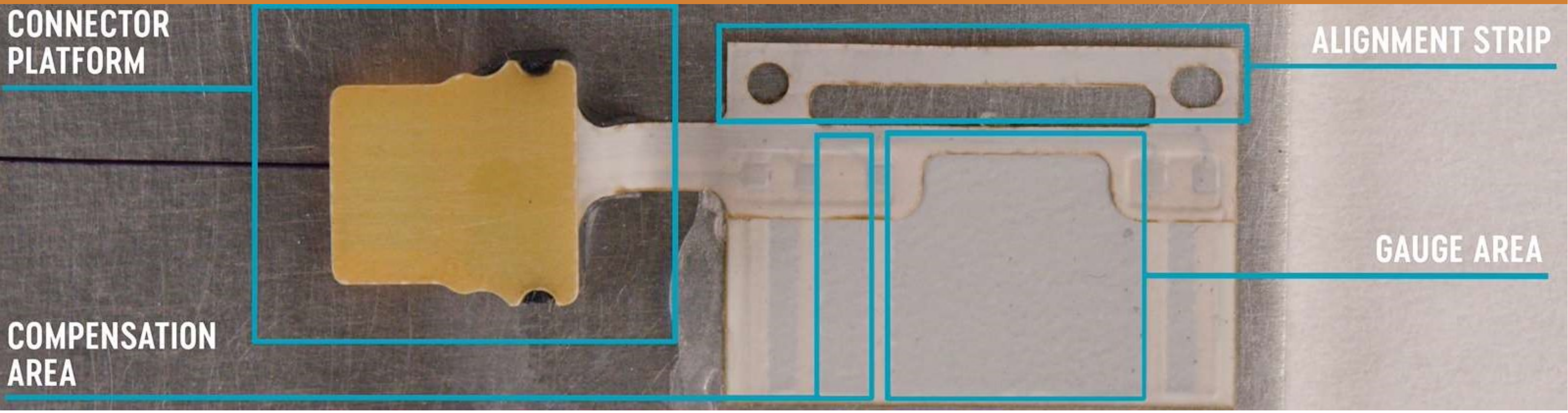
Packaged WISP Solo



Example WISP Reader

- **Miniature (~5cm³) lightweight (~10g) distributed data acquisition**
  - ➢ **Simple to integrate/retrofit without any ties into system power/data**
  - ➢ **Compatible with multiple sensors (crack, corrosion, erosion, digital, etc.)**
- **Uses Bluetooth Low Energy (BLE) & inductive power transfer**
  - ➢ **Standalone version uses no cables or connectors**
  - ➢ **Networked version connects <64 sensors on a <30m 4-wire serial bus**
  - ➢ **Completely passive hardware while not being excited**

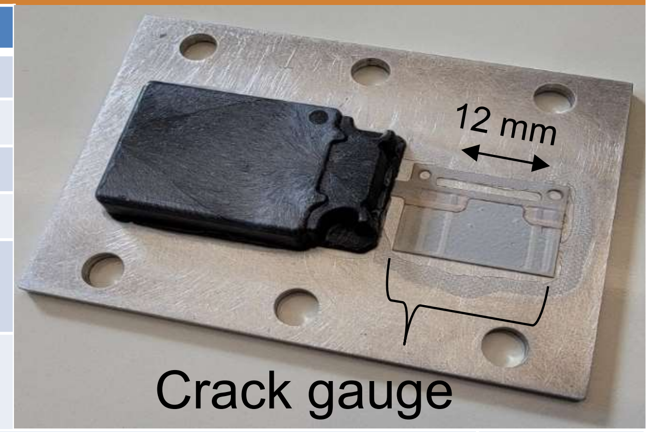
WISP Fatigue Crack Gauge (WISP FCG)



- **Crack gauge physical characteristics**
  - Form-factor: 12 x 12mm gauge area (not a limitation), ~200 micron 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 bond)
  - CNT network electrical resistance changes proportional to crack length
  - Completely passive sensor, crack "recorded" even when no power applied

Airworthiness Testing

Test Name	MIL-STD-810H	Test Value
Temperature (High)	Method No. 501.7	85°C/125°C
Temperature (Low)	Method No. 502.7	-40°C/-65°C
Thermal Shock	Method No. 503.7	10°C/min
Fluids Contamination	Method No. 504.3	See below table
Vibration	Method No. 514.8	W_0= 0.002g²/Hz, W_1= 0.02g²/Hz F_t=2000Hz (random 3-axis)
Crash Hazard Shock	Method No. 516.8	Pulse Duration = 11 msec Pulse Acceleration = 20 g

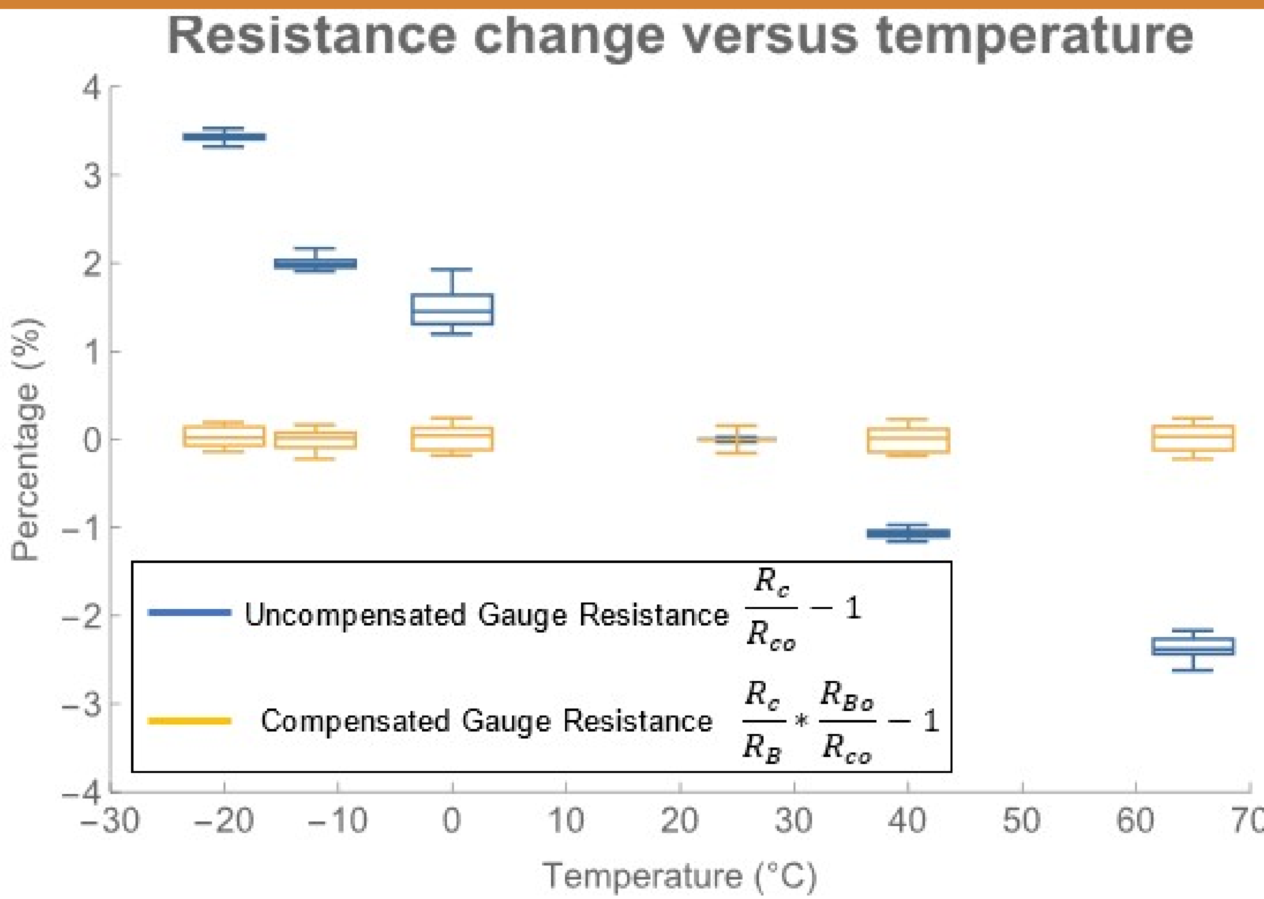


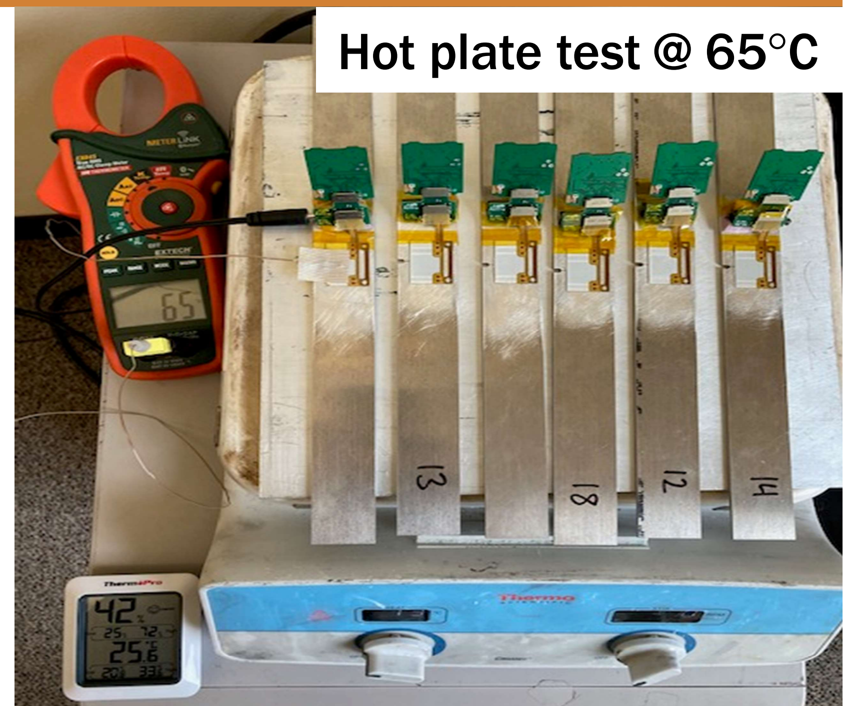
#	Class of Fluid	Contaminating Fluid	Fluid Used for Testing	Temp
1	Salt Water	ASTM D1141	Distilled water with a 5% salt	23°C
2	Cleaning Solvents	2-propanol	Isopropyl alcohol	50°C
3	Antifreeze Fluids	Ethylene glycol	Mobil Delvac Coolant	23°C
5	Fuel	Jet A w/FSII, SDA, & CI/LI	JP-8	70°C
6	Lubricating oil, general	MIL-PRF-32033	Royco 308CA	70°C
7	Lubricating oil, engine	MIL-L-23699C MIL-L-7808J	Aeroshell 560 Eastman Turbo Oil 2389	70°C
8	Grease	MIL-G-81322	Aeroshell 22	70°C
9	Hydraulic fluid, synthetic	MIL-PRF-83282 MIL-PRF-87257	Castrol Brayco Micronic 882 Castrol Brayco Micronic 881	70°C
10	Coolant fluid	Polyalphaolefin MIL-PRF-87252	Castrol Brayco 889	70°C

Design of Experiment (DOE) Test Matrix

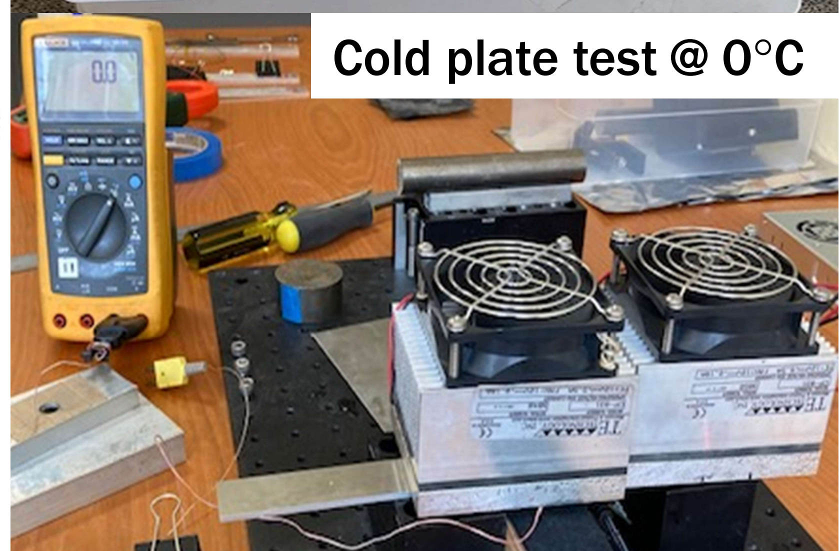
- Pool of 6 WISP Solo & 18 FCG randomly paired for each test
- Temperature testing (6 of each)
  - Elevated temperature (25, 40, 65 °C)
  - Reduced temperature (25, 0, -20 °C)
- Strain testing (6 of each)
  - Tensile (0, 1500, 3000 με)
  - Compressive (0, -1500, -3000 με)
- Humidity (0, 50, 100%RH) (6 of each)
- Ageing Study (6 of each)
  - Natural ageing (1 month)
  - Ageing under vacuum (1 Bar for 24 hours)
  - Ageing under elevated temperature (65 °C for 24 hours)
  - Ageing under static strain (3000 με for 24 hours)
  - Ageing under fatigue loading (1500 με for 1M cycles)
- Hardware Study (6x6 matrix of sensors & hardware)

DOE Temperature Test Results





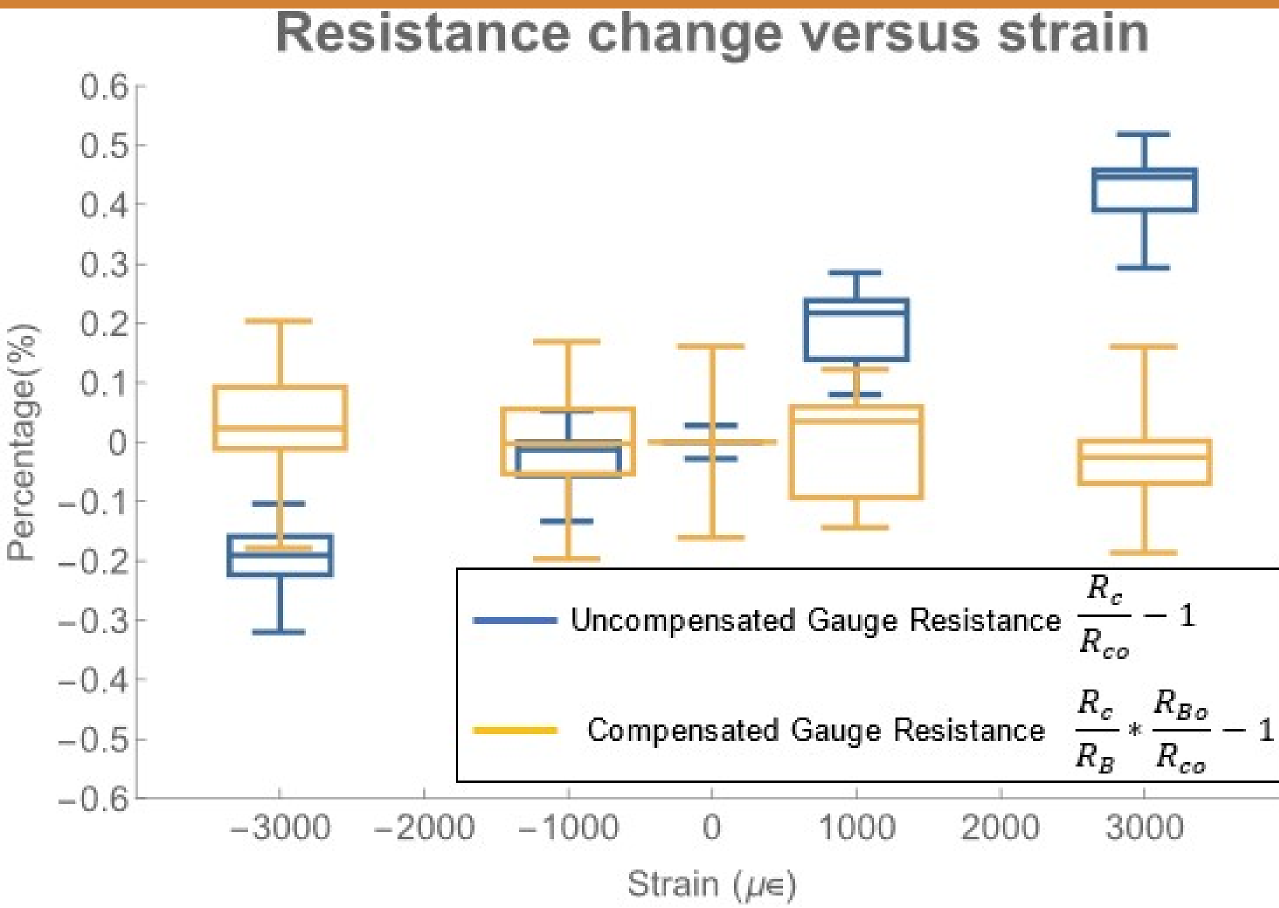
Hot plate test @ 65°C

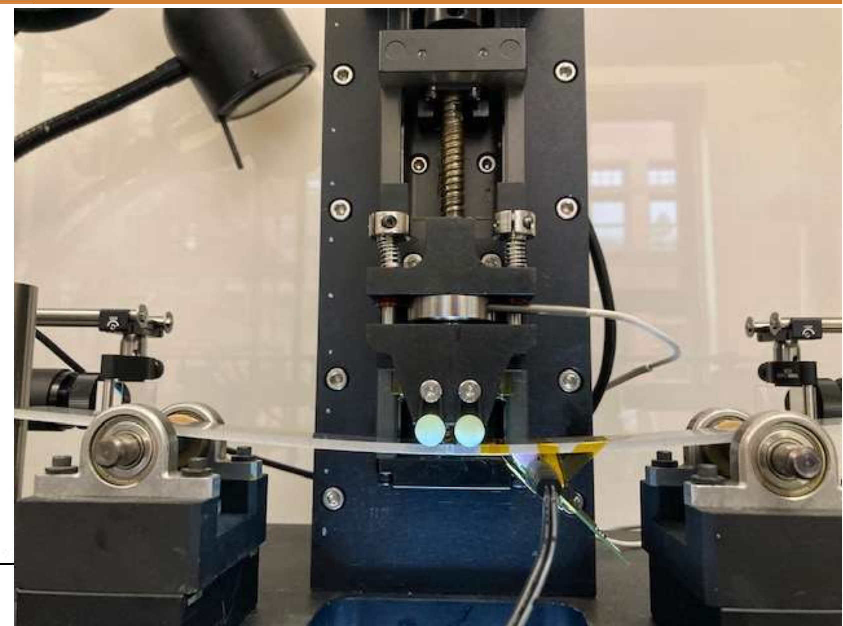


Cold plate test @ 0°C

- **Strongest variable influence**
  - ➢ Resistance inversely proportional to temp
  - ➢ <1%/10°C, ~±2% within operating range
- **In-build compensation was effective**

DOE Static Strain Test Results





$$\varepsilon = \frac{value - 0.350376}{0.758447}$$

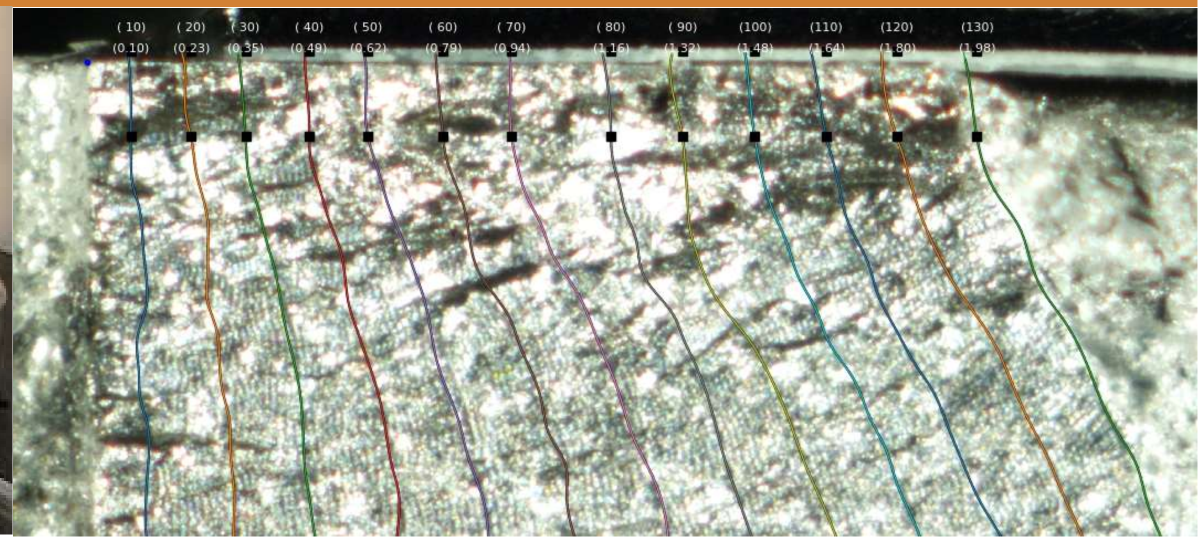
- **Second strongest variable influence**
  - ➢ Resistance directly proportional to strain
  - ➢ ~0.15%/1000με, <±0.5% in range
- **In-build compensation was effective**

DOE Statistical Analysis

Coefficients:	Estimate	Std Error	t value	Pr(>|t|)
(Intercept)	1.95E-01	3.26E-03	59.802	< 2E-16
temperature	-2.79E-05	5.48E-05	-0.508	0.612
temp_time	1.71E-04	1.81E-04	0.947	0.345
strain	-1.17E-08	9.29E-07	-0.013	0.990
strain_time	1.76E-04	1.82E-04	0.968	0.334
strain_cycles	9.00E-09	1.00E-08	0.898	0.370
vacuum	6.38E-05	1.81E-04	0.353	0.725
RH	1.19E-05	6.12E-05	0.195	0.846
elapsed time	2.18E-05	1.32E-04	0.166	0.869

- DOE for compensated data analyzed by David Forsyth (TRI Austin)
- Most variability in R is contained in sensor-to-sensor variability
  - ➢ Because system variability is low, indicates other variables are insignificant
  - ➢ Model fit shows no variable statistically significant for measurement of R
- Determined that no variables needed to be included in POD study

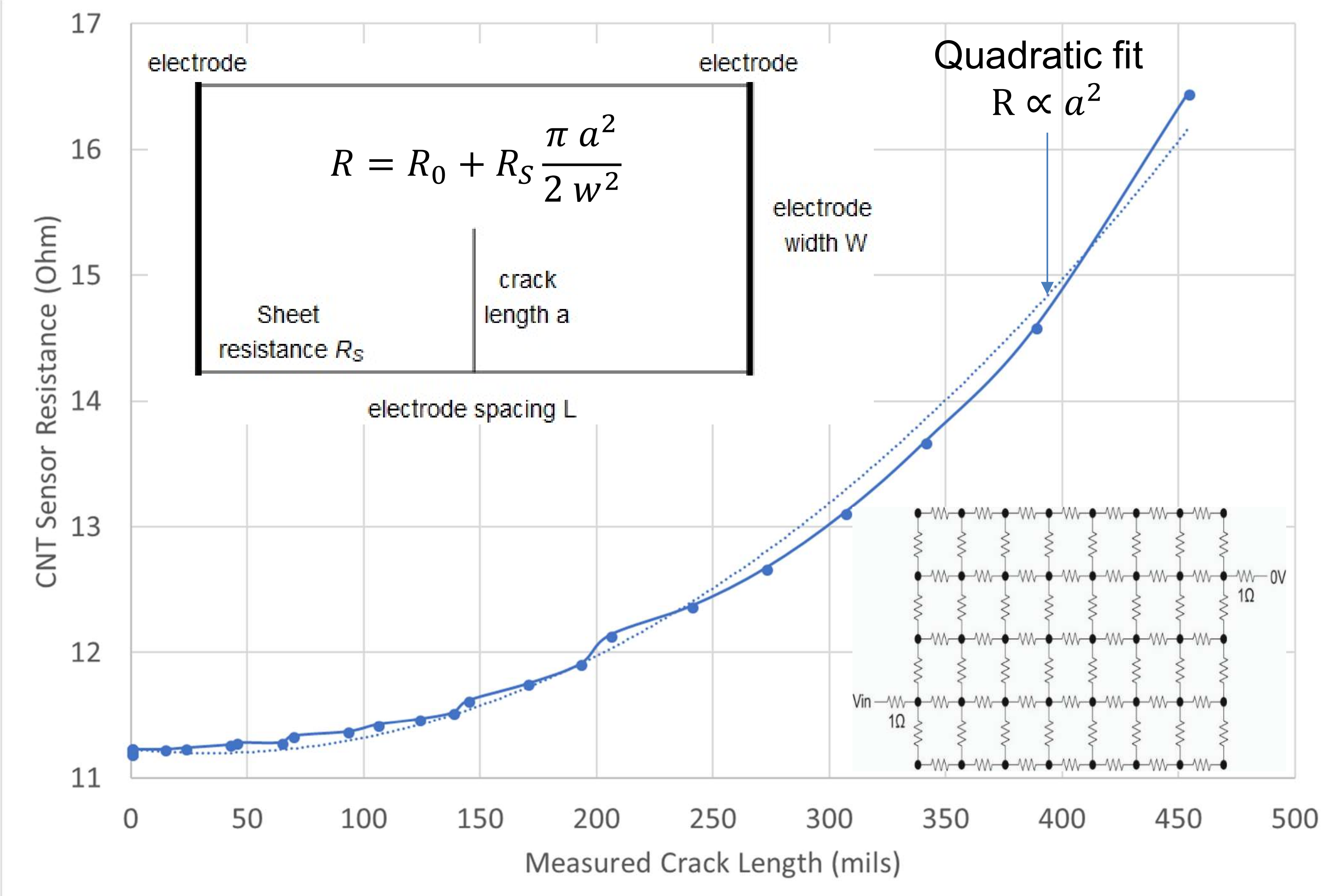
Probability of Detection (POD) Assessment



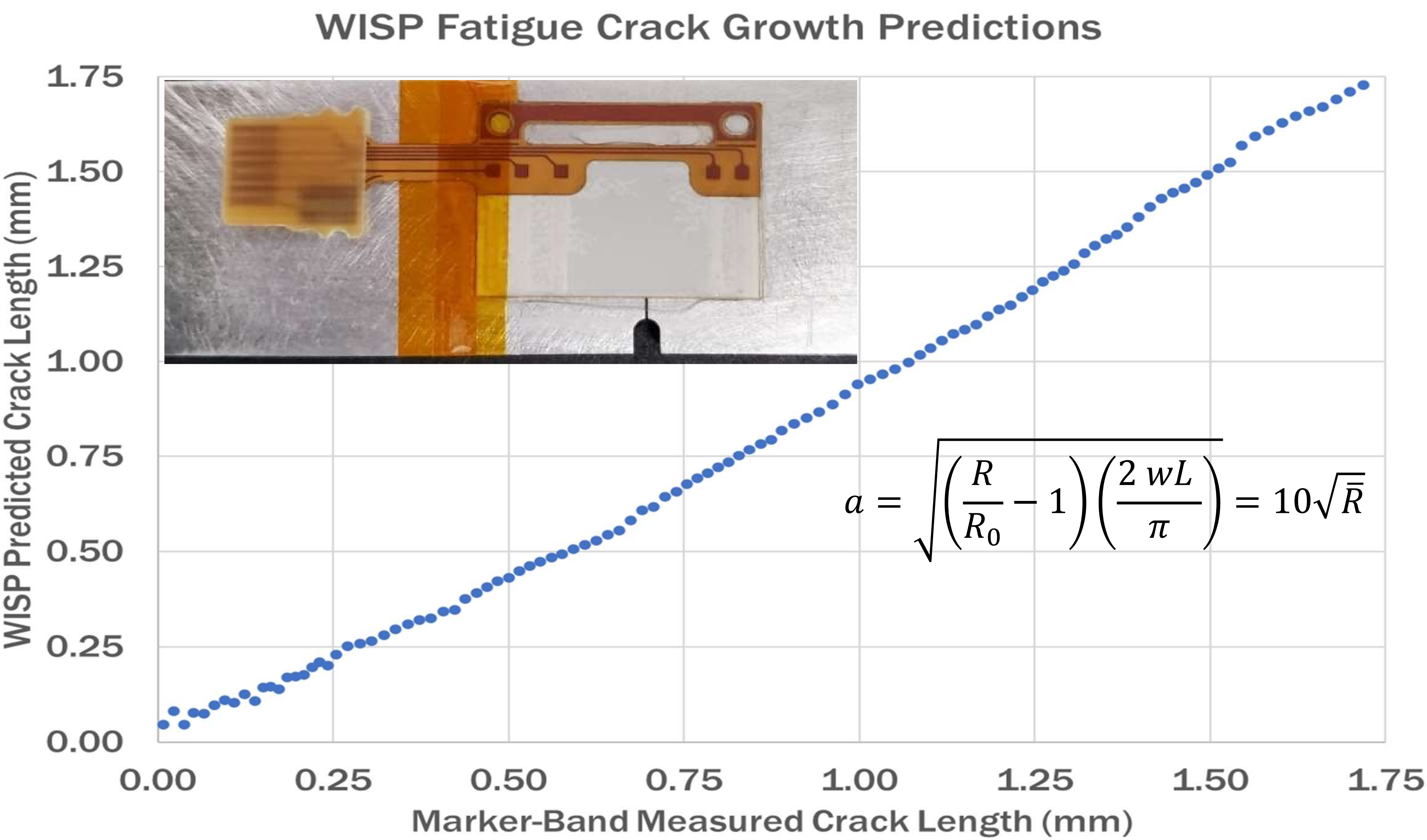
- Evaluated detection sensitivity using 100 WISP FCG specimens
  - 4-pt bending with EDM notch on tensile side, 1000 $\mu\varepsilon$ with R ratio of 0.1
  - Truth data collected in post-processing via induced marker bands
  - WISP data collected every 100 cycles (unloaded state), 100 points/test

- Develop approaches to more efficiently evaluate POD
  - Traditional MIL-1823A analysis using single datapoint from each specimen
  - Proposed procedures & models that can reduce sample size requirements

WISP FCG Resistance vs Measured Crack



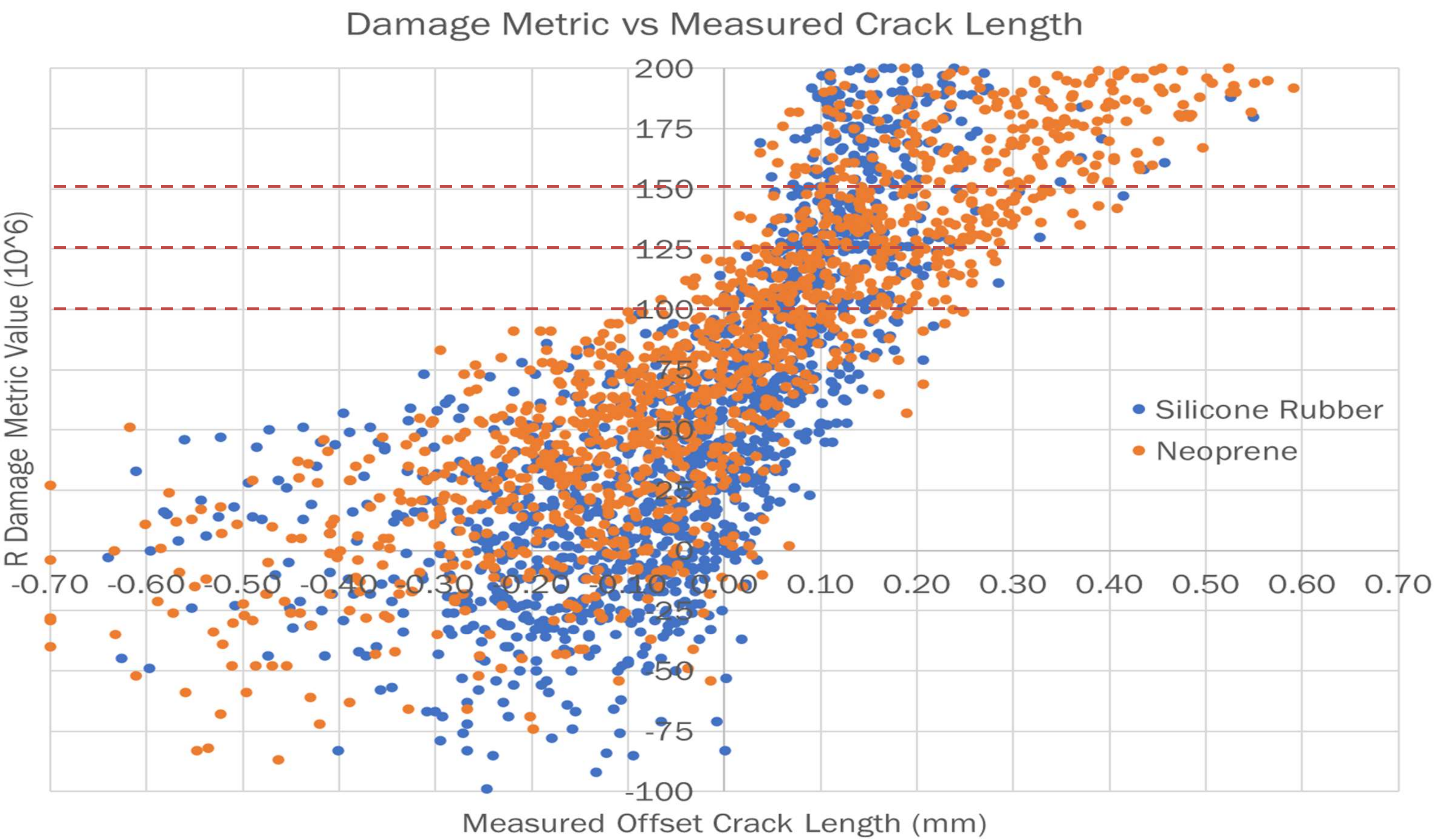
WISP FCG Example Data from Fatigue Test



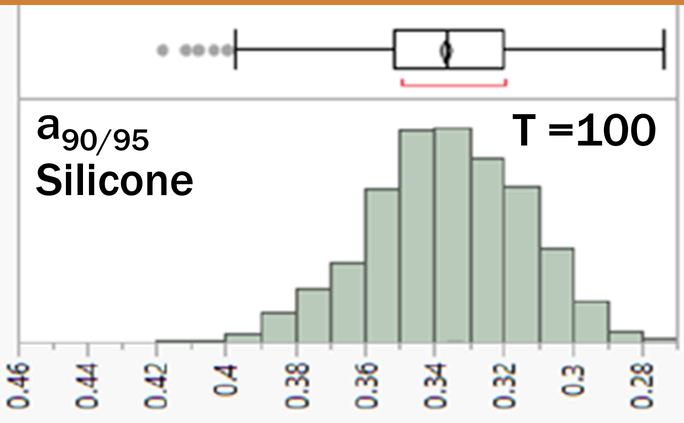
MIL-HDBK-1823A POD Assessment

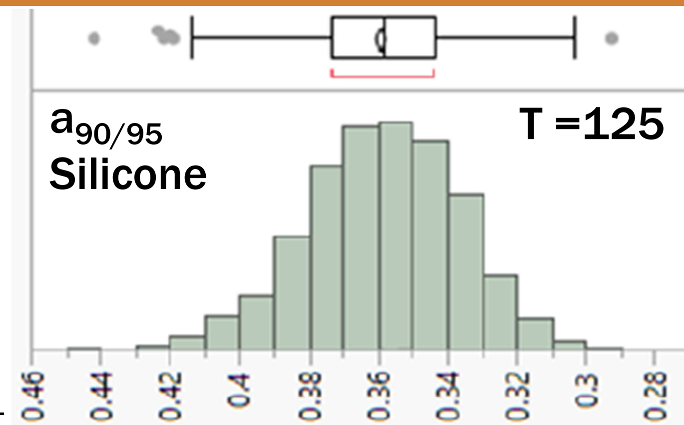
- Standard methodology for a vs â was used (with bootstrapping)
  - Dataset consisted of single random draw from each of the 100 specimens
  - Repeated 1000x to generate unique sets of 100 independent observations
  - Considered noise threshold values of 100, 125 & 150
  - $a_{90/95}$ calculated for each set using delta method to generate covariances
    - R-value was transformed via square root, x-axis variable was crack length minus offset
    - Linear regression fit between variables, requires 500+ regressions to estimate variance
- Measured crack length vs offset crack length
  - Offset measured variable distance between EDM notch & bonded FCG
  - Mean offset ~0.33mm (standard dev. 15mm), 0mm min & 0.75mm max
- Grouping specimens by pressure application method
  - 1st half specimens bonded w/neoprene & 2nd half w/silicone rubber pads
  - Silicone rubber provided better bond, resulting in 2x improved sensitivity
  - Analysis performed for all 100 specimens, also each group individually

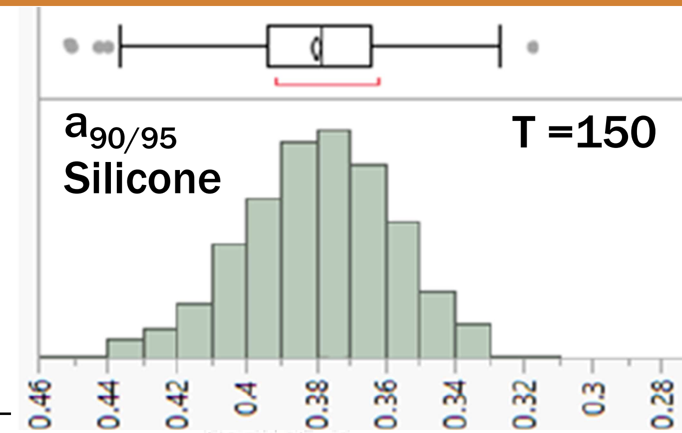
Threshold Value Selection



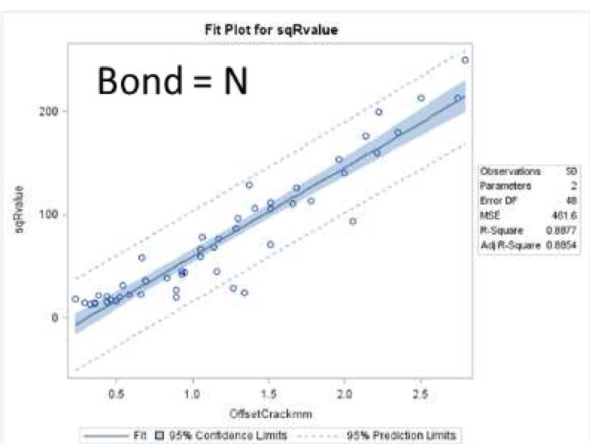
Traditional 1823A POD Results

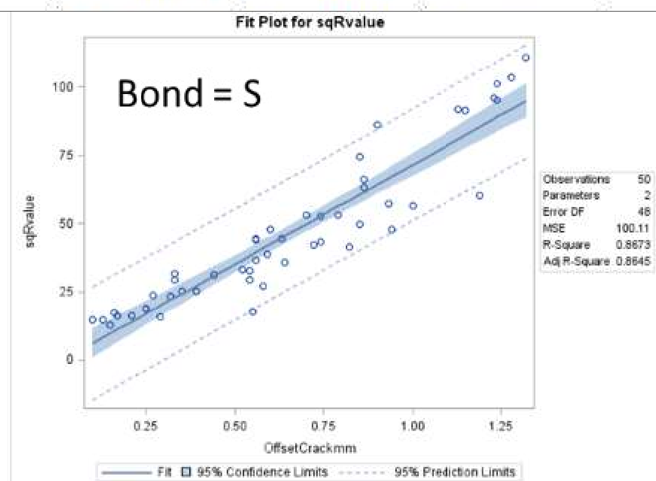


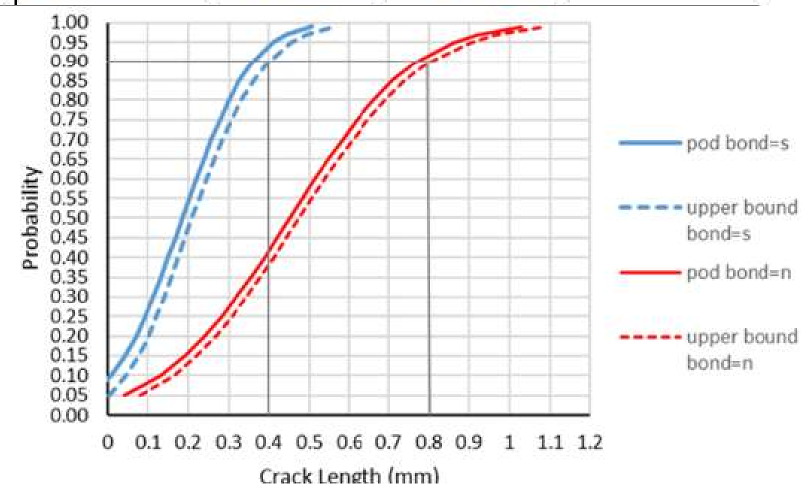




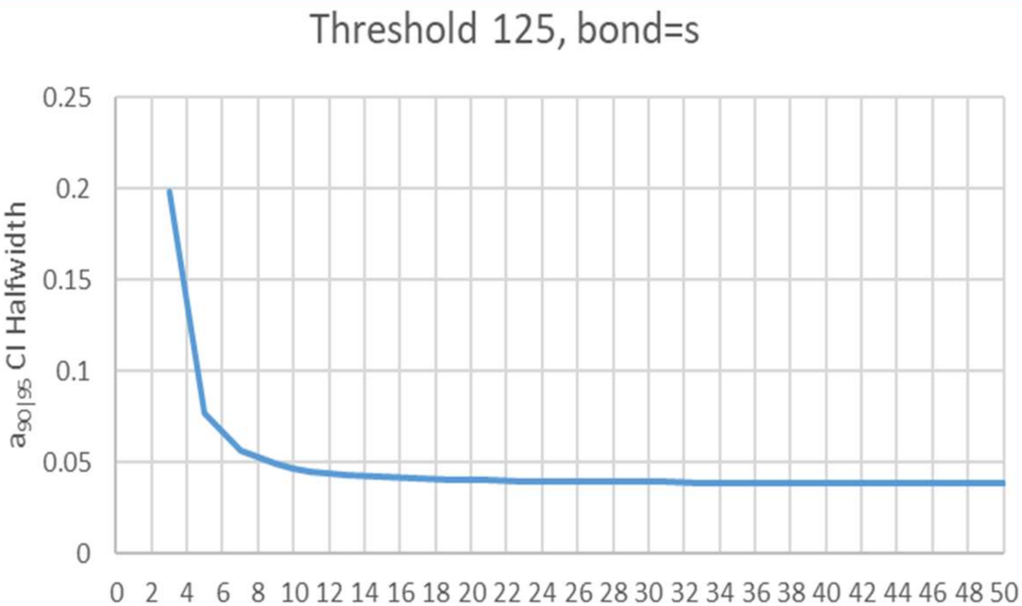
$a_{90/95}$		bond=n				bond=s			
		mean	std	min	max	mean	std	min	max
Threshold	100	0.7052	0.0495	0.5093	0.8407	0.3367	0.0227	0.2742	0.4181
	125	0.7408	0.0465	0.5374	0.8752	0.3589	0.0220	0.2924	0.4418
	150	0.7732	0.0441	0.5680	0.8974	0.3796	0.0217	0.3173	0.4509



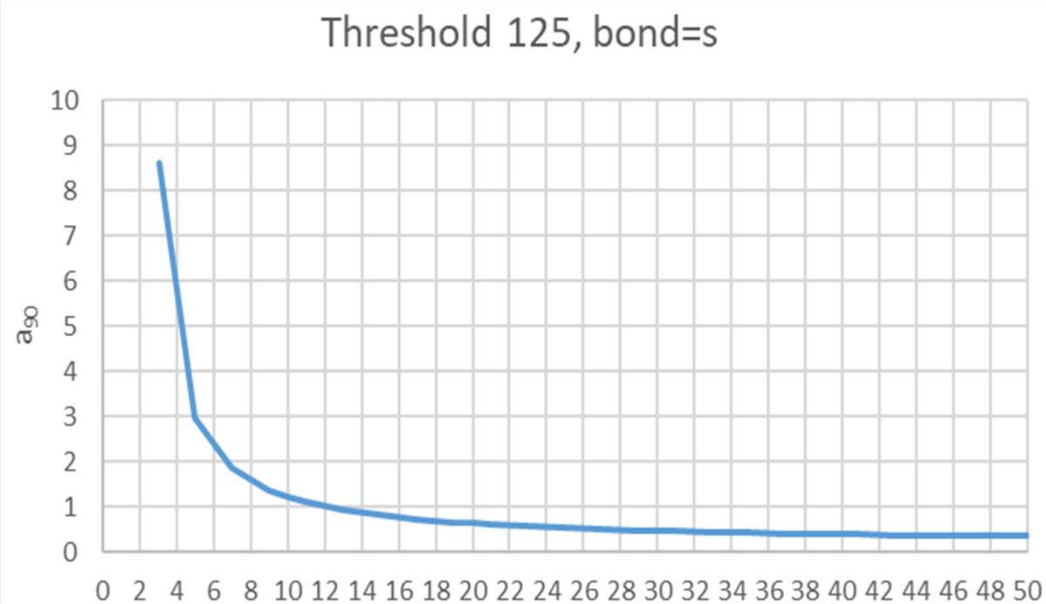




Convergence of 1823 a_{90} Value with Sample Size



Threshold=125	CI half-width $a_{90\|95}$			
	Sensitivity			
Sample Size	mean	std	min	max
5	0.0720	0.006167	0.0521	0.0889
10	0.0452	0.002443	0.0378	0.0515
15	0.0410	0.001939	0.0357	0.0465
20	0.0396	0.001803	0.0350	0.0449
25	0.0390	0.00175	0.0346	0.0442
30	0.0386	0.001724	0.0344	0.0438
35	0.0384	0.001711	0.0342	0.0435
40	0.0382	0.001702	0.0340	0.0433
45	0.0381	0.001697	0.0339	0.0432
Data Estimated	0.0380	0.001694	0.0338	0.0431



Threshold=125	a_{90}			
	Sensitivity			
Sample Size	mean	std	min	max
5	2.7549	0.236106	1.9979	3.5399
10	1.1419	0.087055	0.8767	1.4447
15	0.7697	0.053918	0.6122	0.9612
20	0.6043	0.040082	0.4947	0.7473
25	0.5108	0.032903	0.4198	0.6334
30	0.4507	0.028745	0.3672	0.5602
35	0.4088	0.026171	0.3306	0.5092
40	0.3779	0.024502	0.3036	0.4716
45	0.3542	0.023382	0.2829	0.4427
Data Estimated	0.3355	0.022609	0.2665	0.4199

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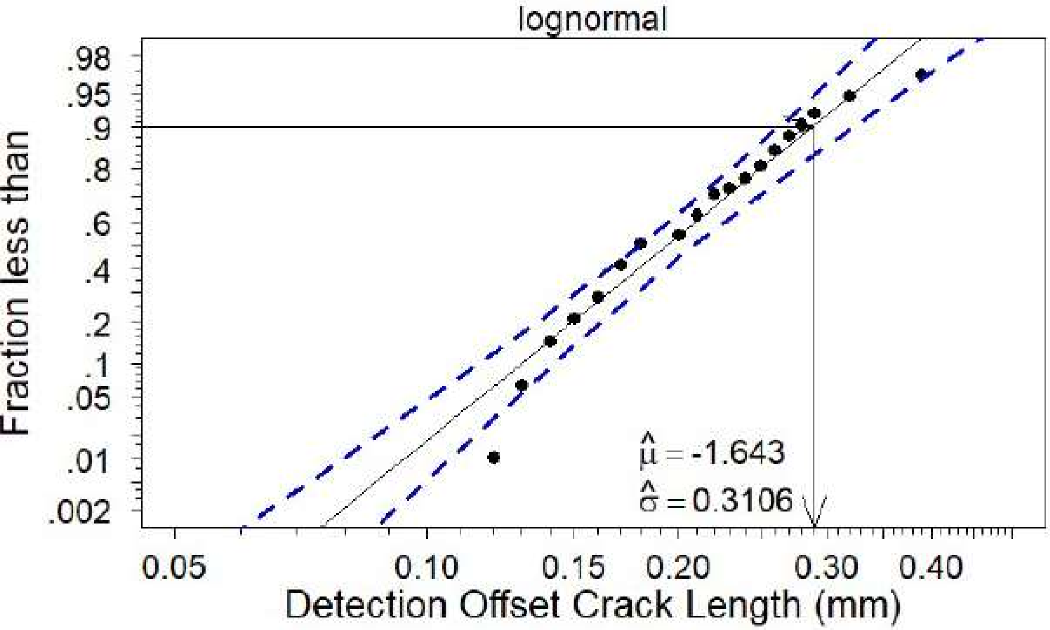
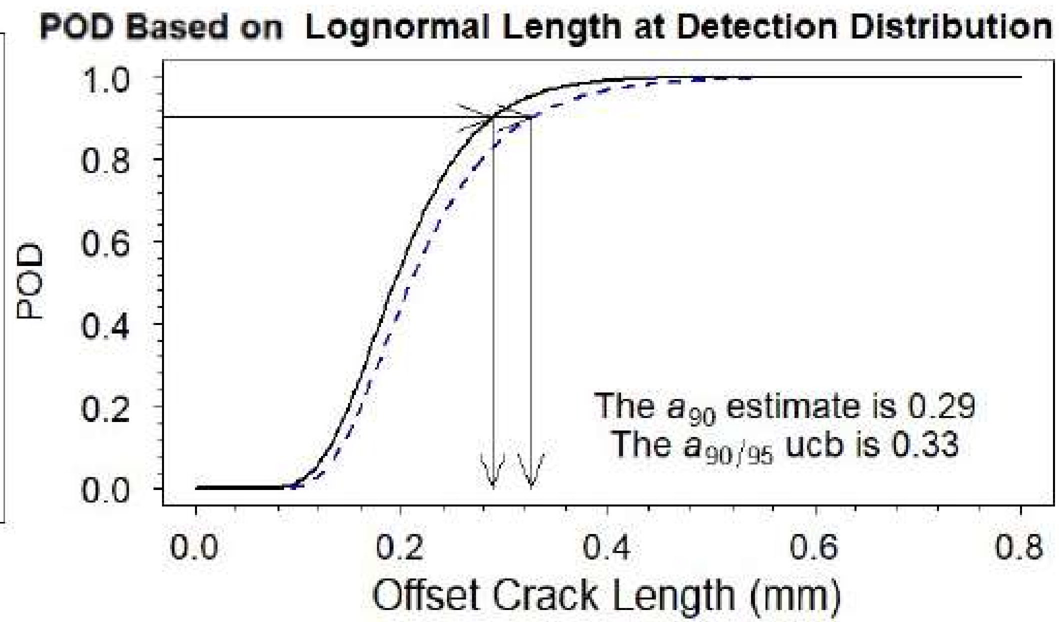
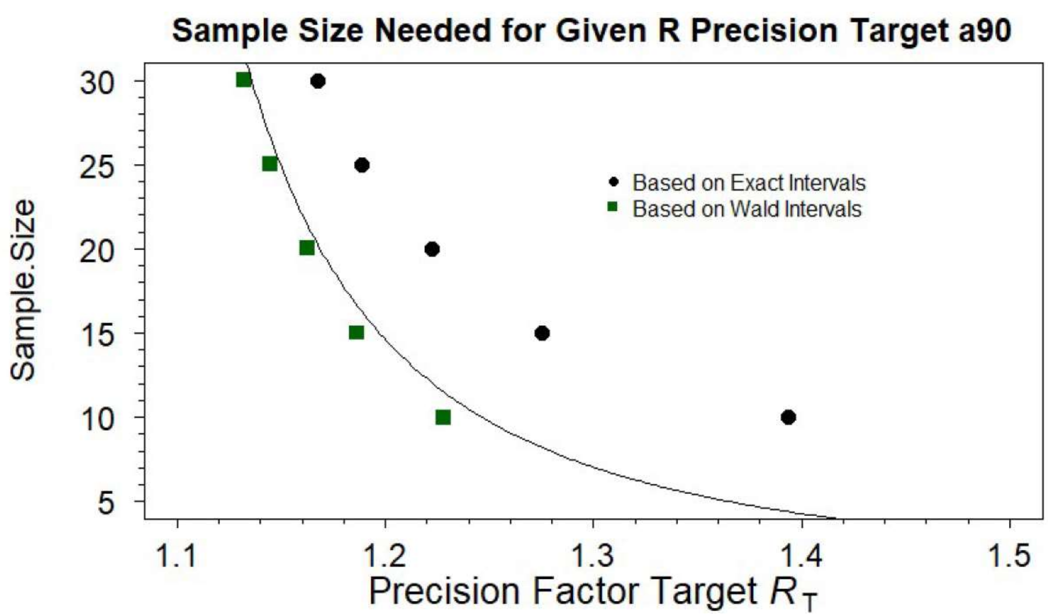
Length at Detection (LaD) for Sample Selection

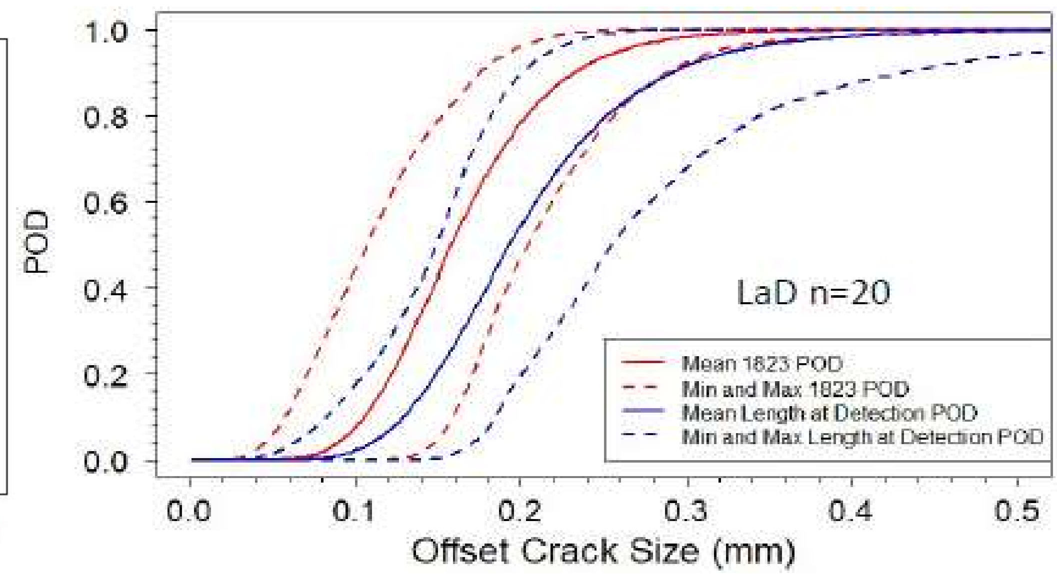
- Alternative approach for selecting points used for POD regression
  - Experiments conducted to failure with continuous SHM data collection
  - Only point actually used in POD analysis is length at detection
  - Defined by first point where all subsequent points are above threshold level
- Traditionally points are randomly distributed amongst flaw range
  - Includes points with large obvious flaws with 100% detection
  - Includes points with very small flaws with 0% detection
  - Includes false positives where sensor detects due to noise
- LaD is much 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
  - Data used for regression is still completely independent
    - Unique specimen, unique sensor, unique installation, unique flaw for each LaD
    - Valid but impractical for NDI because quantity of manual inspection, perfect for SHM

Convergence of LaD a_{90} Value with Sample Size









Determining Appropriate LaD Sample Size

- Collect "seed" set of data with simple experimental procedure
  - 30 tests with continuous SHM, additional tests until mean 1823 a_{90} settles
  - Intended to identify distribution & characterize representative data spread
  - Calculate 1823 a_{90} & $a_{90/95}$ values using entire set of seed data
  - Calculate target precision factor for LaD a_{90} based on 1823 values
  - Use exact intervals to determine sample size to achieve statistical goal

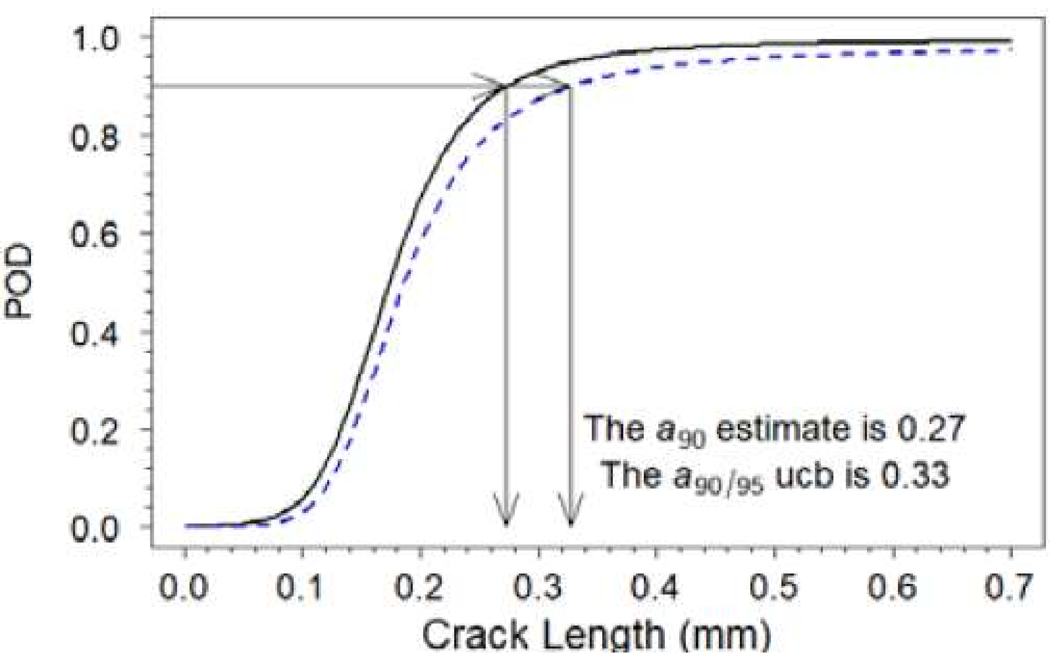
- Future more complex POD studies can then be conducted
  - Minimum sample size to be used for initial planning purposes
  - May decide to include additional specimens to tighten 95% confidence

- Other models being investigated to further take advantage of repeated measures that are presently being ignored

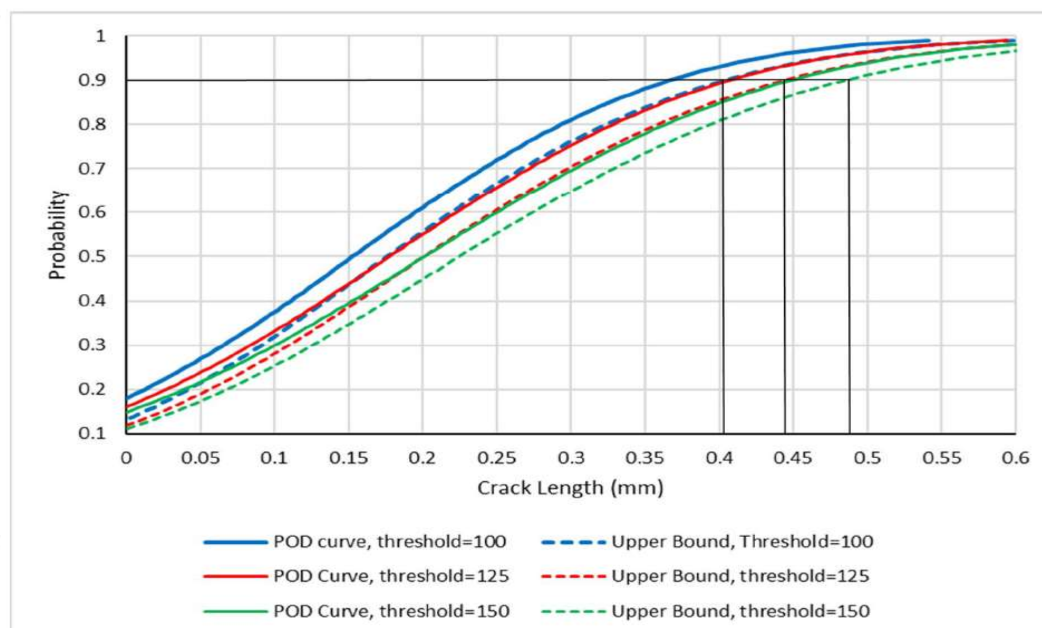
Random Parameters & Random Effects Models

- Similar Statistically Equivalent POD models (SEPOD)
  - ➢ Statistically correct generalization of a vs â for repeated measures
  - ➢ Directly models crack-to-crack variability as well as variability within cracks
  - ➢ Regression model where each crack has its own intercept & slope
  - ➢ POD computed in a manner similar to MIL-HDBK 1823
  - ➢ Provides useful framework for MAPOD

POD Based on Random Parameters Model (Meeker)



POD Based on Random Effects Model (Shubert-Kabban)



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Summary

- Program conducted to qualify novel nanoengineered crack gauge
  - MIL-STD-810 assessment demonstrated airworthiness
  - DOE to determined compensated data sufficiently eliminated all variables
  - Data taken from 100 specimens to quantify detection sensitivity
    - Specimens bonded with 2 materials, proved to be a critical factor to be considered
    - Placement offset of similar value to $a_{90/95}$, decided to consider separately, could improve
- POD calculated for 50 independent specimens bonded w/rubber
  - $a_{90/95}$ of 0.33mm for traditional 1823A using threshold metric of 100
  - $a_{90/95}$ of 0.33mm for Length at Detection using lognormal distribution
  - $a_{90/95}$ of 0.33mm for Random Parameter model
- Still a work in progress
  - How to establish "gold standard" $a_{90/95}$ for validation of new approaches
  - Formalize process for selecting appropriate sample size of new sensors
  - Novel model development for integration with MAPOD

Acknowledgements

- AFWERX FA8649-20-9-9068 – Tyler Gruters & Dr. Eric Lindgren
- Program collaborators
  - Metis Design Corporation
    - Michael Borgen (package design & testing)
    - Dr. Christopher Dunn (analytical model)
    - Dr. Gregory Jarmer (truth data analysis)
    - Dr. Estelle Cohen (sensor design)
  - Analog Devices
    - Yosi Stein (hardware design)
    - Hazarathaiah Malepati (software design)
  - Massachusetts Institute of Technology
    - Professor Brian Wardle (sensor design)
    - Dr. Luiz Acauan (sensor design)
  - Consulting statisticians
    - Professor Christin M. Shubert-Kabban (Air Force Institute of Technology)
    - Professor William Q. Meeker (Iowa State University)
    - David Forsyth (TRI Austin)

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