Air Force Life Cycle Management Center

Assessing Limited Pedigree da/dN Crack Propagation Data

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U.S. AIR FORCE

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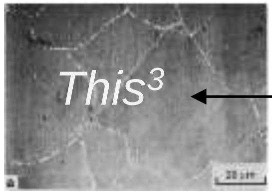
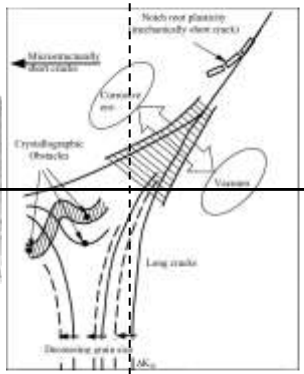
- Dr. Tom Mills (AP/ES)
- Dr. Scott Carlson (Lockheed)
- A-10 Structures and Aero Team

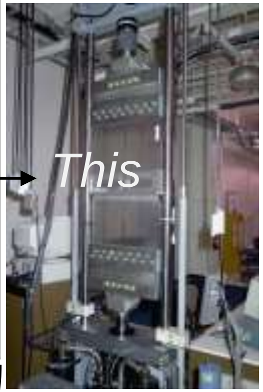
Overview

- **Motivation**
- **Data Evaluation Example**
  - **7050**
    - **Fixed Ranges of da/dN (Scatter of 2)**
    - **Fixed Ranges of ΔK (+/- 5%)**
      - **R = 0.1, 0.4, 0.8**
  - **2024**
    - **Fixed Ranges of ΔK (+/- 5%)**
      - **R = 0.1**
- **Observations**
- **Concluding Remarks**

Is the earth flat or spherical? Turns out that even though evidence has suggested otherwise since about Aristotle's time, it is a recurring debate![2]







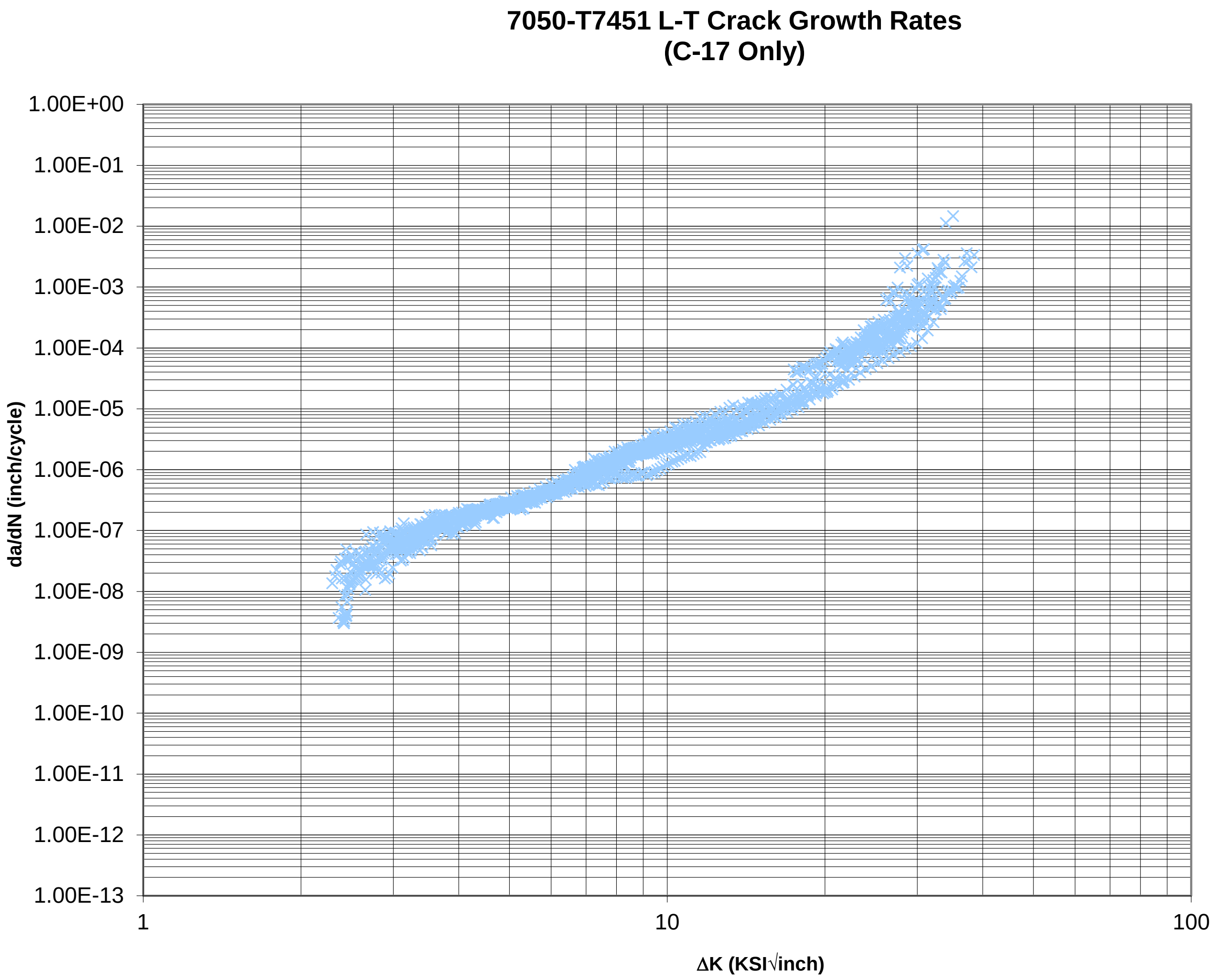
Motivation

- **Access to da/dN v ΔK data in the public domain is limited to**
  - MMPDS, Damage Tolerance Design Handbook, Software/models, AFMAT, etc.
- **Data pedigree is often minimal**
  - $\Delta K_{Applied}$ or $\Delta K_{Effective}$, etc.
  - Constant Amplitude (CA), K-Decreasing, K-Increasing, etc.
  - Product Form, thickness range, test environment, etc.
- **Modification and sustainment engineers and DERs struggle to acquire data**
  - Limited expertise in
    - Testing and data evaluation
    - Scatter, test invalidities (angle, symmetry, etc.)
  - Limited funding

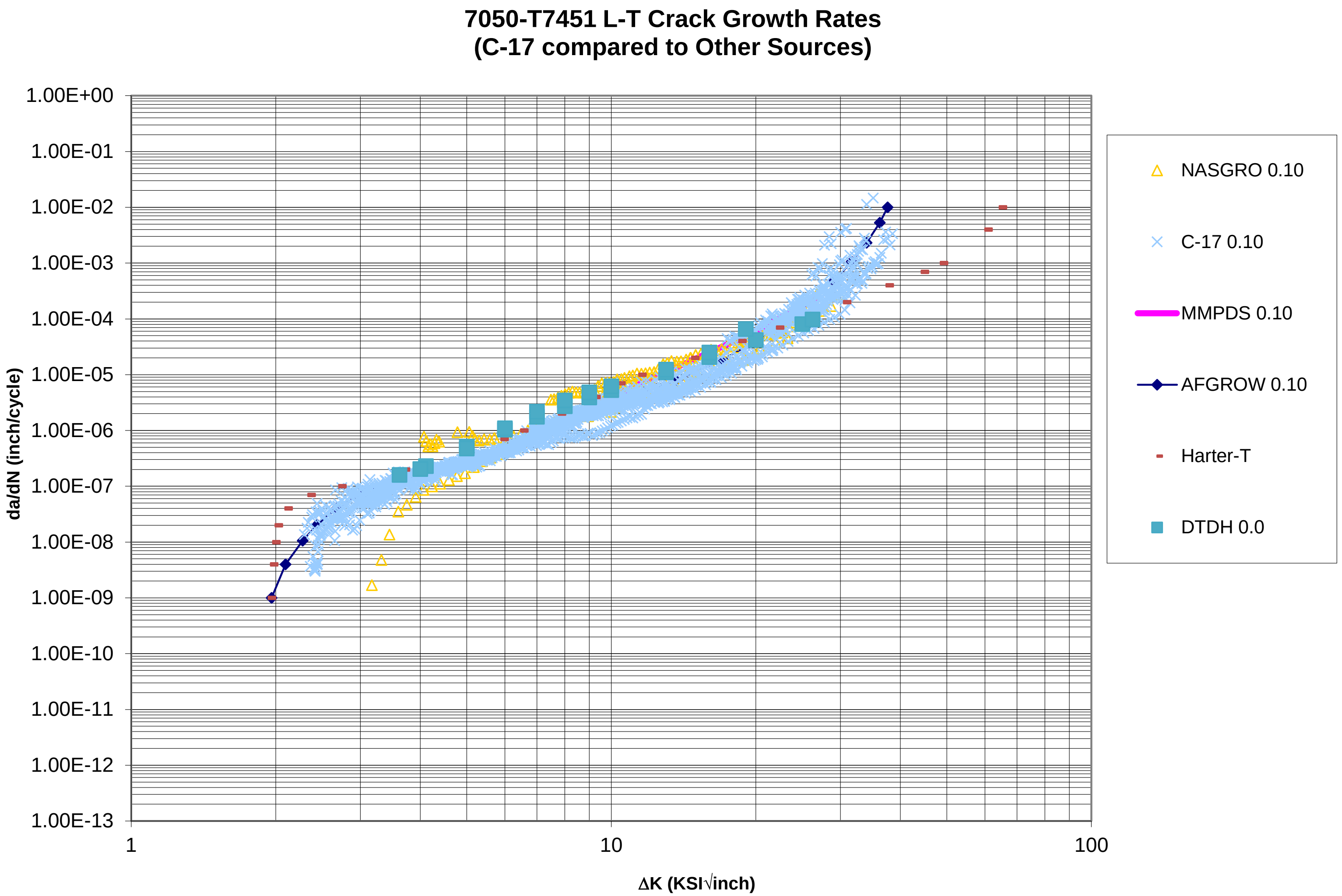
Specific Example

- **7050-T7451 L-T**
  - What we know about this data set
    - 7050 is a controlled damage tolerant alloy: Composition and processing are controlled to meet specific requirements, e.g. strength, toughness, and corrosion resistance to include stress corrosion
    - Stress Ratio
    - Range of ΔK
    - Grain orientation
  - What we do not know
    - Specimen configuration
    - Product form thickness
    - Testing environment and frequency
    - Test Type (CA, K-Decreasing, etc.)
    - Test data supplier
    - Producer/lot variation

Generic Test Data Example



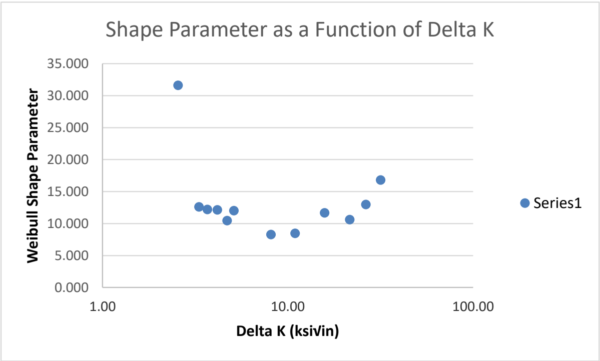
Data Comparison (Establishing 'Confidence')



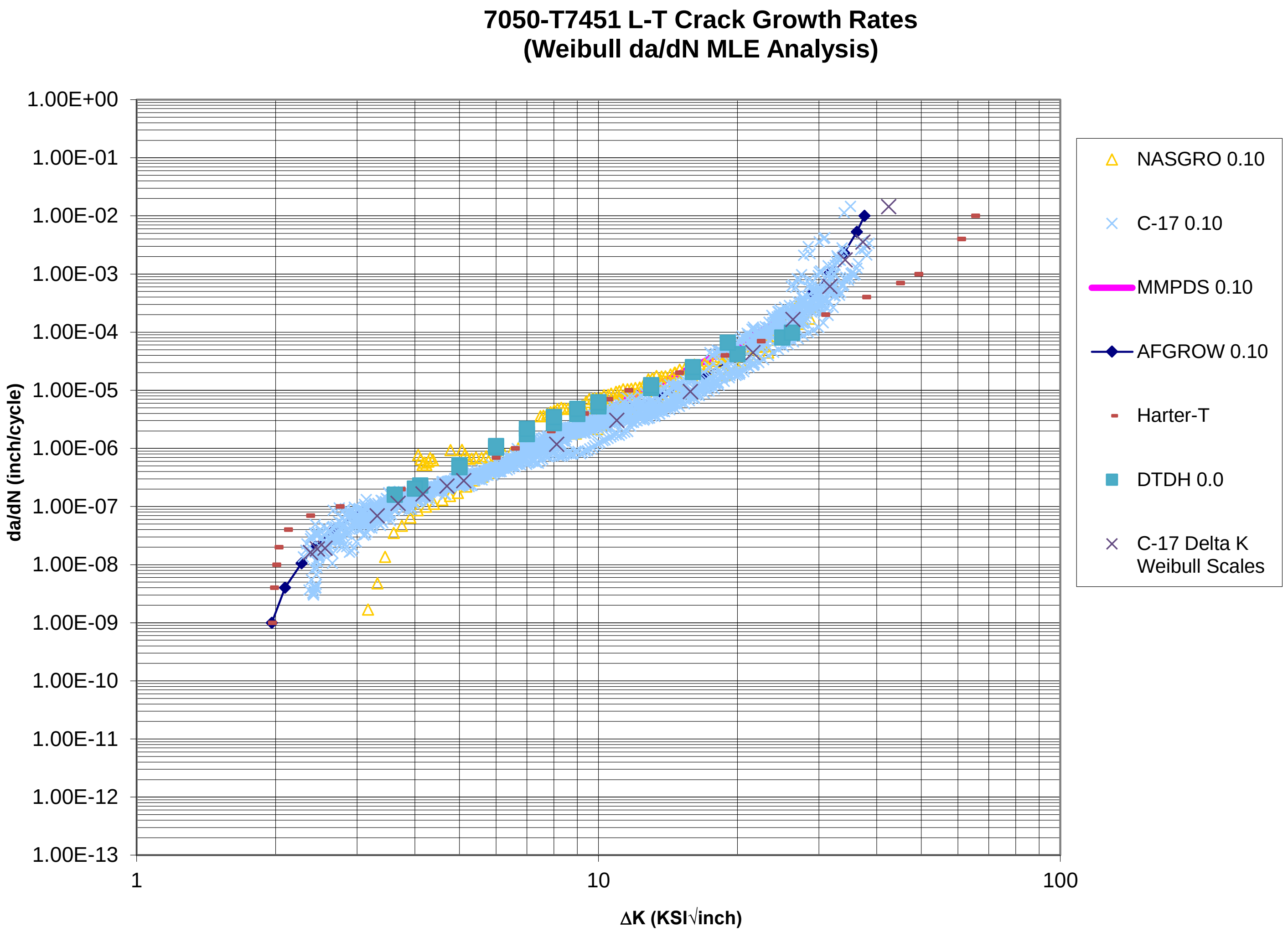
Option 1: Analyze ΔK in Ranges of da/dN

- **Choose ranges of da/dN (Max/Min = 2) to analyze from total population of data**
  - No justification on scatter factor of 2 (folklore)
- **Develop Maximum Likelihood Estimation (MLE)[4] distribution parameters for ΔK within each given range of da/dN**
  - 1388 data pairs across 13 da/dN ranges
  - Approximately 107 ΔK points/da/dN
- **Resulting shape parameters as a function of ΔK**

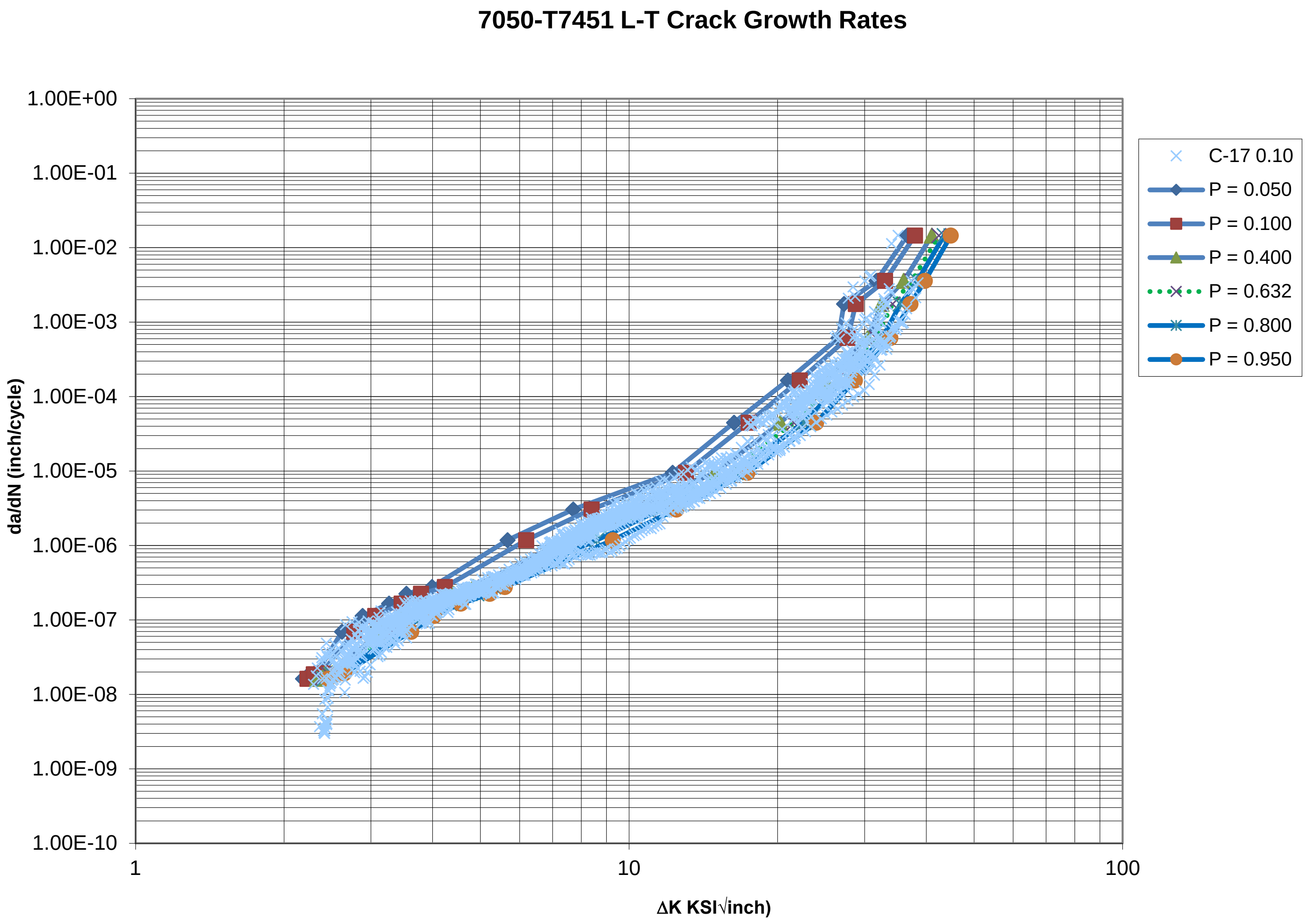
Fixed da/dN Midpoint	Weibull parameters for Delta K	
da/dN	Delta K	Shape
1.920E-08	2.56	31.615
6.940E-08	3.32	12.620
1.130E-07	3.68	12.200
1.650E-07	4.17	12.143
2.240E-07	4.70	10.457
2.770E-07	5.11	12.020
1.176E-06	8.12	8.285
3.050E-06	10.95	8.458
9.490E-06	15.81	11.675
4.460E-05	21.59	10.608
1.650E-04	26.35	12.993
6.110E-04	31.69	16.812
1.750E-03	34.18	13.136



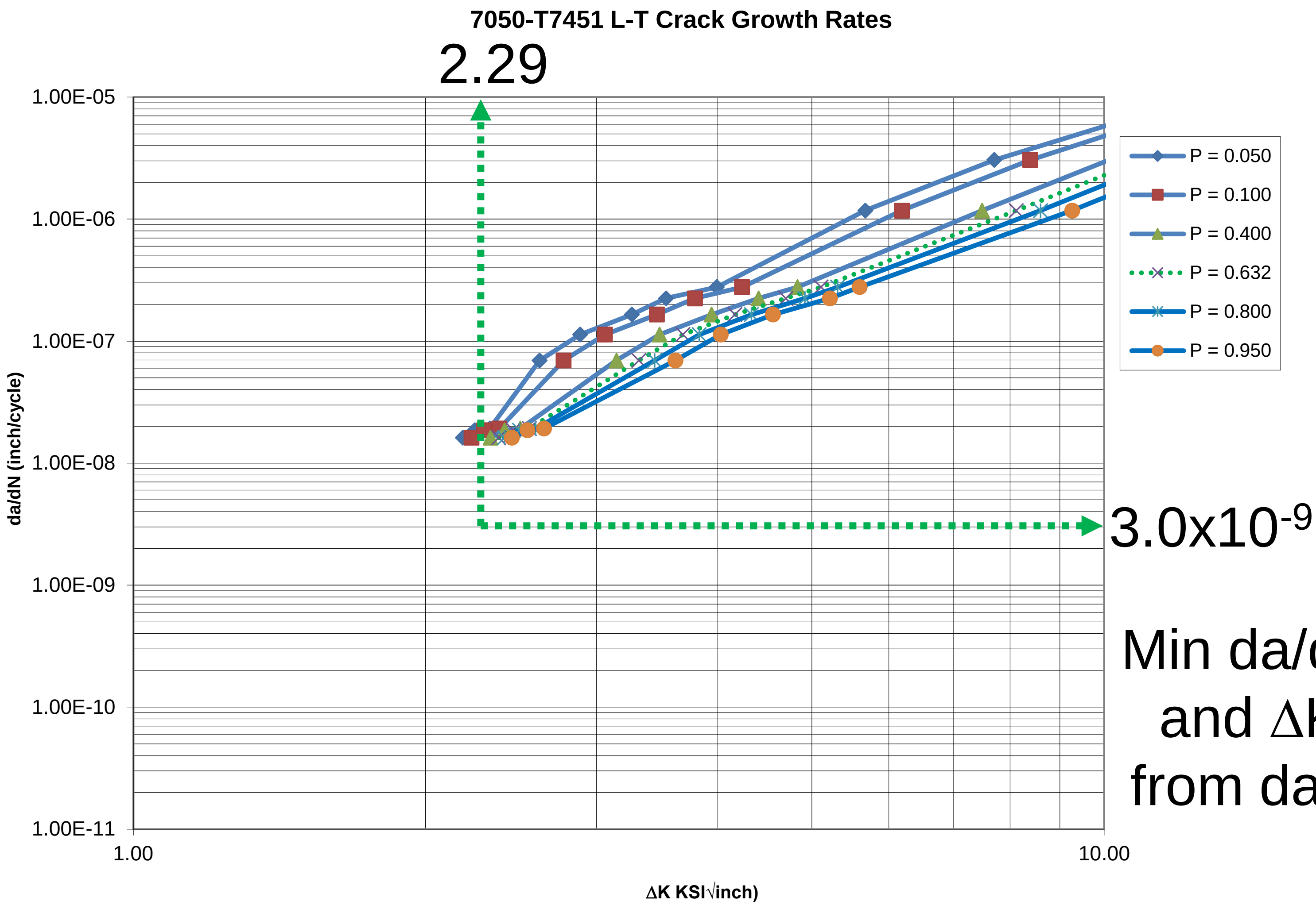
Characterizing C-17 Data (2-P Weibull R = 0.1 ΔK)



Constant Probability Curves (ΔK R = 0.1)

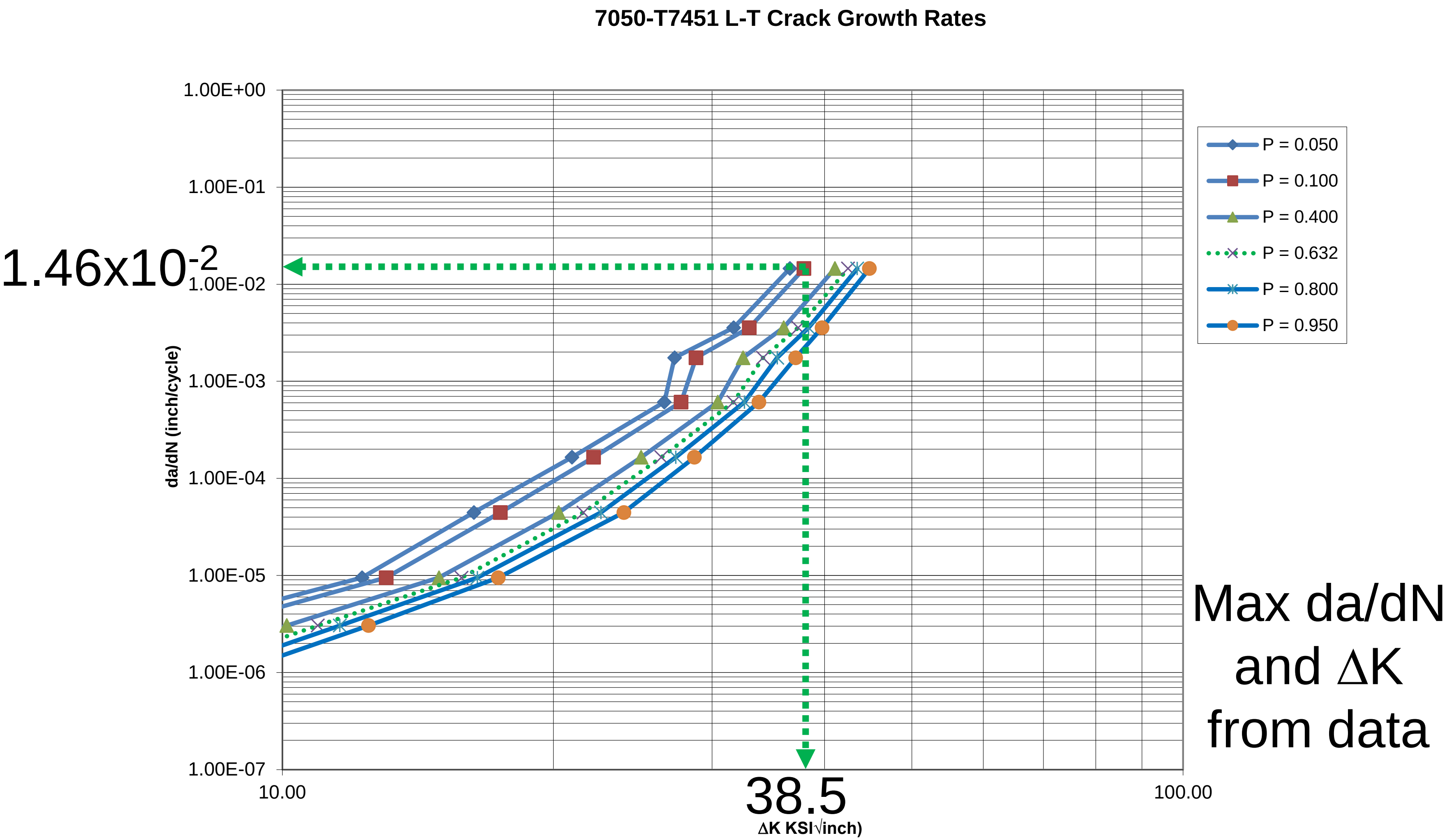


Constant Probability (Low da/dN R = 0.1)

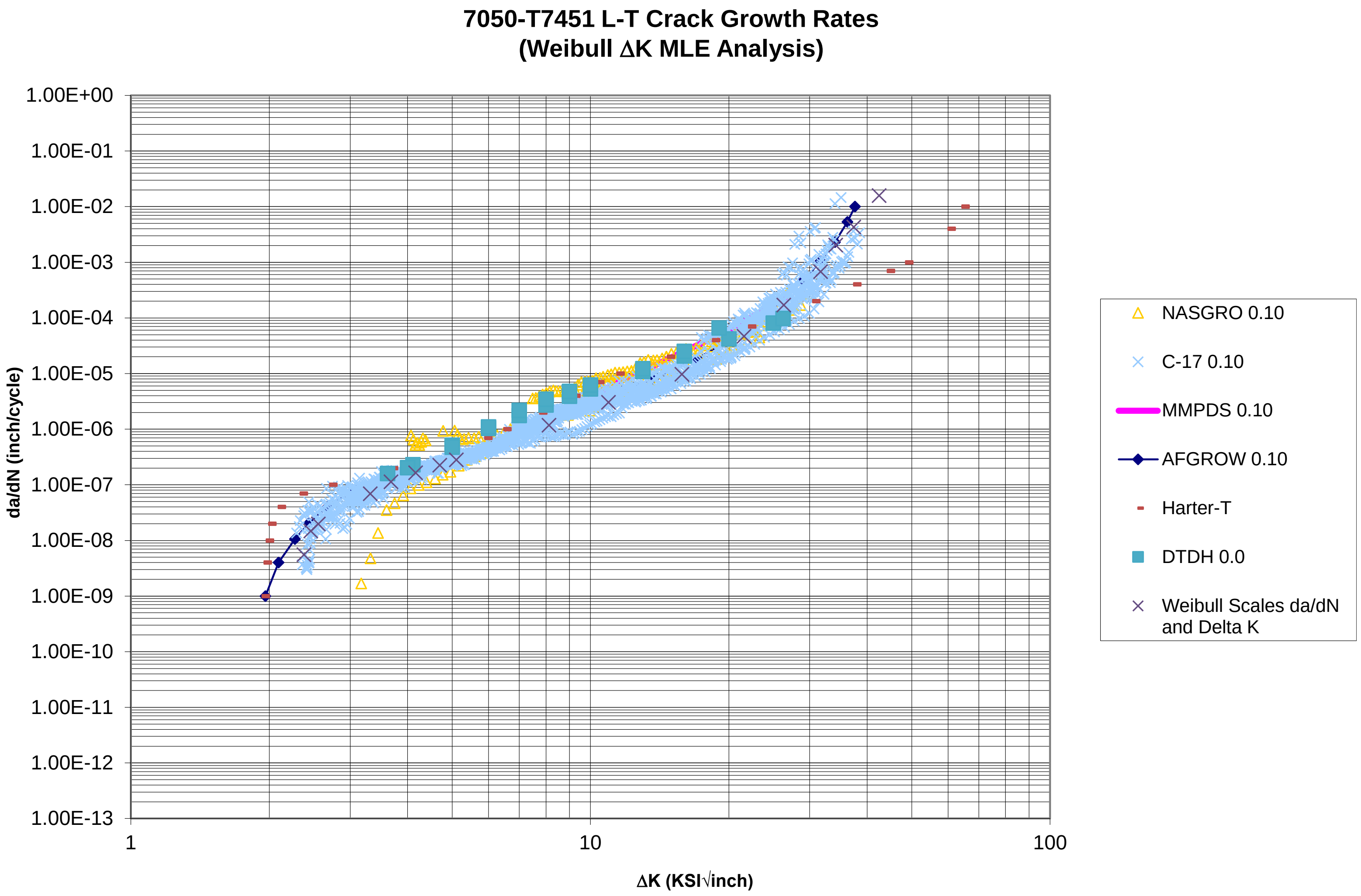


Min da/dN and ΔK from data

Constant Probability (High da/dN R = 0.1)



63% Look-up Curve (R = 0.1)



Option 2: Analyze da/dN in Ranges of ΔK (R = 0.1)

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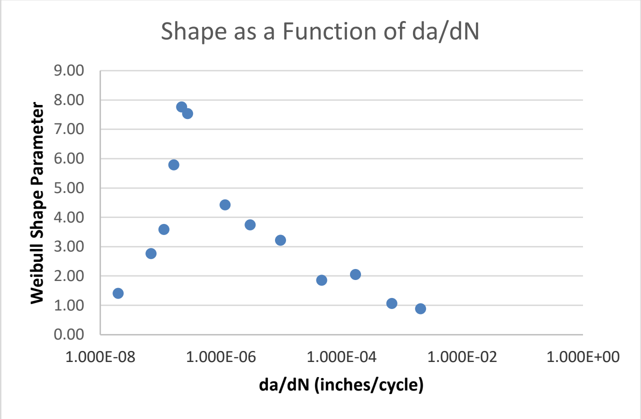
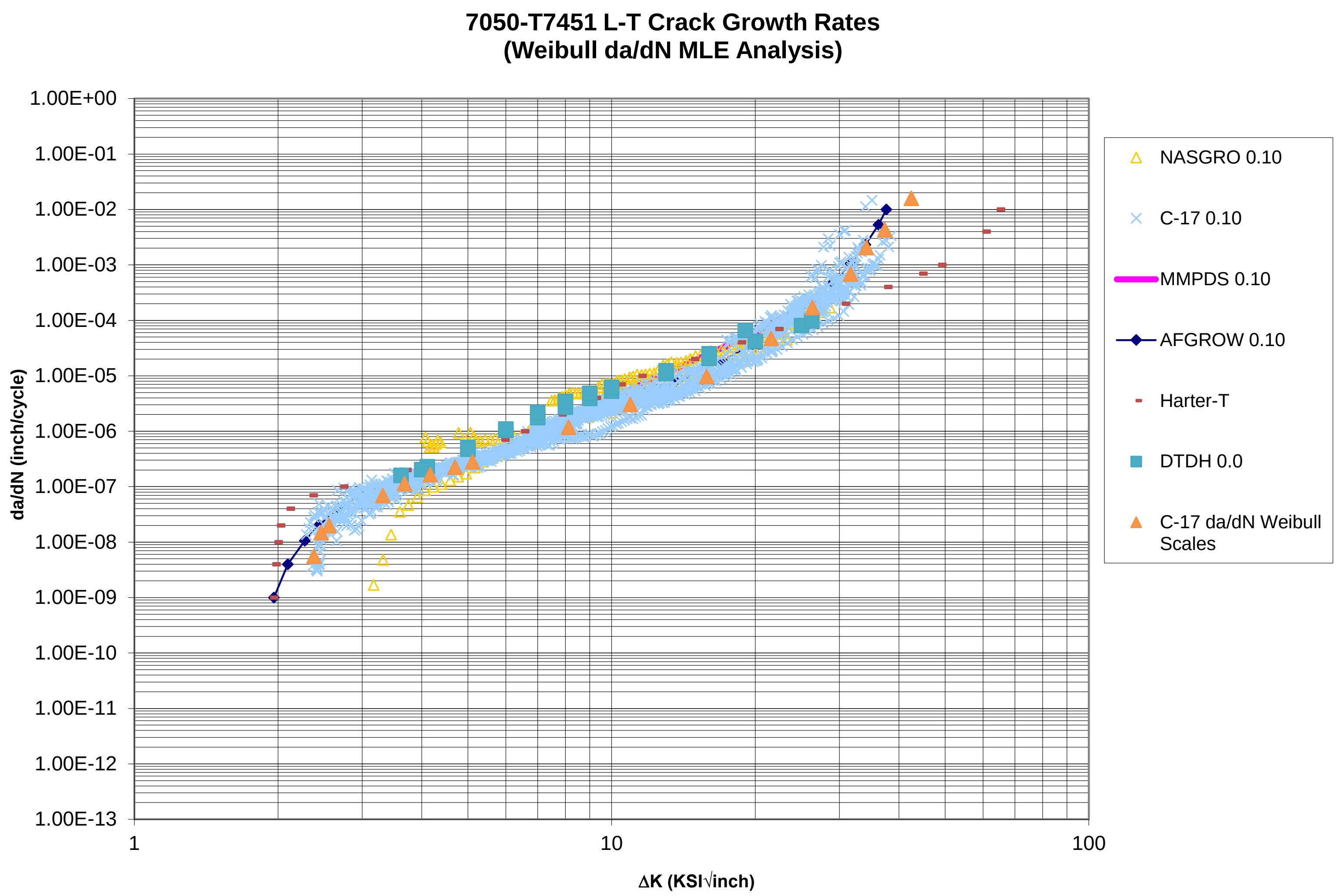
- **Choose ranges of ΔK (+/- 5%) to analyze from total population of data**
  - 1616 data pairs
  - 5% based on loads accuracy
- **Develop Maximum Likelihood Estimation (MLE) distribution parameters for da/dN within each chosen range of ΔK**
  - 799 data pairs across 13 ΔK ranges
  - Approximately 61 da/dN points/ΔK range
- **Resulting shape parameters as a function of da/dN**

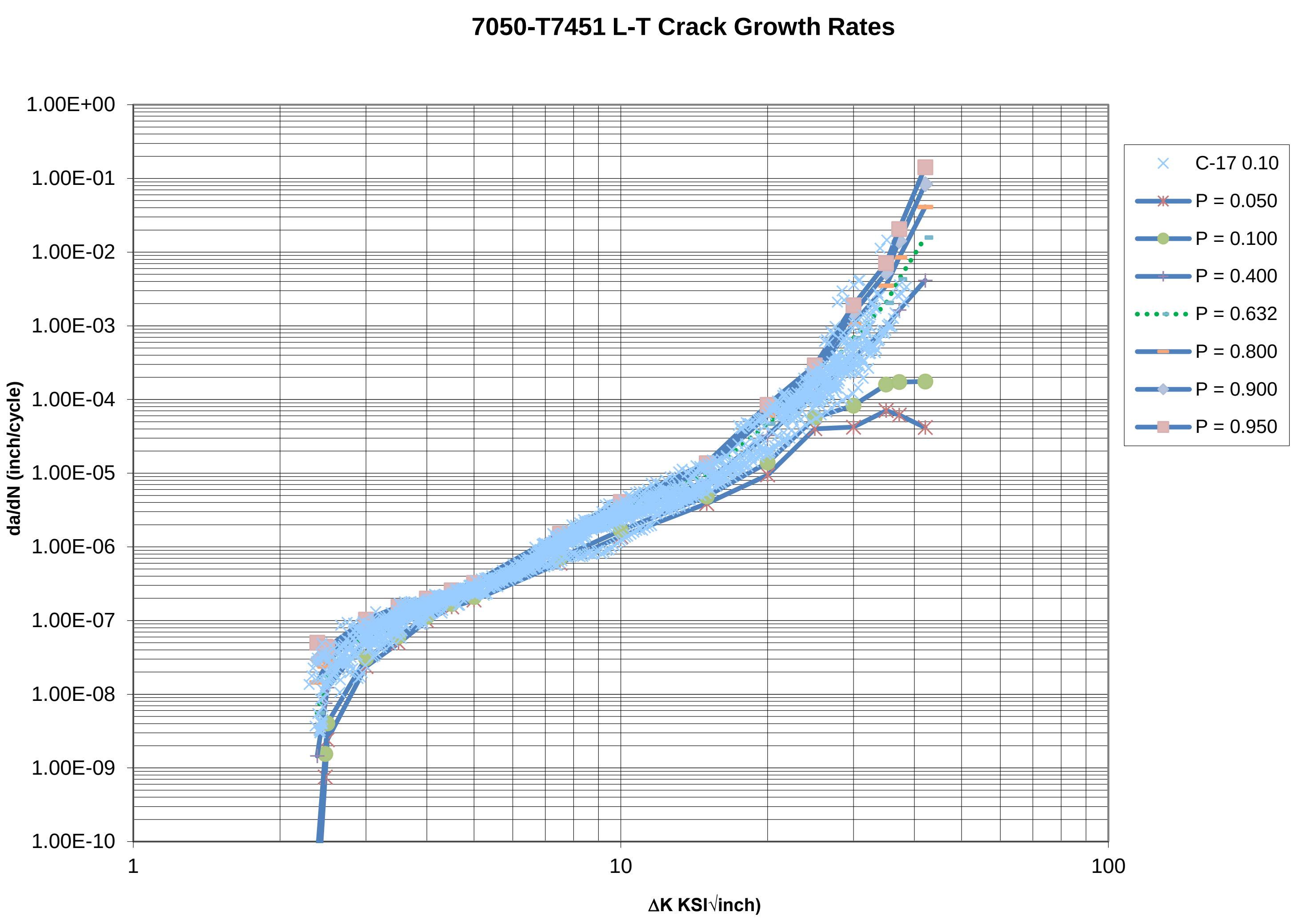
Weibull Parameters for da/dN at Fixed ΔK		Target for da/dN Distributions	
Shape	Scale	ΔK	Range
1.41	1.985E-08	2.50	2.375-2.625
2.77	6.936E-08	3.00	2.850-3.150
3.59	1.136E-07	3.50	3.325-3.675
5.79	1.650E-07	4.00	3.800-4.200
7.77	2.240E-07	4.50	4.275-4.725
7.54	2.810E-07	5.00	4.750-5.250
4.42	1.176E-06	7.50	7.125-7.875
3.74	3.049E-06	10.00	9.500-10.500
3.22	9.724E-06	15.00	14.250-15.750
1.85	4.698E-05	20.00	19.000-21.000
2.05	1.701E-04	25.00	23.750-26.250
1.07	6.814E-04	30.00	28.500-31.500
0.88	2.047E-03	35.00	33.250-36.750



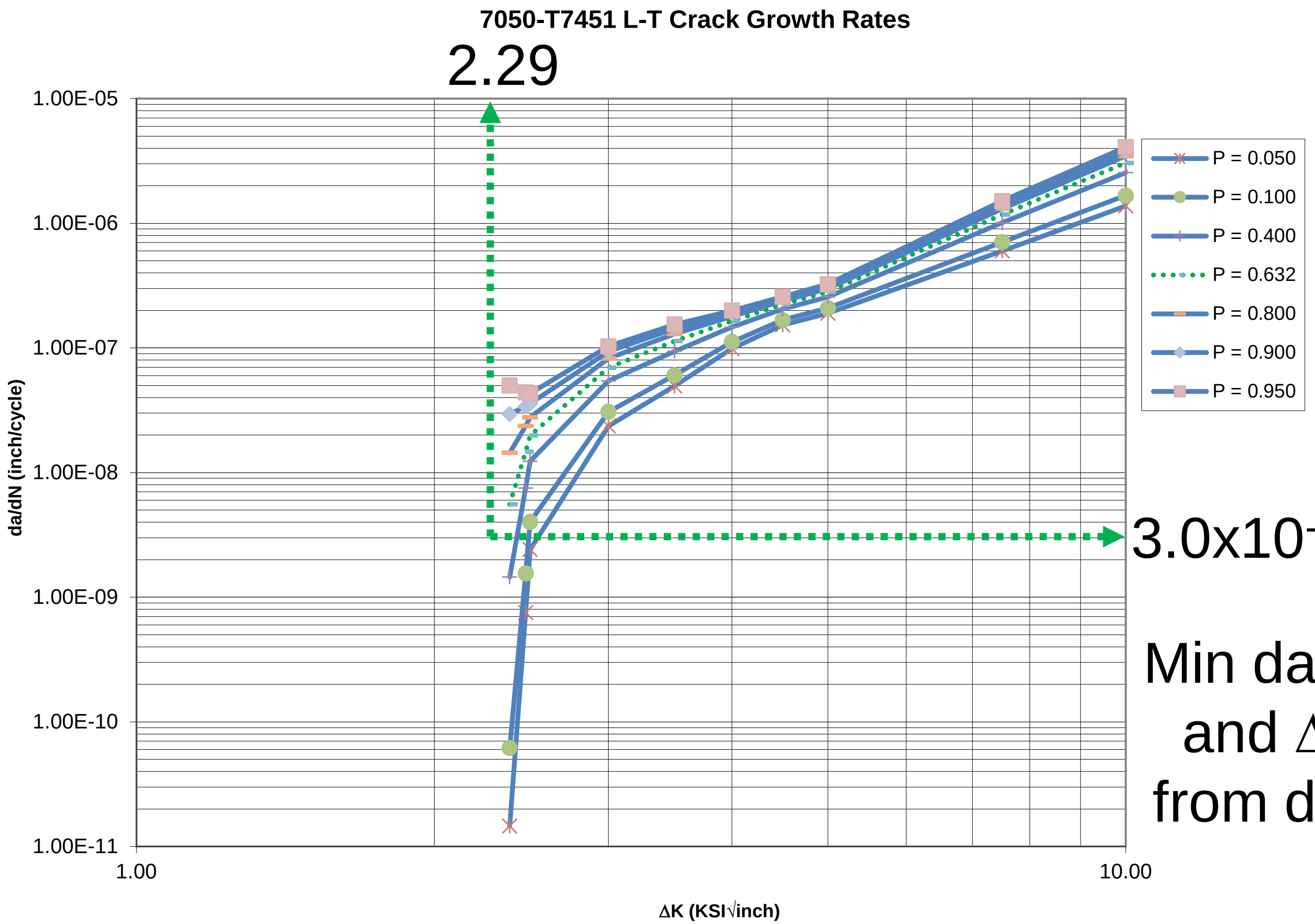
Characterizing C-17 Data (2-P Weibull R = 0.1 da/dN)



Constant Probability Curves (R = 0.1 da/dN)

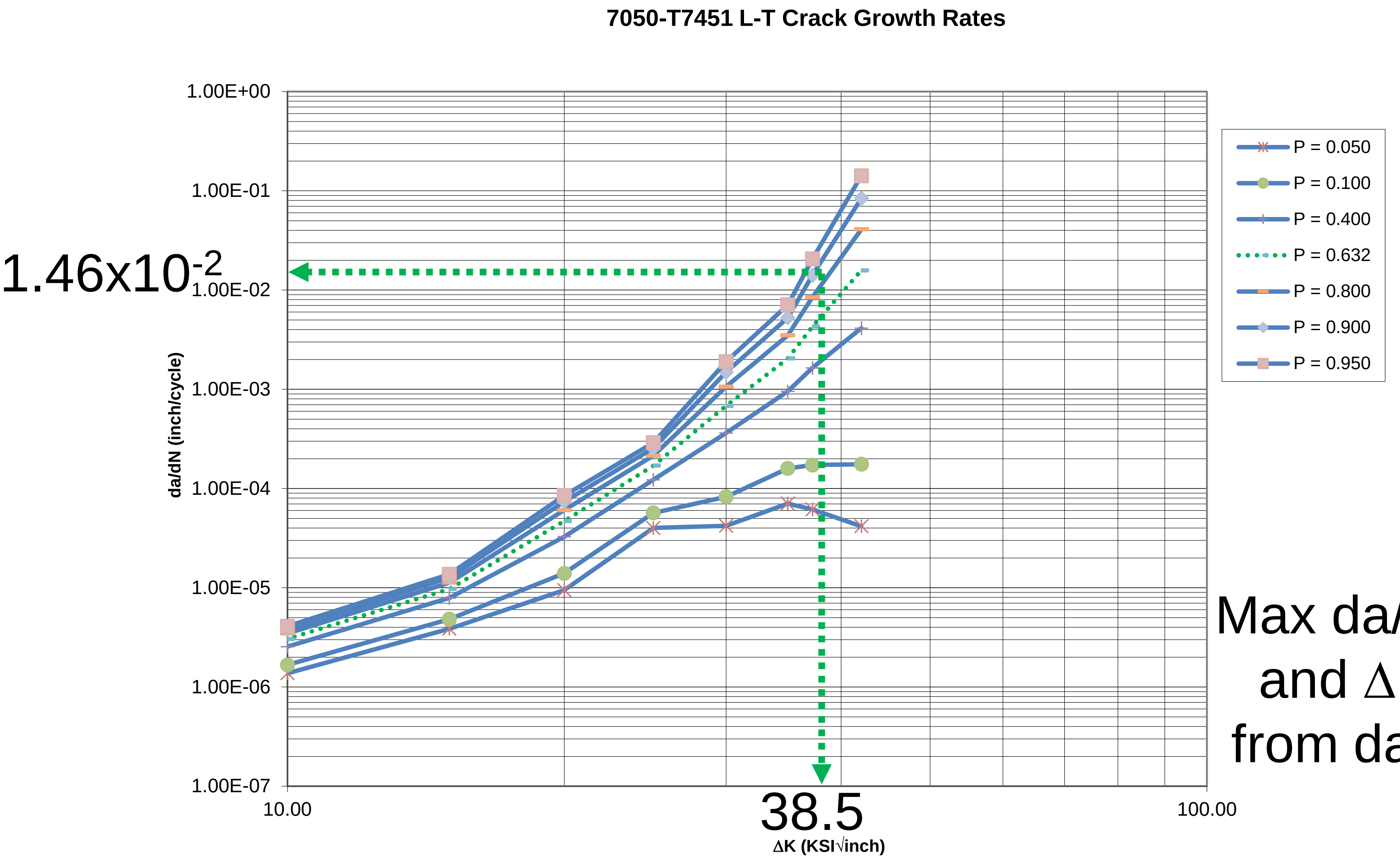


Constant Probability (Low ΔK R = 0.1)



Min da/dN and ΔK from data

Constant Probability (High ΔK R = 0.1)



Max da/dN and ΔK from data

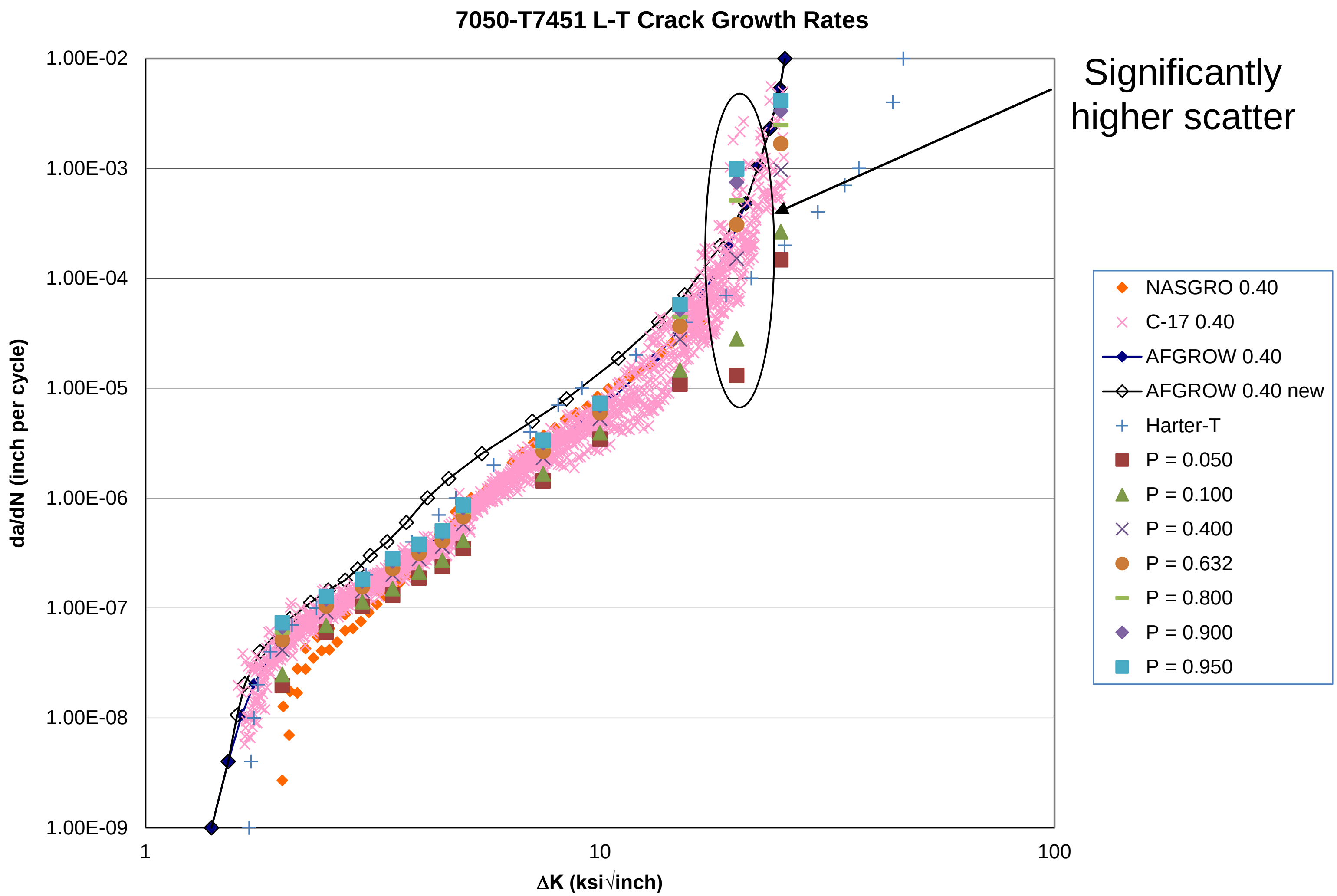
Scatter in da/dN (R = 0.1)

- **Is a factor of 2 sufficient?**
  - At 1.65×10^{-7} in/cycle it captures 90% of the data
  - At 1.18×10^{-6} in/cycle it captures 82% of the data
  - In order to capture more than 80% of the data at the lowest and highest growth rates, scatter factors of 17 and 95, respectively, result

Middle Growth Rates Scatter							
		Probability		Bottom			
	1.65E-07	0.63		1.99E-08			
Scatter = 2	1.10E-07	0.09		3.76E-09	Scatter =	17	
	2.20E-07	0.99	90%	6.46E-08			90%
		Probability		Top			
	1.18E-06	0.63		2.05E-03			
Scatter = 2	7.84E-07	0.15		1.43E-04	Scatter =	95	
	1.57E-06	0.97	82%	1.35E-02			82%

- **Only about 1 decade of data fits within a scatter factor of 2**

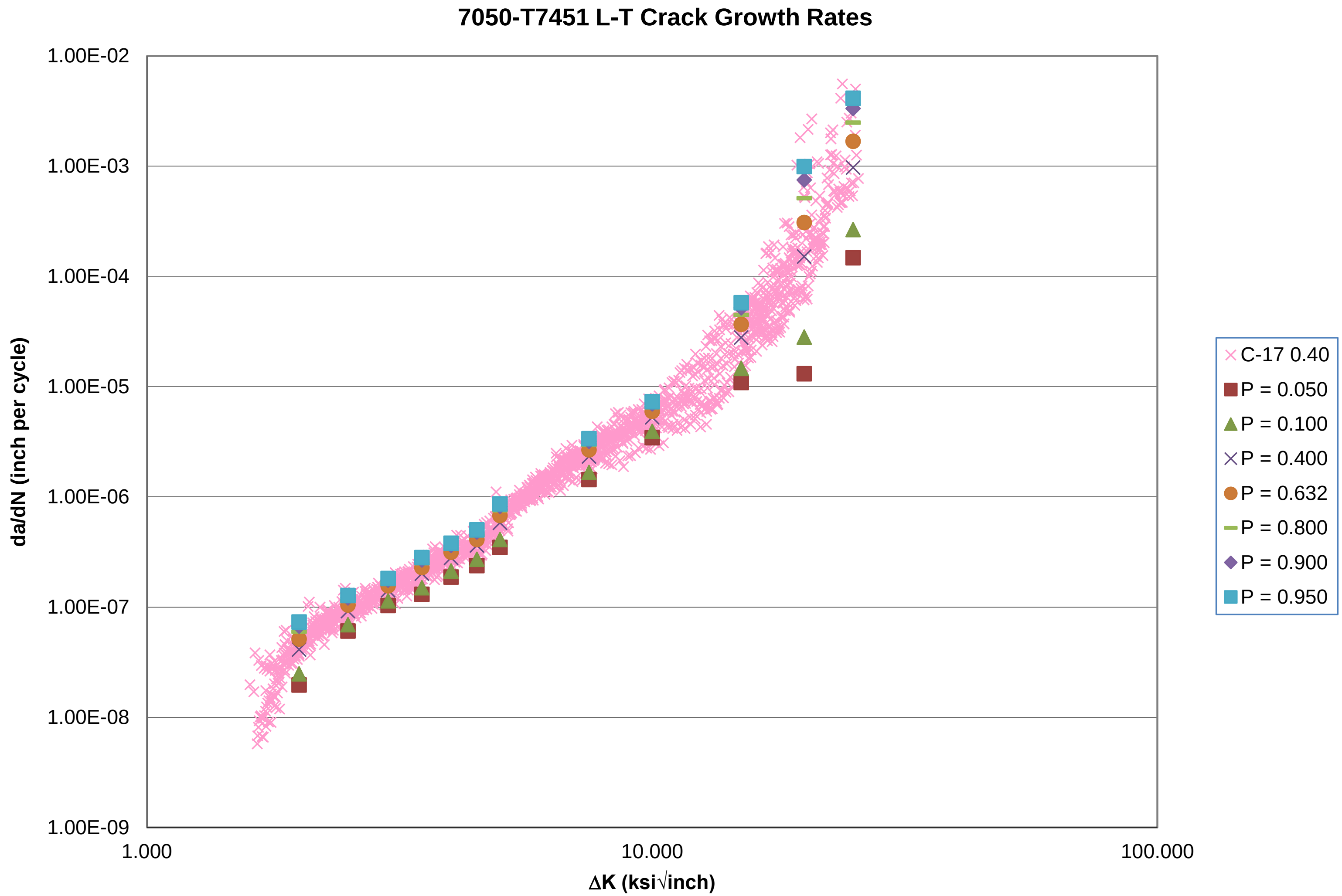
Characterizing C-17 Data (2-P Weibull R = 0.4 da/dN)



1601 total data pairs 17 tests

653 da/dN points analyzed across 12 ΔK ranges

Constant Probability (R = 0.4 da/dN)



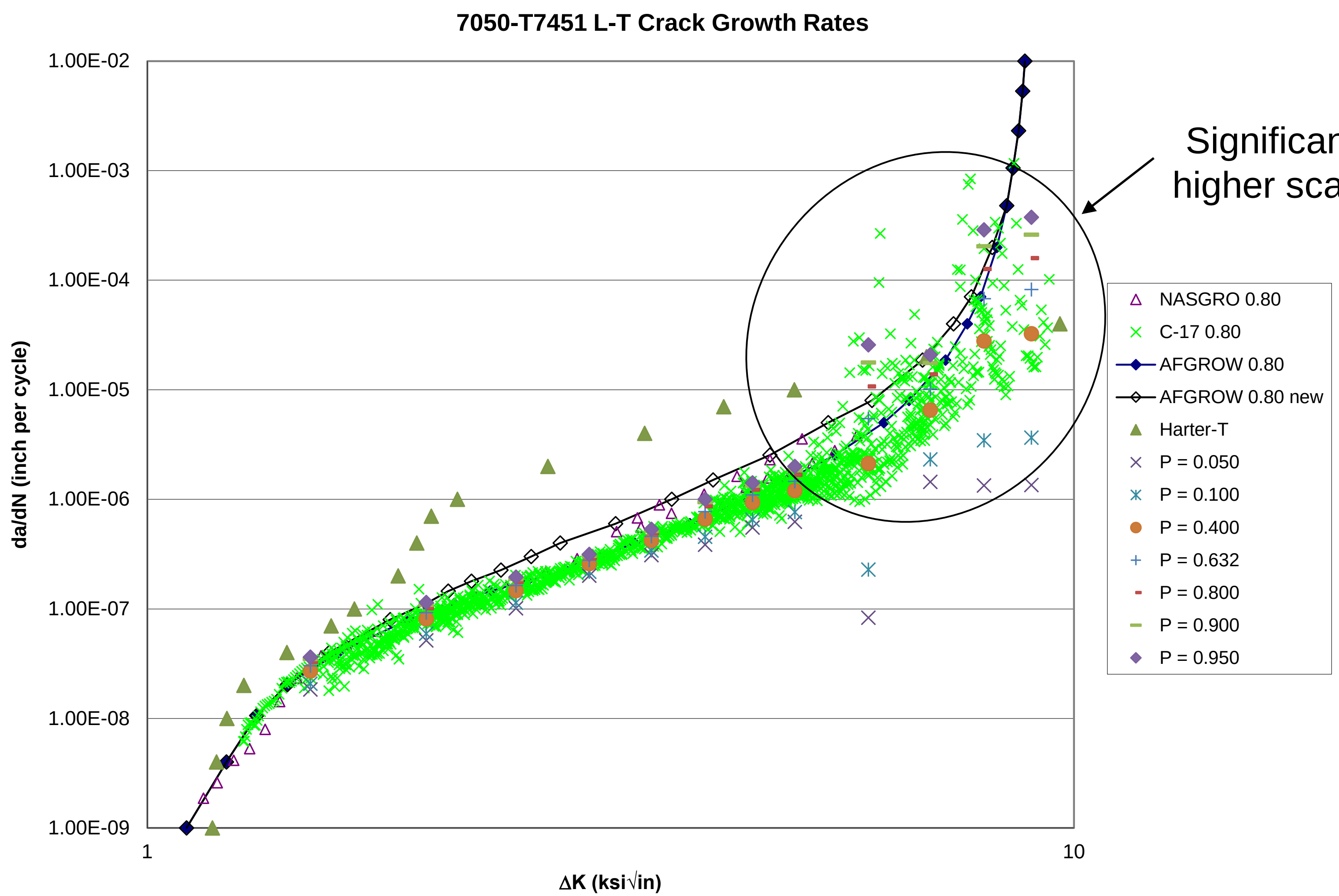
Scatter in da/dN (R = 0.4)

- **Is a factor of two sufficient?**
  - At 1.04×10^{-7} in/cycle it captures 89% of the data
  - At 5.97×10^{-6} in/cycle it captures 89% of the data
  - In order to capture more than 80% of the data at the lowest and highest growth rates, scatter factors of 3 and 21, respectively, result

Middle Growth Rates Scatter							
		Probability		Bottom			
	1.04E-07	0.63		5.13E-08			
Scatter = 2	6.95E-08	0.10		2.50E-08	Scatter =	3	
	1.39E-07	0.99	89%	8.56E-08			89%
		Probability		Top			
	5.97E-06	0.63		1.68E-03			
Scatter = 2	3.98E-06	0.11		2.80E-04	Scatter =	21	
	7.95E-06	0.99	89%	6.00E-03			89%

- **About 1.5 decades near the lower da/dN range falls within the scatter factor of 2**

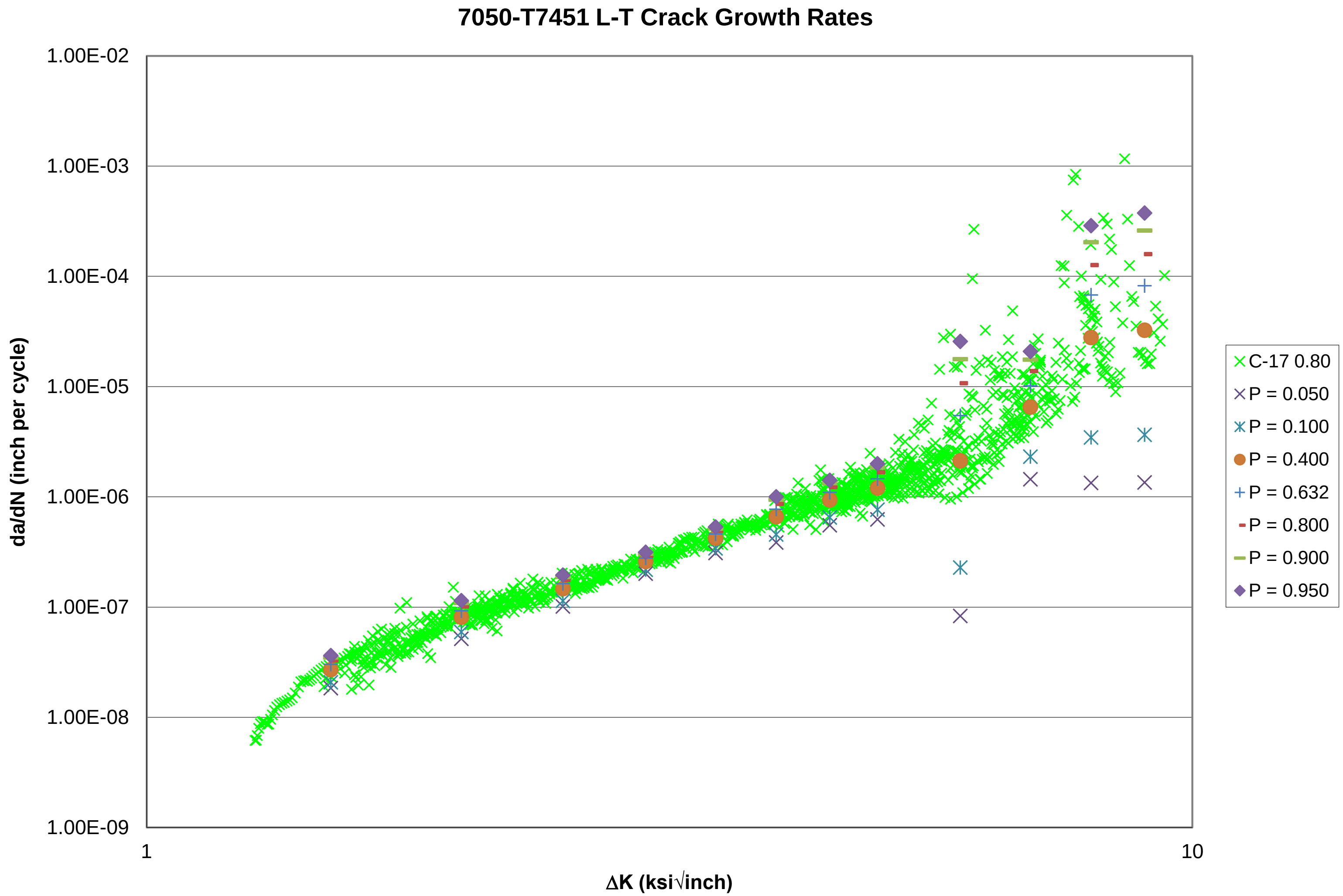
Characterizing C-17 Data (2-P Weibull R = 0.8 da/dN)



1280 total data pairs across 17 tests

767 da/dN points analyzed across 12 ΔK ranges

Constant Probability (R = 0.8 da/dN)



Scatter in da/dN (R = 0.8)

- **Is a factor of two sufficient?**
  - At 3.03×10^{-8} in/cycle it captures 91% of the data
  - At 4.61×10^{-7} in/cycle it captures 95% of the data
  - In order to capture more than 80% of the data at the lowest and highest growth rates, scatter factors of 2 and 1315, respectively, result

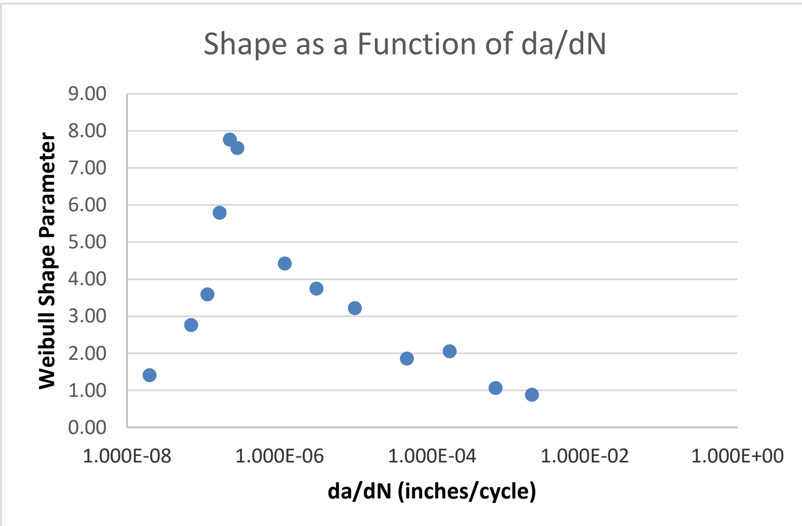
Middle Growth Rates Scatter							
		Probability		Bottom			
	3.03E-08	0.63		3.03E-08			
Scatter = 2	2.02E-08	0.08		2.02E-08	Scatter =	2	
	4.04E-08	1.00	91%	4.04E-08			91%
		Probability		Top			
	4.61E-07	0.63		8.23E-05			
Scatter = 2	3.07E-07	0.05		1.23E-06	Scatter =	1315	
	6.15E-07	1.00	95%	1.62E-03			95%

- **Only the lowest decade da/dN falls within the scatter factor of 2**

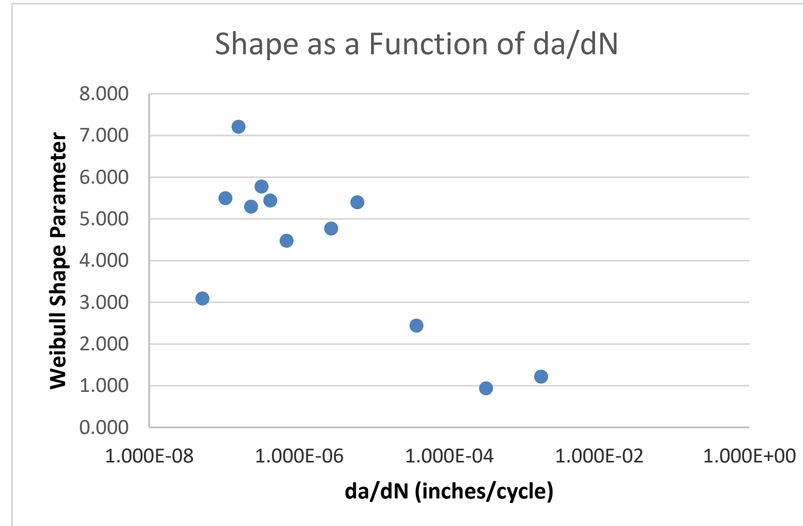
Observations

- **Scatter across the range of da/dN is not consistent**
  - A scatter factor of two for this data set has limited applicability
  - Only about 1-1.5 decades of data on the lower end of the da/dN range fit across all three stress ratios
- **Characterizing behavior based on fixed ranges of da/dN, therefore, is complicated by the inconsistent scatter observed**
- **Weibull shape parameter behavior between stress ratios for distributions of da/dN for fixed ΔK differs significantly**
  - R = 0.4 and 0.8 data tends to converge on very narrow distributions
  - $\Delta K_{Applied}$ and $\Delta K_{Effective}$ affect

Shape Parameter Summary (7050)

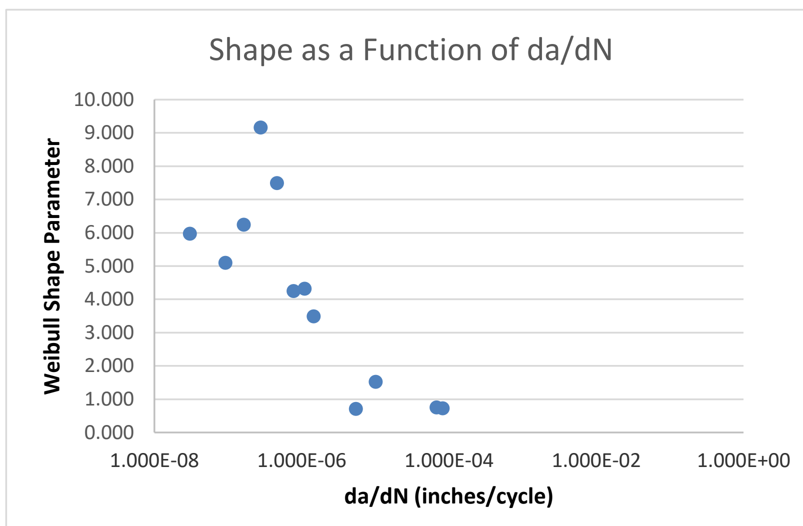


R = 0.1



R = 0.4

- **Does this suggest that at about 0.15 < R < 0.25 $\Delta K_{applied}$ approaches $\Delta K_{effective}$?**

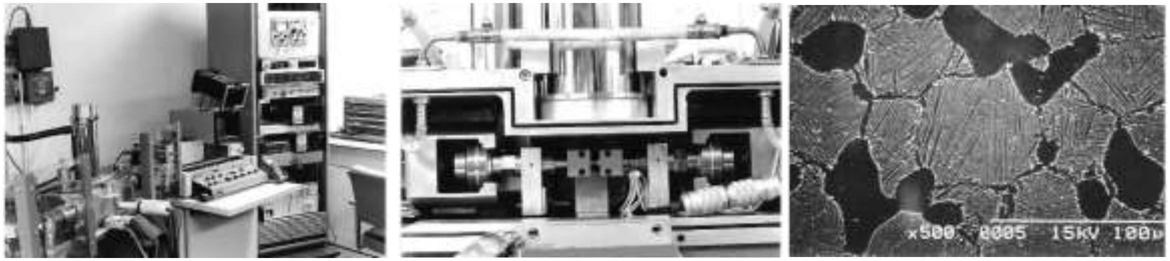


R = 0.8

- **Coincidence?**

Additional Observations (da/dN R = 0.1)

- **Upper bound da/dN distribution is potentially indicative of testing specimen and methods**
  - Net section yield
  - Instability
- **Lower bound (R = 0.1) da/dN distribution might indicate transition from “short crack” behavior**
  - Physically
  - Microstructurally



In-situ short crack growth test system circa 1990

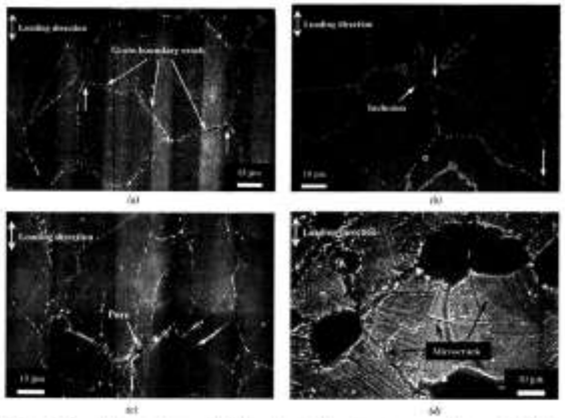
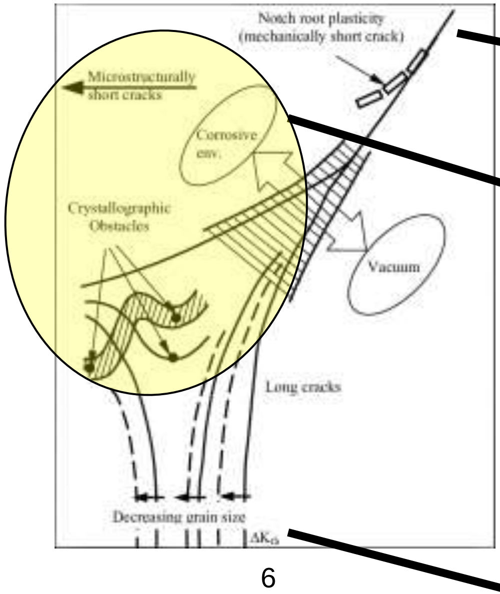


Figure 3.12 Fatigue microcracks that nucleated due to various mechanisms. (*a*) Elevated temperature (700°C) grain boundary crack in Waspaloy. (*b*) Surface inclusion/slip band crack in Waspaloy. (*c*) Elevated temperature (500°C) surface pore/slip band in Waspaloy. (*d*) Cracking within α and β phases in lamellar structure in titanium alloy IMI834 (courtesy of R. R. Stephens). 5

Transitioning from Short Crack Behavior?



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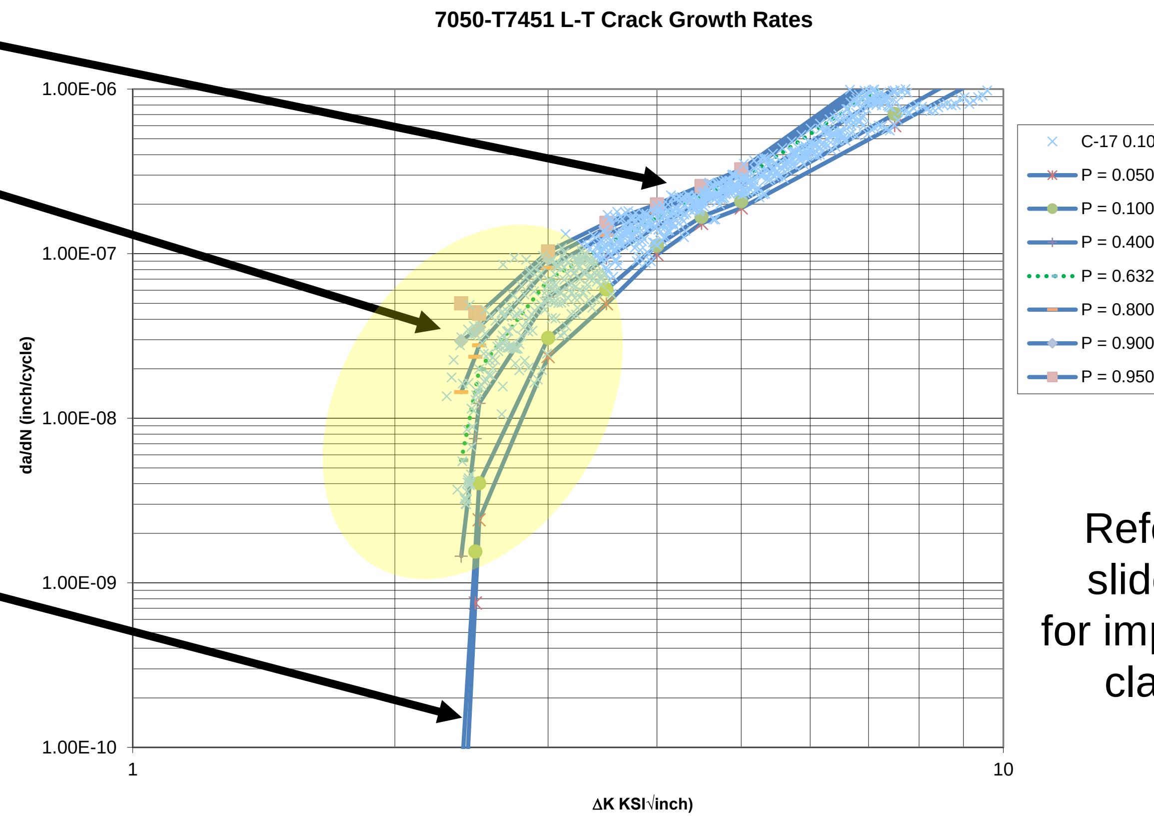


Refer to slide 17 for improved clarity

- **Iso-probabilities highlight potential transition from short crack, i.e. microstructural barriers, corrosion, etc. to long (through thickness) crack behavior**
- **Limited High R, short crack, data and observations**

Further Considerations

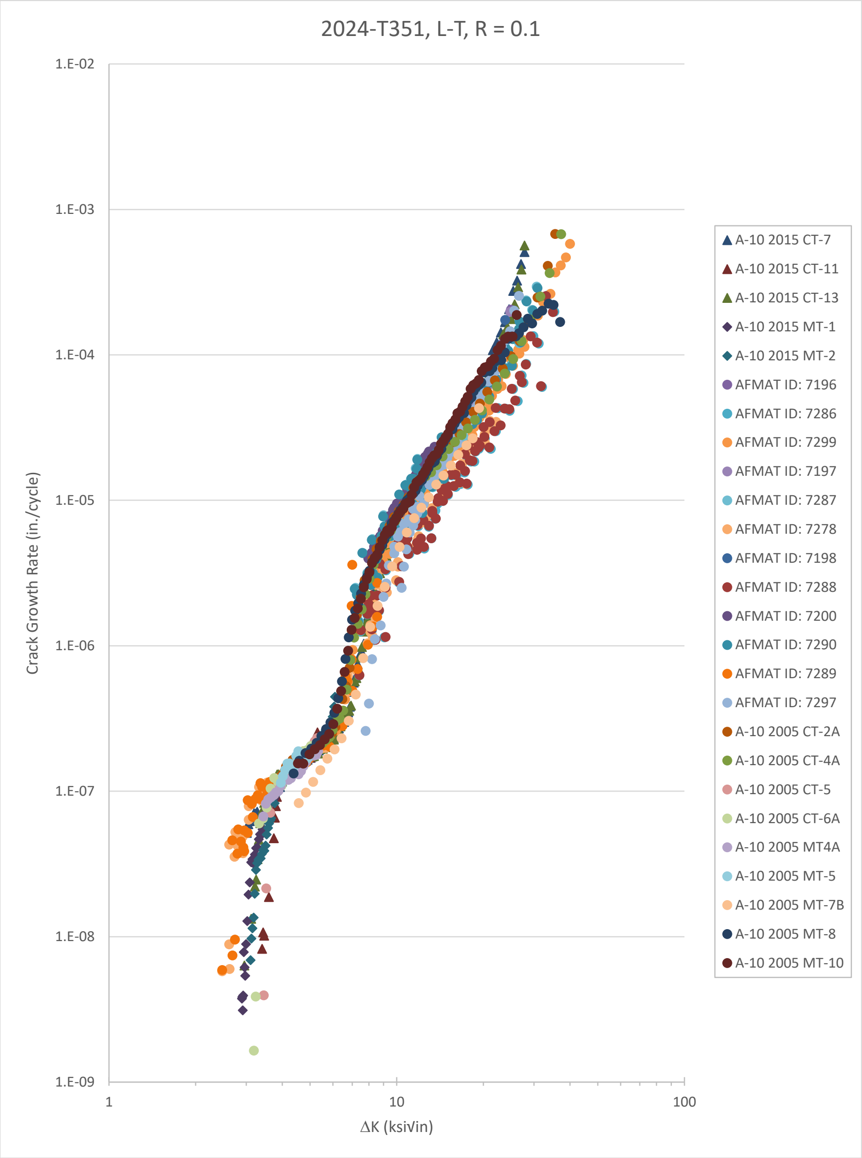
- **"Long Crack Threshold" for R = 0.1 is defined by the NASGRO equation as approximately ΔK = 3.1 ksi√in at 10^{-9} in/cycle (Slide 15) would be expected to occur less than about 1/100,000 times (for distributions of da/dN)**

- **Consistent loads accuracy, +/- 5%*, is recommended (?) as the basis for defining fixed ΔK range to determine distributions on da/dN**
  - *Established practice within aerospace fatigue analysis
  - For a fixed crack size, geometry, applied force, and stress ratio, we calculate ΔK and da/dN results
  - Should the tolerance be tighter? +/-2%, +/-1% (test instrumentation calibration ASTM E4 Force Calibration)?

Alternative Example

- **2024-T351 L-T**
  - What we know about this data set
    - Stress Ratio
    - Range of ΔK
    - Grain orientation
    - Data developed between 1975 and 2015
  - What we do not know
    - Specimen configuration
    - Product form thickness
    - Testing environment and frequency
    - Test Type (CA, K-Decreasing, etc.)
    - Test data supplier
    - Producer/lot variation

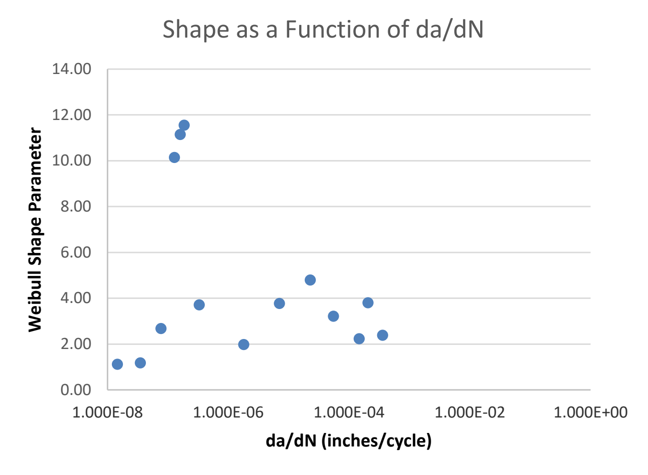
Generic Test Data Example



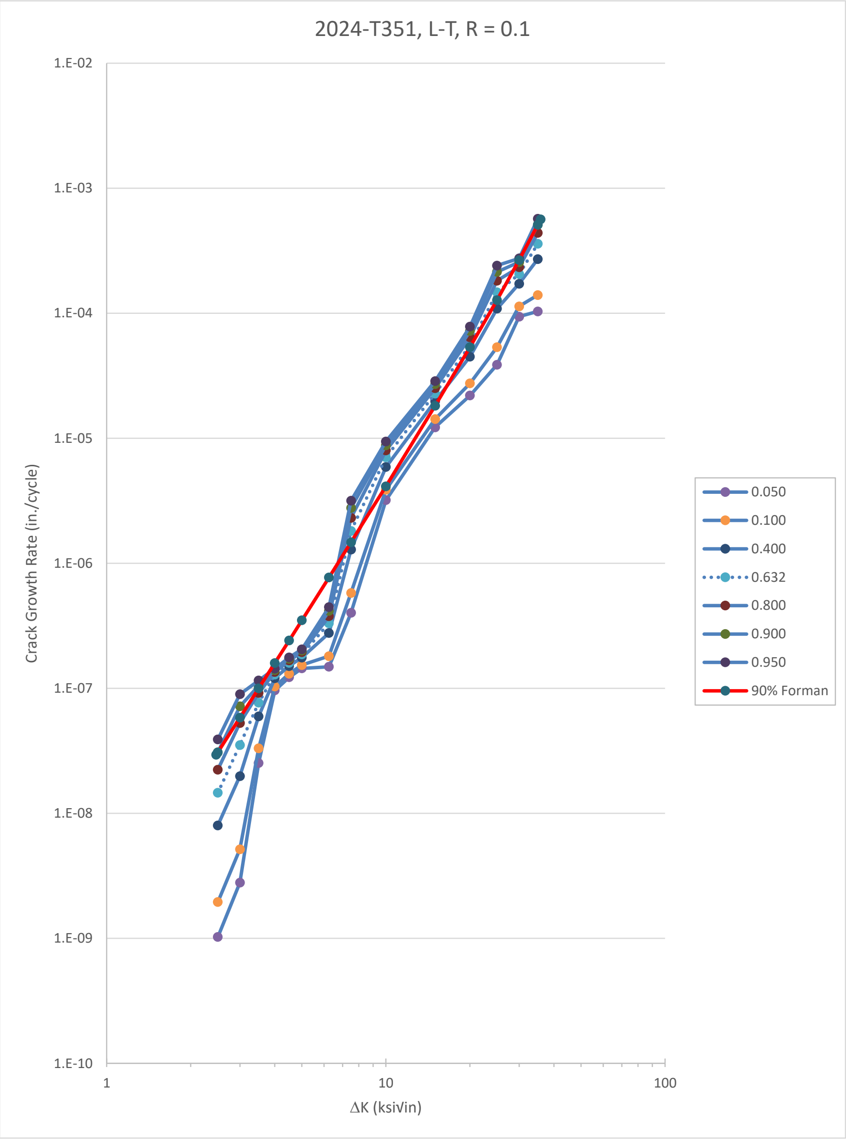
da/dN within Discrete Ranges of ΔK (R = 0.1)

- **Choose ranges of ΔK (+/-5%) to analyze from total population of data**
  - 1625 data pairs
  - 5% based on loads accuracy
- **Develop Maximum Likelihood Estimation (MLE) distribution parameters for da/dN within each chosen range of ΔK**
  - 749 data pairs across 14 ΔK ranges
  - Approximately 54 da/dN points/ΔK range
- **Resulting shape parameters as a function of da/dN**

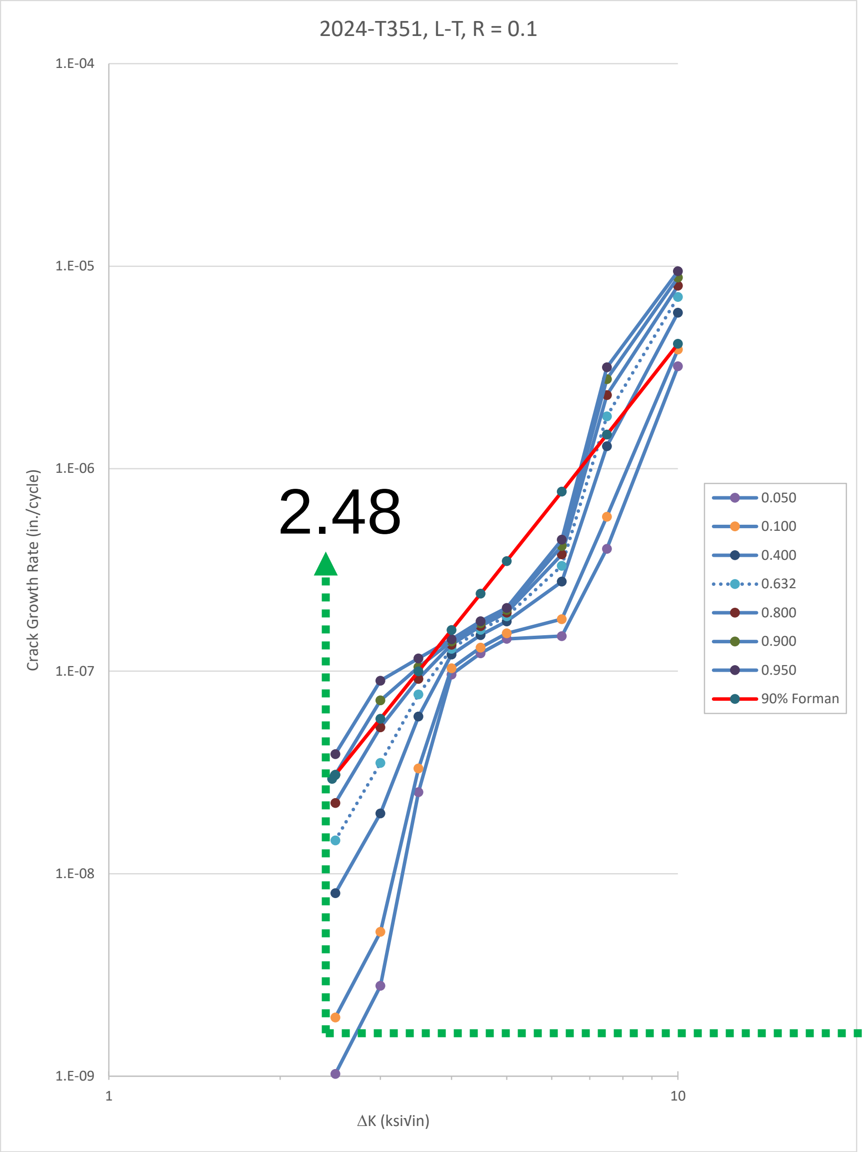
Weibull Parameters for da/dN at Fixed ΔK		Target for da/dN Distributions	
Shape	Scale	ΔK	Range
1.12	1.461E-08	2.50	2.375-2.625
1.17	3.521E-08	3.00	2.850-3.150
2.68	7.675E-08	3.50	3.325-3.675
10.14	1.290E-07	4.00	3.800-4.200
11.14	1.601E-07	4.50	4.275-4.725
11.54	1.868E-07	5.00	4.750-5.250
3.71	3.32E-07	6.25	5.938-6.563
1.97	1.815E-06	7.50	7.125-7.875
3.77	7.051E-06	10.00	9.500-10.500
4.79	2.277E-05	15.00	14.250-15.750
3.21	5.550E-05	20.00	19.000-21.000
2.23	1.472E-04	25.00	23.750-26.250
3.79	2.058E-04	30.00	28.500-31.500
2.38	3.600E-04	35.00	33.250-36.750



Constant Probability Curves (R = 0.1 da/dN)



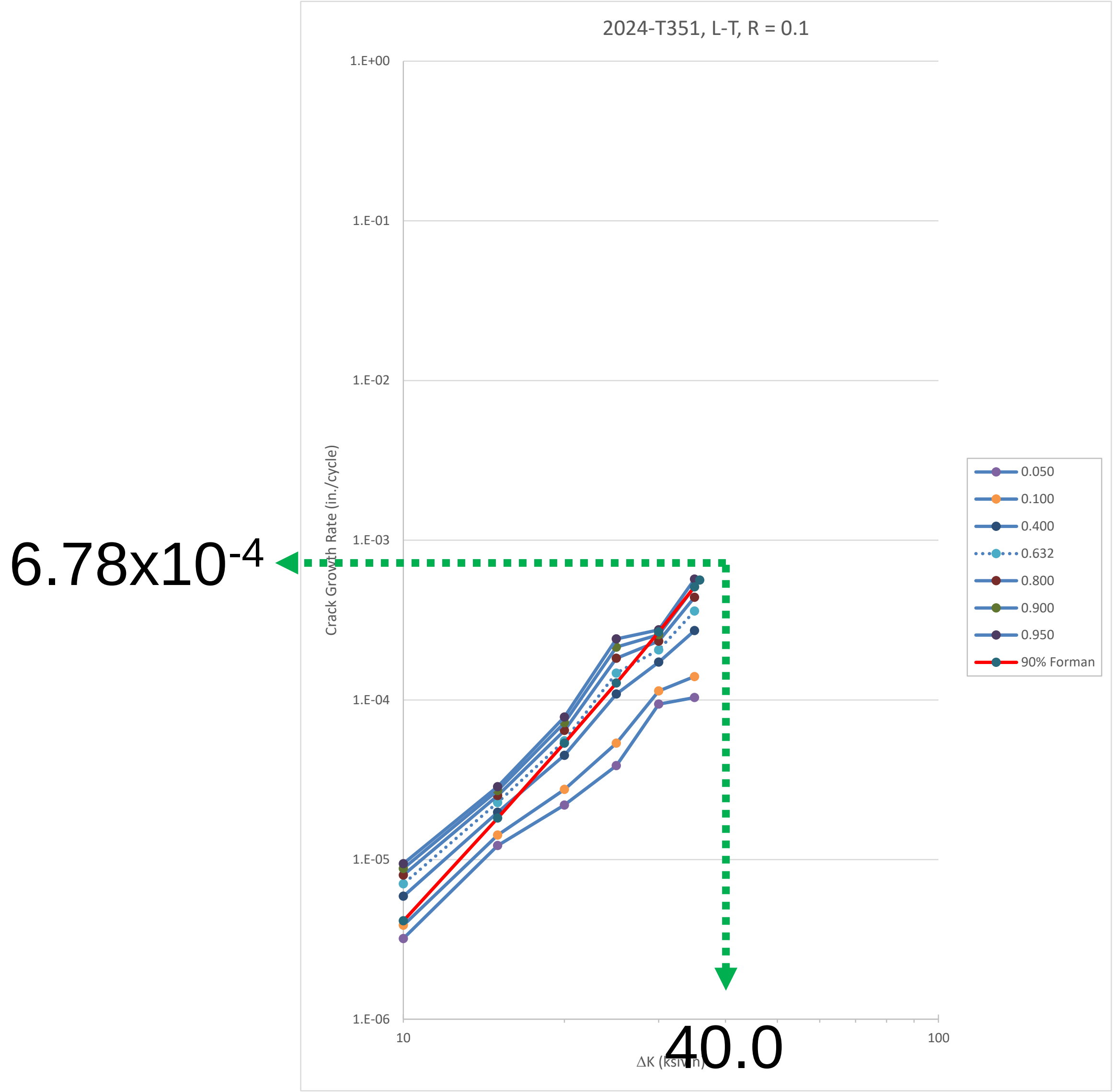
Constant Probability (Low ΔK R = 0.1)



Min da/dN and ΔK from data

$1.7\text{x}10^{-9}$

Constant Probability (High ΔK R = 0.1)



Max da/dN and ΔK from data

Concluding Remarks

- **Obtaining crack growth data and establishing a working 'confidence' in that data can be a tedious process**
- **Implementing consistency in how this data is further characterized for use in damage tolerance assessments is open to debate**
- **These examples highlighted the following**
  - da/dN scatter can vary widely across the range of ΔK
  - Statistical representations can provide insight into the applicability of established concepts and why challenges in predictions can occur
  - The behavior of the R = 0.1 data, specifically, at low ΔK values shares similarity to Short Crack behavior
    - Coincidence?

References and Related Bibliography

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