U.S. AIR FORCE

Lessons Learned: Stress Ratio Influence on *da/dN* when using the Generalized Willenborg Model

Chad King

T-38 Structural Integrity and Analysis Section

13 September 2016

Reference No. 75ABW-2016-0061

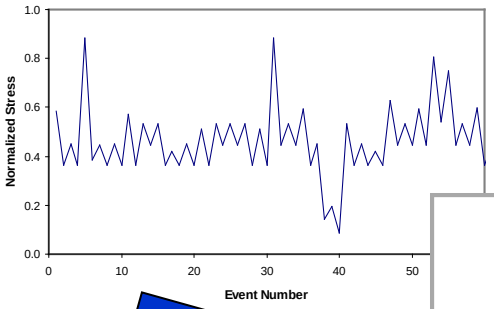
Outline

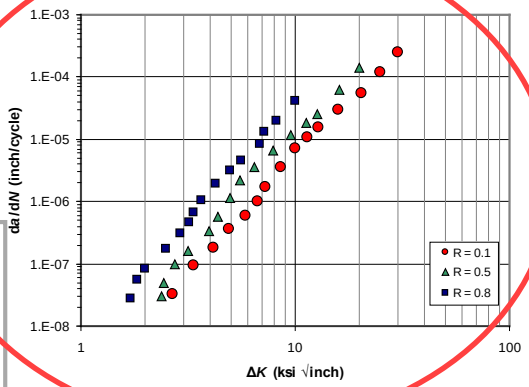
- Background
- Issue
- Initial Thoughts
- Generalized Willenborg Model
- R vs R_{eff}
- Summary

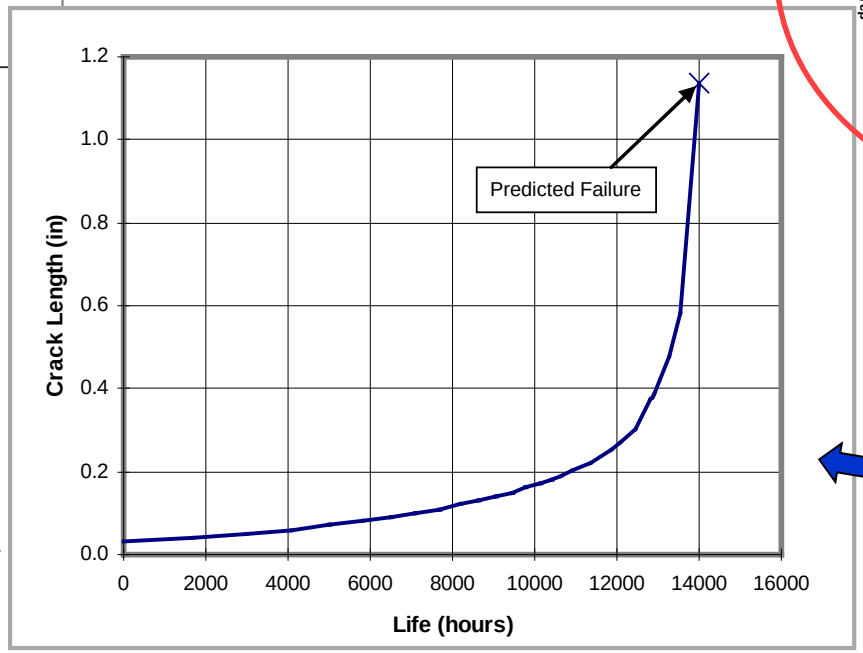
Background

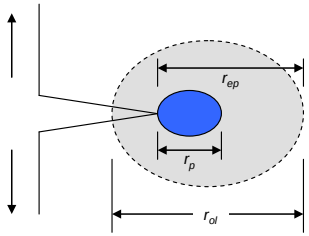
- **Damage Tolerance Analysis**

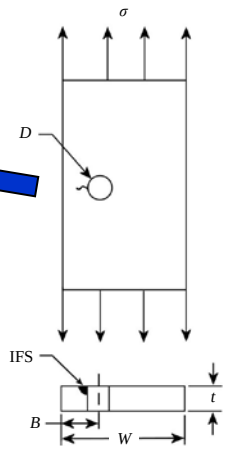
$$a_n = a_i + \sum_{j=1}^{n} da_j$$











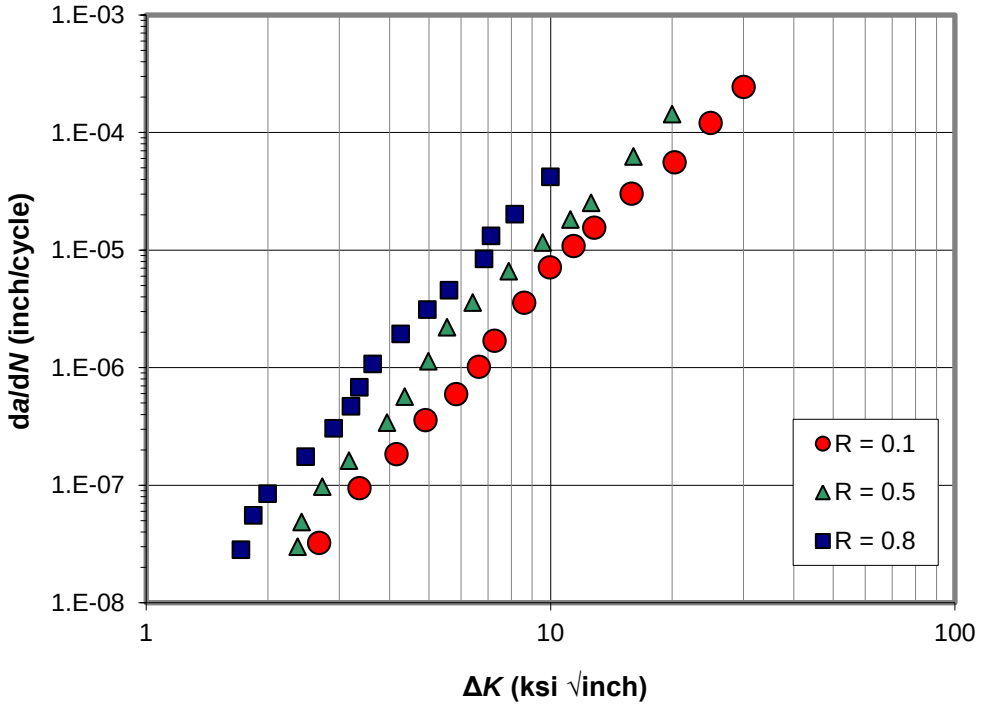
Background (cont.)

- **Fatigue Crack Growth Rate (aka *da/dN*)**
- ***da/dN = f(ΔK, R)***

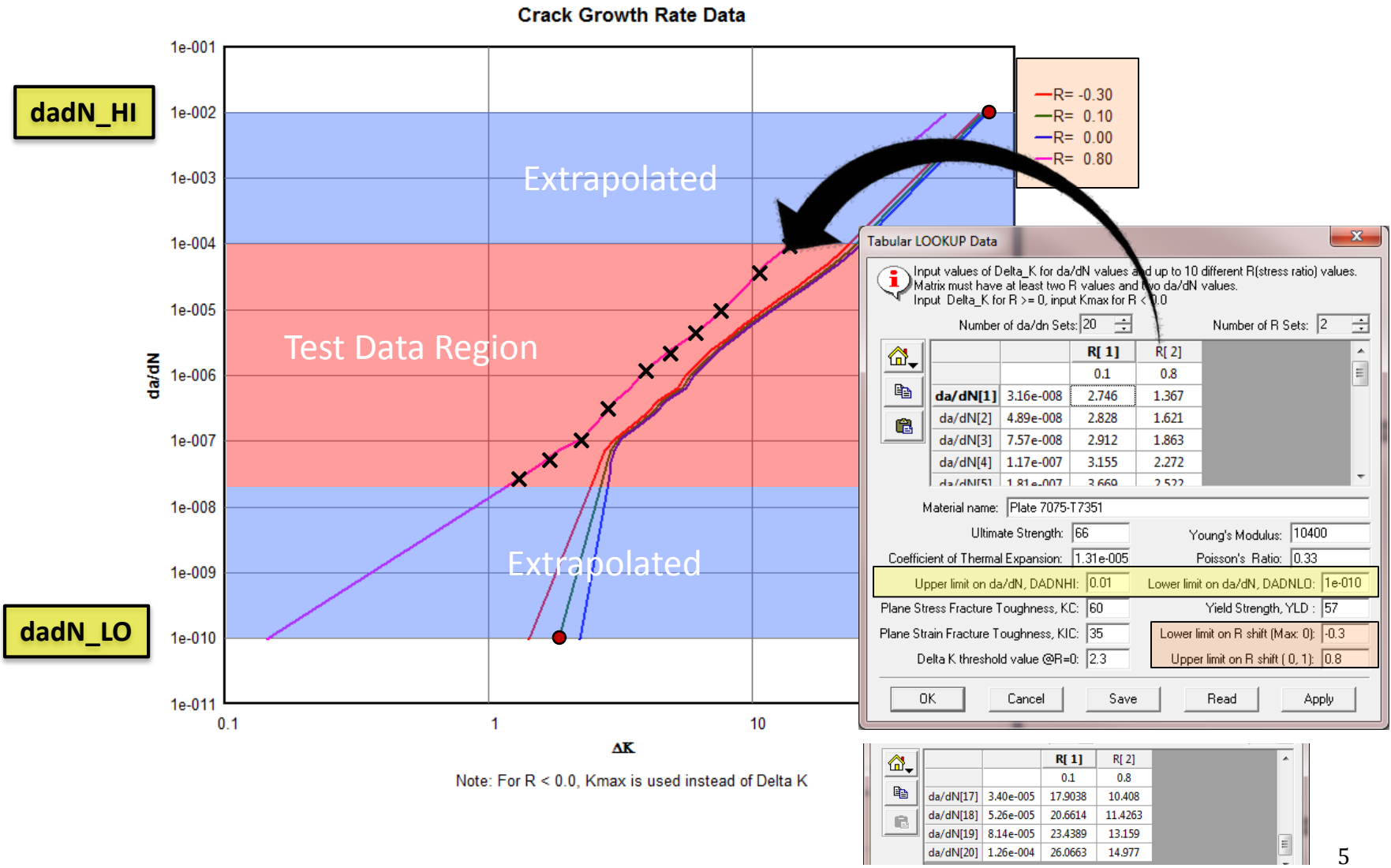
$$\Delta K = \Delta\sigma\sqrt{\pi a}\,\beta$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$



Background (cont.)

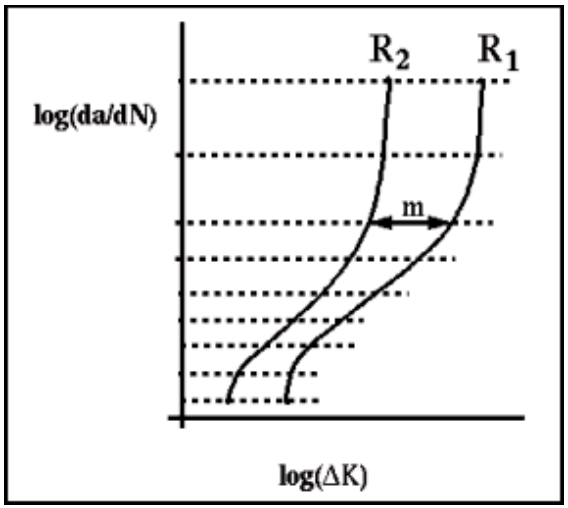


Background (cont.)

- **Harter-T Method**
  - **Shifts *da/dN* curves for any *R***
  - **Applies Walker Equation (point-by-point basis)**

For a given crack growth rate:

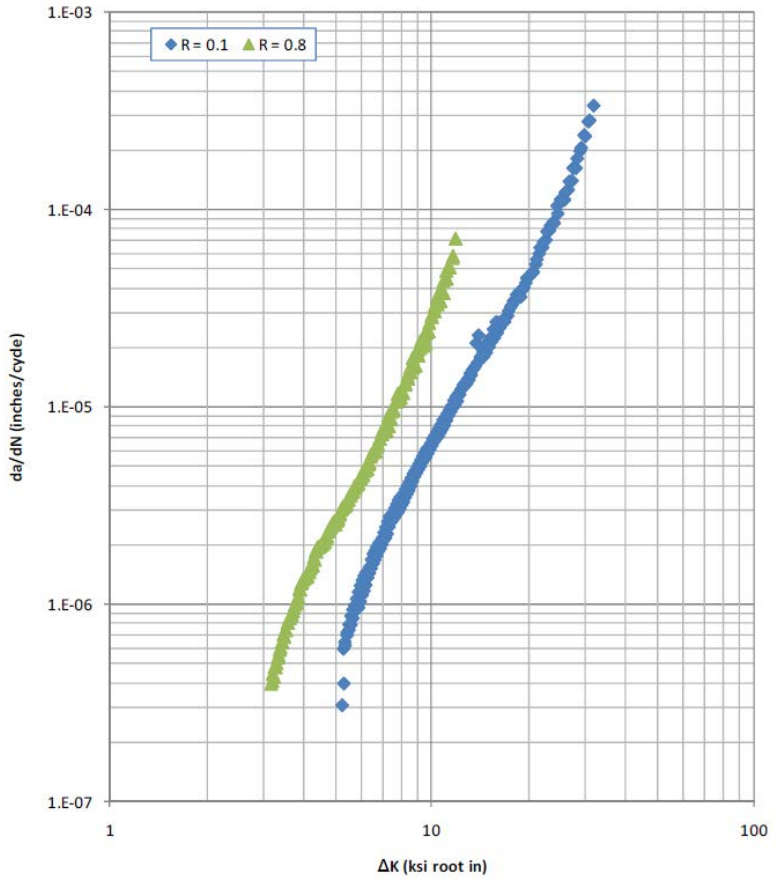
$$\Delta K_1 (1 - R_1)^{(m-1)} = \Delta K_2 (1 - R_2)^{(m-1)}$$ (When, R1 & R2 > 0)



(from AFGROW Advanced Training)

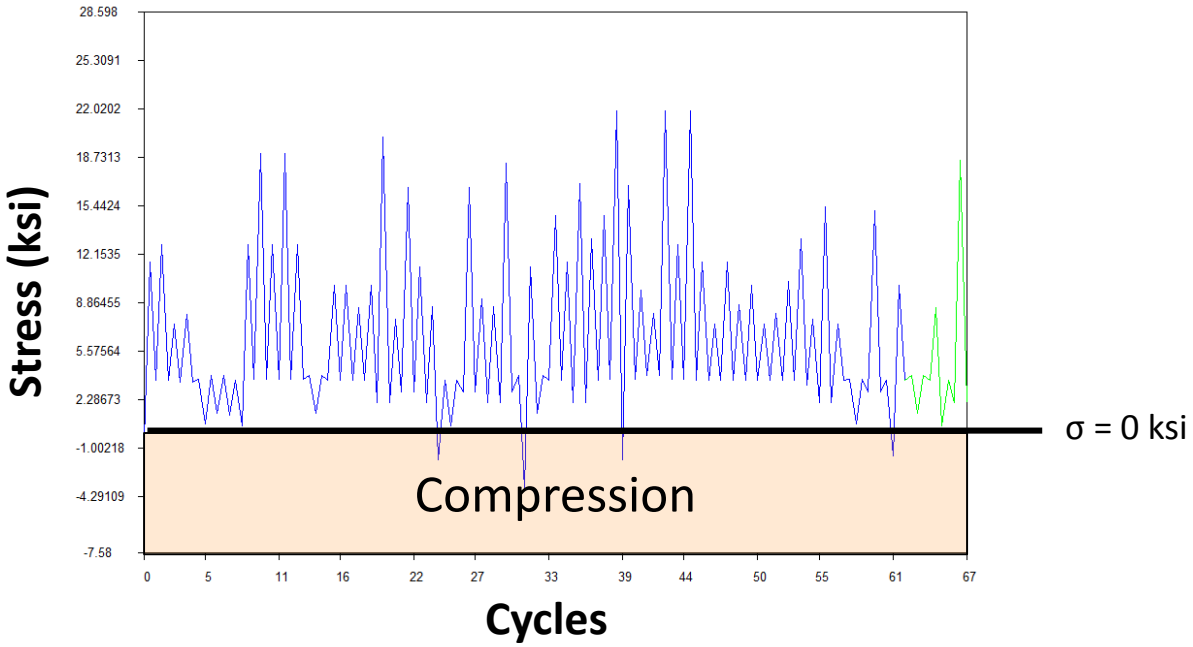
Issue

- **What stress ratios would be most beneficial for future *da/dN* testing of 7075-T7351?**

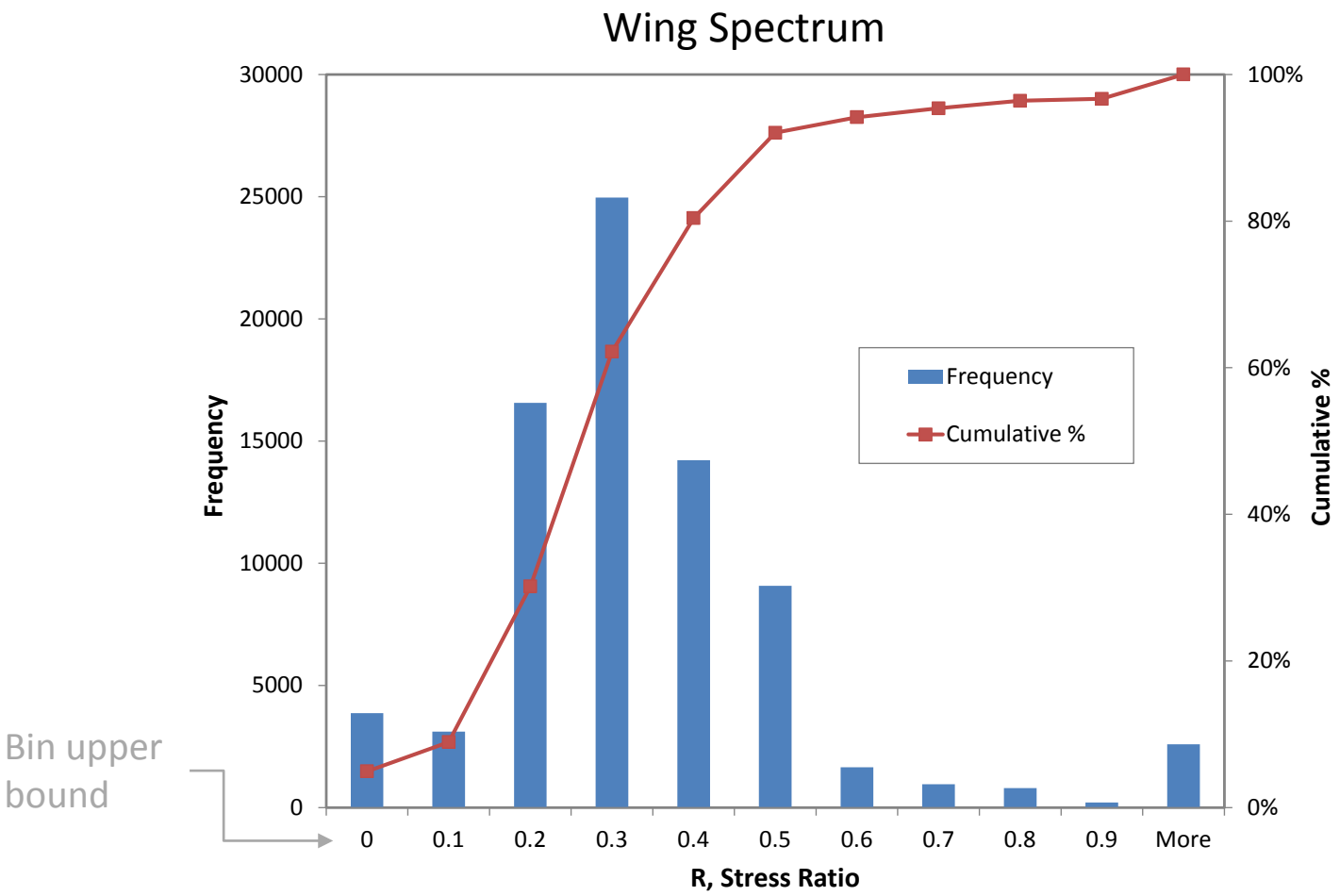


Initial Thoughts

- **Consider Current Data**
  - **Tested stress ratios**
    - ***R* = 0.1, 0.8 are most common; some *R* = 0.5**
  - **Wing stress spectra**



Stress Ratio (*R*) Histogram



When using the Generalized Willenborg Model, this is NOT the *R* that is used to determine *da/dN*

Generalized Willenborg Model

- **Adjusts *da/dN* by reducing *R* to R_{eff}**

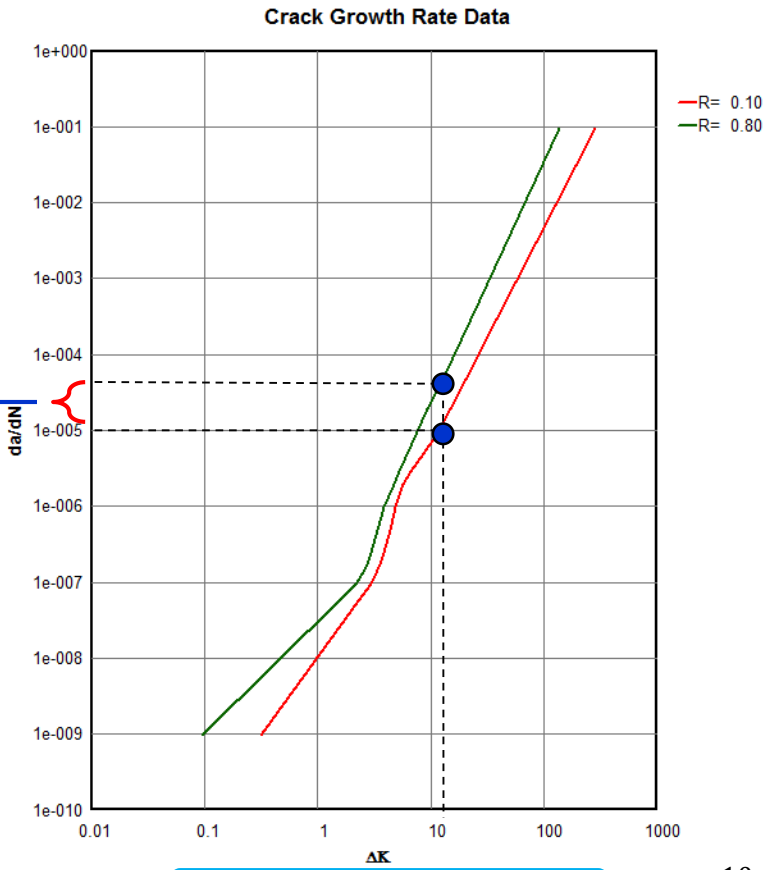
$$K_r = \frac{1-\frac{\Delta K_{th}}{K_{\max}}}{(SOLR-1)}\left[K_{OL}\sqrt{1-\frac{x-x_{OL}}{r_{OL}}}-K_{\max}\right]$$

$$K_{\min,eff} = K_{\min} - K_r$$

$$K_{\max,eff} = K_{\max} - K_r$$

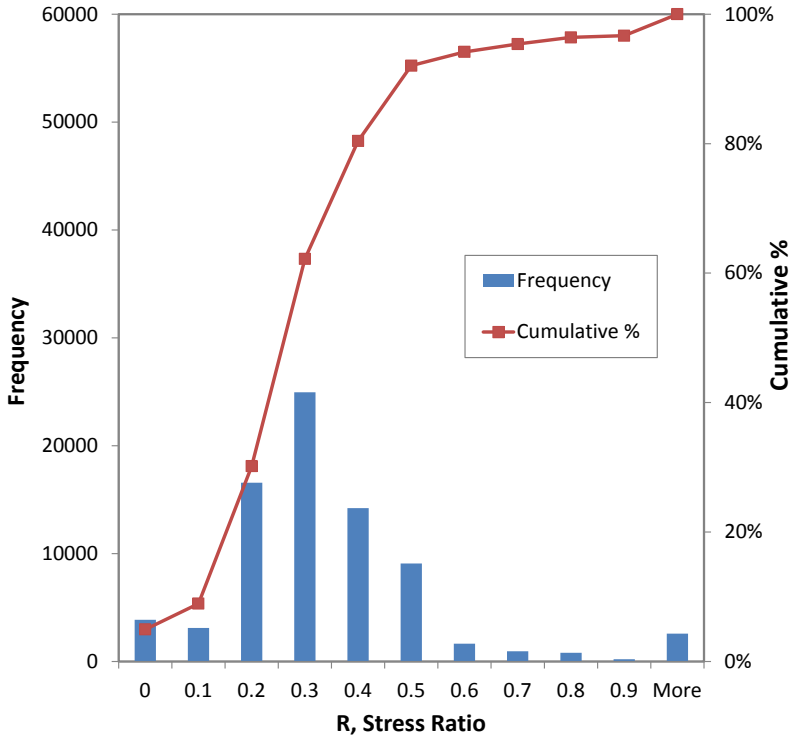
$$R_{eff} = \frac{K_{\min,eff}}{K_{\max,eff}}$$

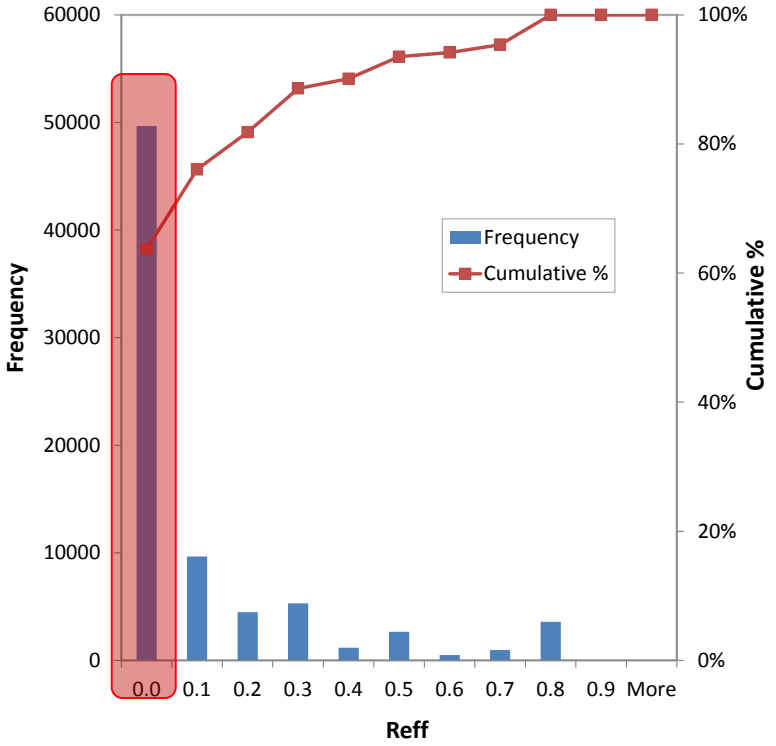
Retardation Effect:
Reduction in *da/dN*



R vs R_{eff}

Wing Spectrum





***R*, Stress Ratio**

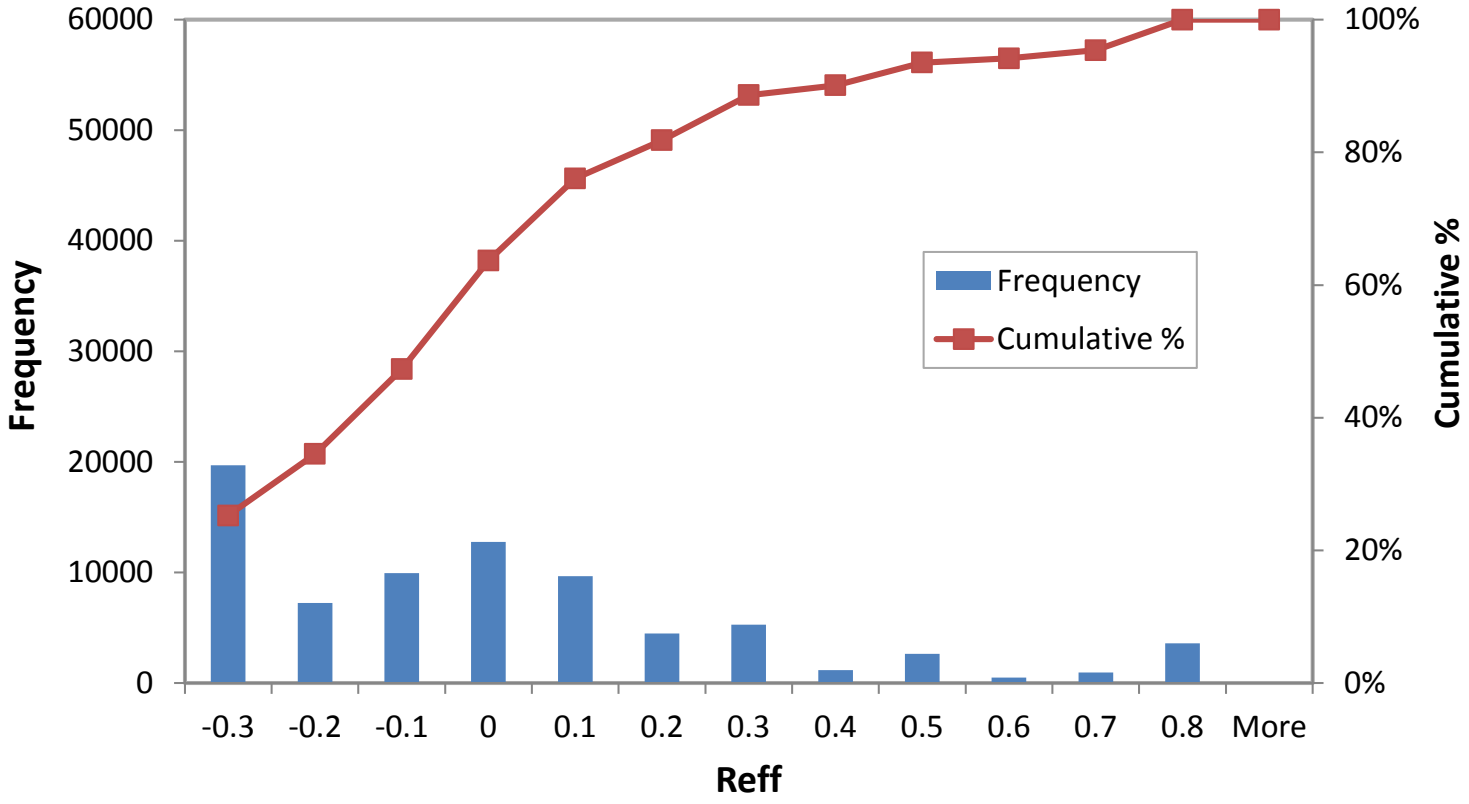
***R*$_{eff}$, Effective Stress Ratio**

1st 1000 hours

R_{eff}

1st 1000 hours

Wing Spectrum

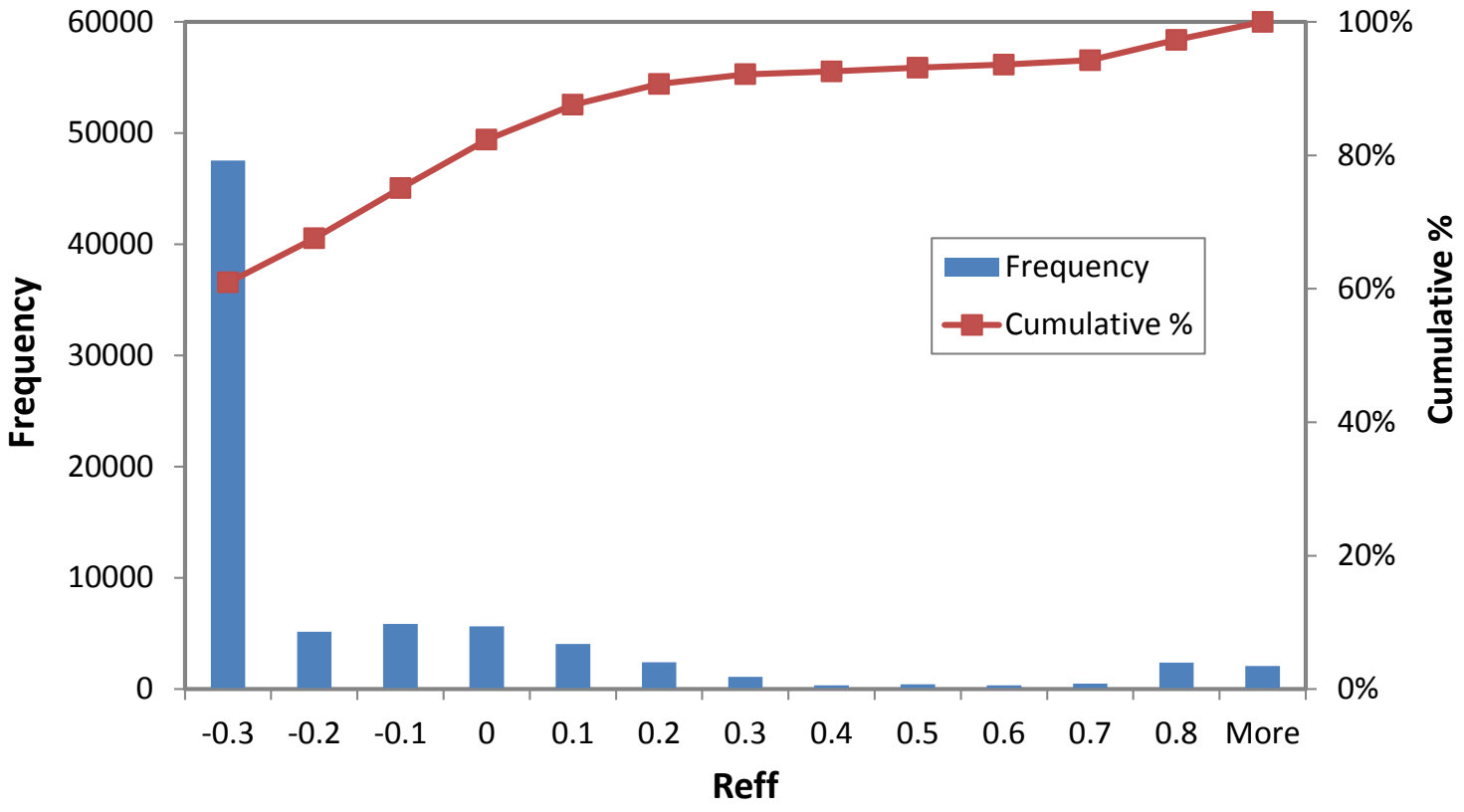


R_{eff}, Effective Stress Ratio

R_{eff}

2nd 1000 hours

Wing Spectrum

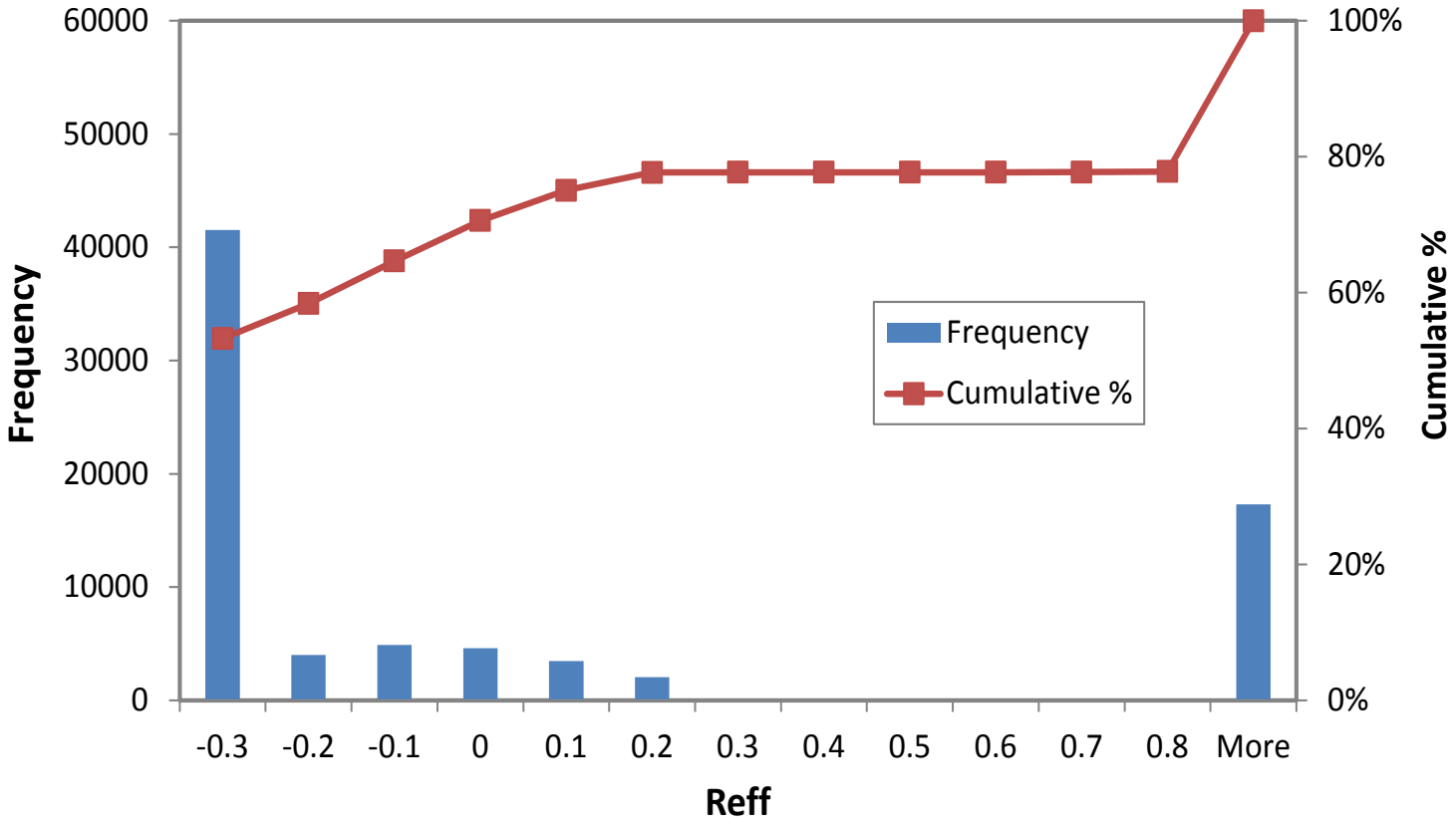


R_{eff}, Effective Stress Ratio

R_{eff}

3rd 1000 hours

Wing Spectrum



R_{eff}, Effective Stress Ratio

AFGROW .pl2

- $K_{min,eff}$ and $K_{max,eff}$ are negative
- $da/dN = 0$

$$R_{eff} = \frac{K_{\min,eff}}{K_{\max,eff}}$$

C Length	Cycles	Pass	DeltaK C	dC/DN	Max Stress	R(final) C	R
0.43085	233958	4	6.566	1.95E-06	12.22	-0.300	0.33
0.43085	233959	4	9.098	5.60E-06	13.39	-0.300	0.30
0.43086	233960	4	0.000	**0.00E+00**	7.93	**3.786**	0.49
0.43086	233961	4	0.000	**0.00E+00**	8.62	**10.175**	0.45
0.43086	233962	4	0.000	**0.00E+00**	4.14	**1.661**	0.25
0.43086	233963	4	0.000	**0.00E+00**	4.39	**1.559**	0.41
0.43086	233964	4	0.000	**0.00E+00**	4.39	**1.586**	0.38
0.43086	233965	4	0.000	**0.00E+00**	4.04	**1.680**	0.22
0.43086	233966	4	9.103	5.61E-06	13.39	-0.300	0.31

Additional FCLs Investigated

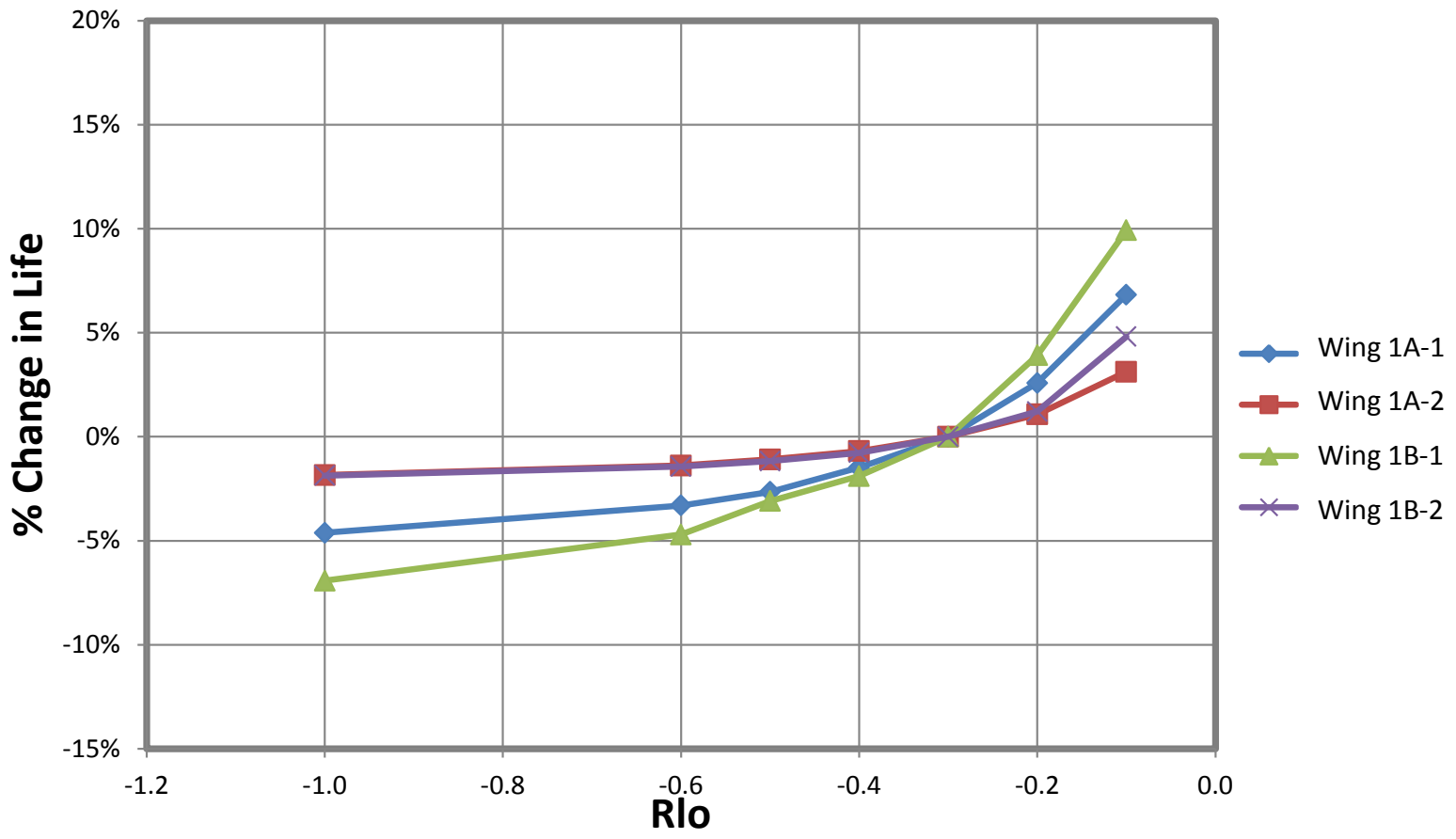
- Two Wing
- Two Fuselage
  - Aluminum and steel
- Multiple Usages
- Same Trends Seen
  - Significant shift in R vs R_{eff}
  - Continues to shift with subsequent passes

Question

- What percentage of the crack growth is due to cycles with $R_{eff} < 0$?

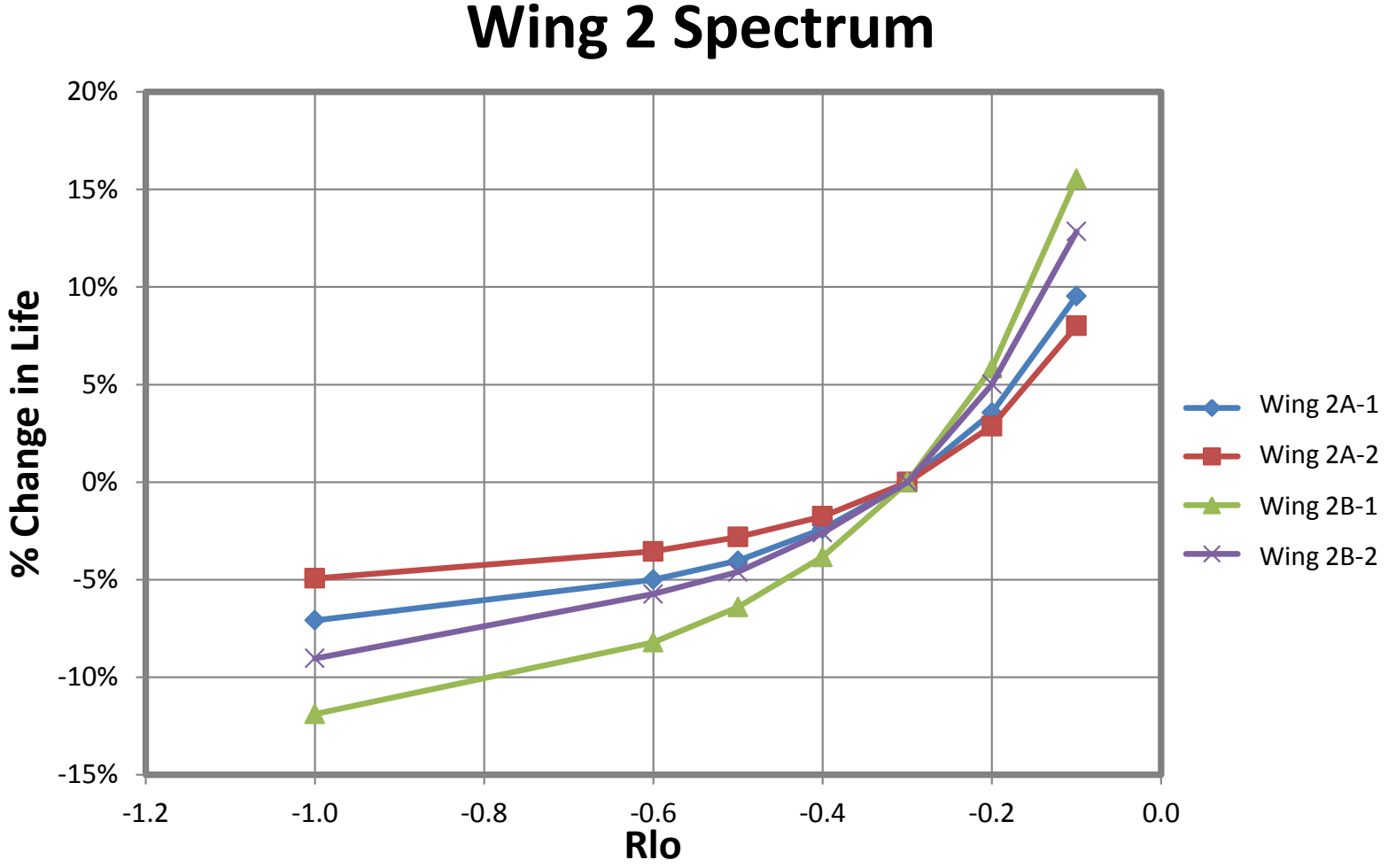
Location	Usage	% of Growth at $R_{eff} < 0$	% of Growth at $R_{eff} = -0.3$ (R_{LO})	Material
Wing 1A	1	55%	11%	7075-T7351
Wing 1A	2	61%	19%	7075-T7351
Wing 2A	1	66%	19%	7475-T7351
Wing 1B	1	56%	12%	7075-T7351
Fuselage 1	1	20%	5%	7075-T73511
Fuselage 2	1	22%	2%	4130
Fuselage 2	2	45%	9%	4130

R_{LO} Sensitivity

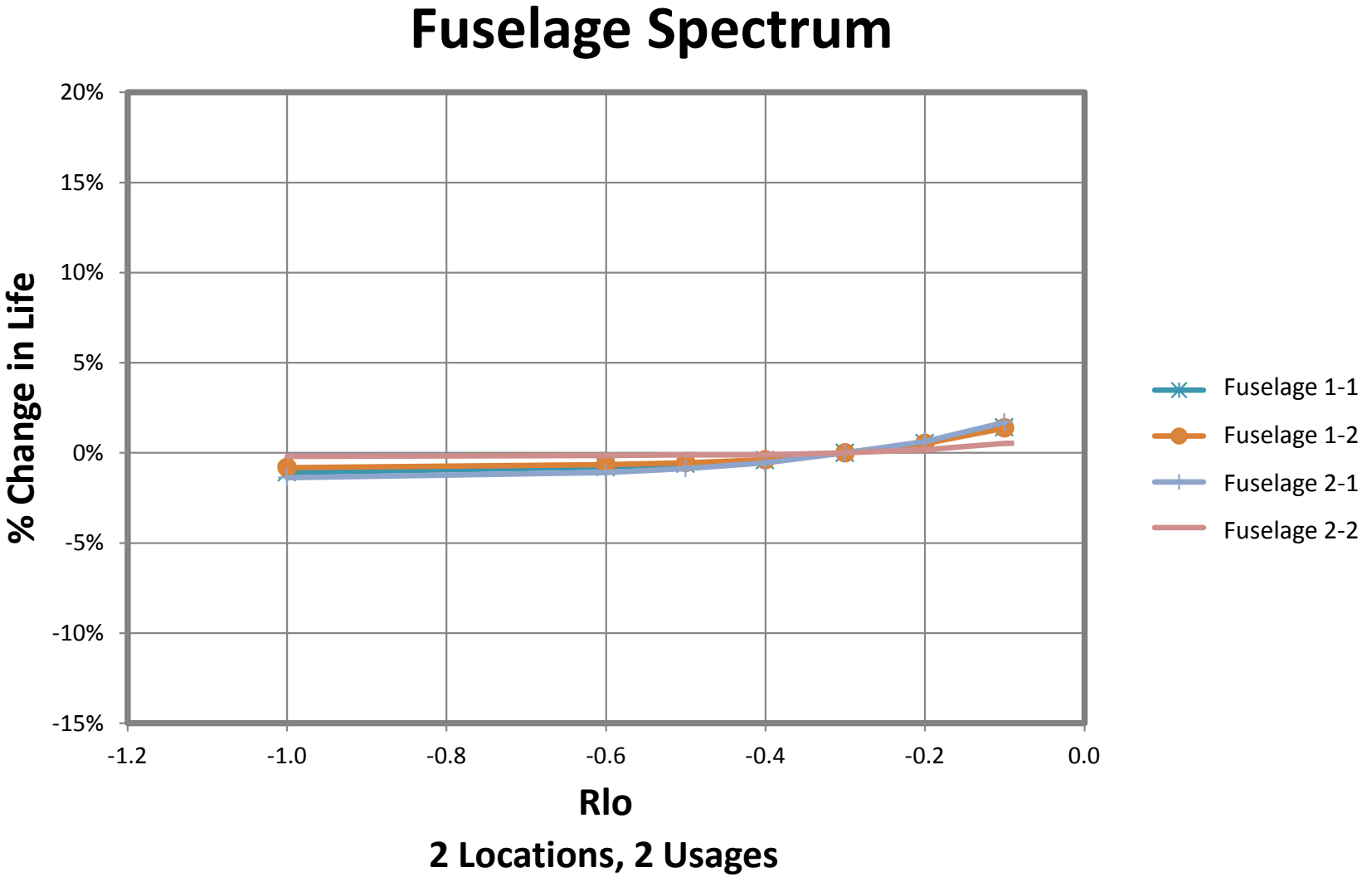


2 Locations, 2 Usages

R_{LO} Sensitivity



R_{LO} Sensitivity



Summary

- Test Program at $R < 0$
  - R = -1.0, -0.5, -0.3
  - Compare test data to extrapolation at $R < 0$
  - Determine R_{LO}
- Lessons Learned
  - Generalized Willenborg: think R_{eff}
  - *da/dN:* extrapolation vs interpolation

Questions?