

# ***Center for Aircraft Structural Life Extension***

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*Providing Structural Integrity Technology to the Aerospace Community*



## **Environmental Effects on Fatigue Crack Growth**

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# Acknowledgements

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- This research is funded by the OSD Corrosion Policy and Oversight Office, OuSD AT&(L) (FA7000-11-2-0011)
- Mr. Dan Dunmire, Director, OSD-CPO
- Mr. Rich Hays, Deputy Director, OSD-CPO
- Dr. Greg Shoales, Director, CASTLE, USAFA



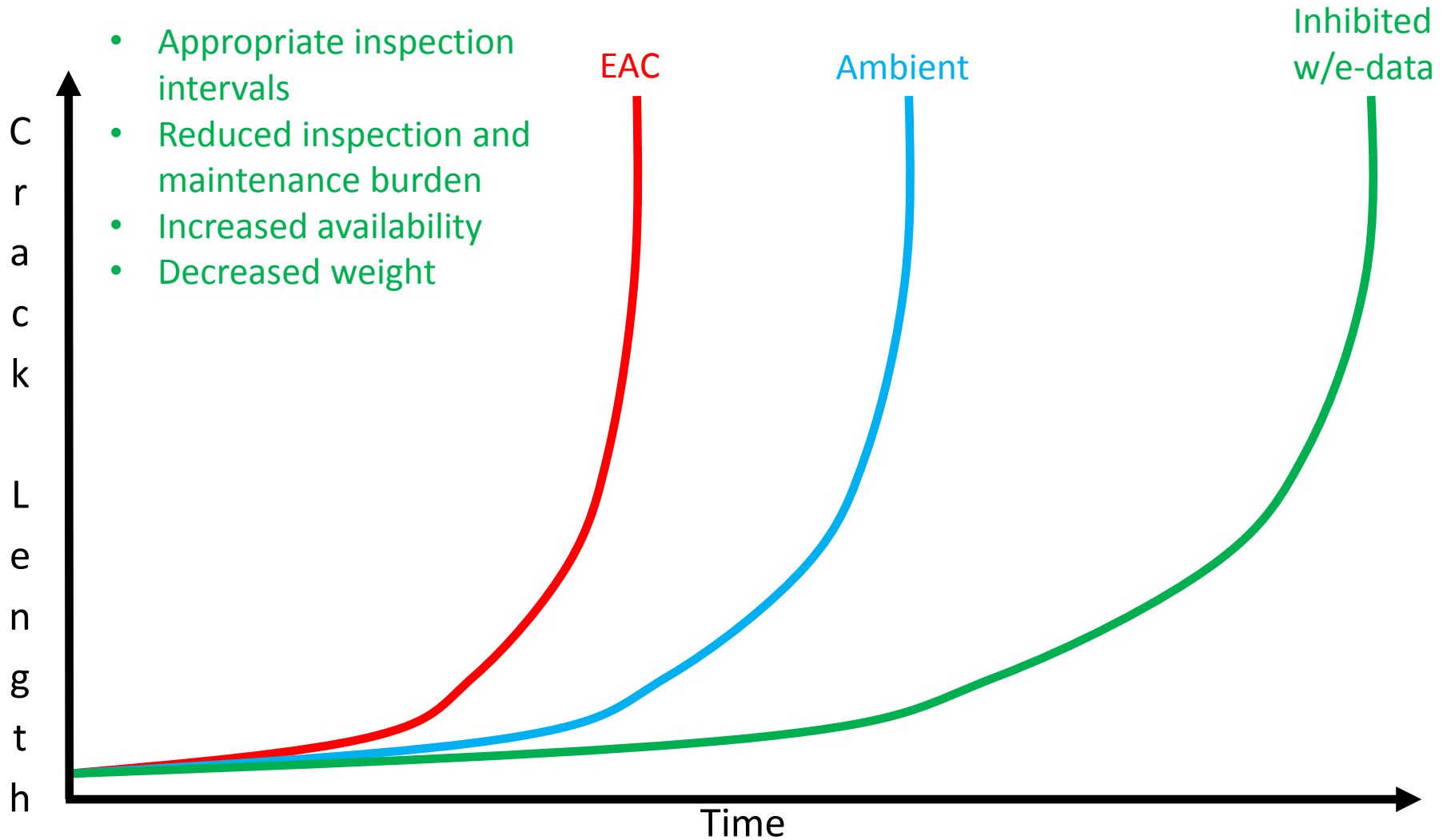
# Outline

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- Relevance
- Background
- Flight Environment
- Preliminary Results
- B707 Wing Detail Example
- Business Jet Wing Detail Example
- Next Steps



# Relevance





# Background

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- How does the environment affect crack growth
  - Develop a robust database of crack growth rate data as a function of exposure ( $P_{H2O}/f$ )
  - Understand the environmental fatigue process
- Can we slow the corrosion fatigue rate?
  - Standard test protocol for inhibitor evaluation
  - Effect of chromate on crack growth rate
  - Effect of ionic inhibitors on crack growth rate
  - Inhibitor leaching behavior
- Update life prediction software to
  - Use appropriate rate data for given mission segment
  - Track damage accumulation by segment
  - Include new stress intensity factor solutions



# Flight Environment



## Primary Loading

- Aggressive Maneuvers
- **≈30,000 ft = -44°C**
- $f = 0.005-0.2$  Hz
- *Aicher, 1976; Aronstein, 1997*



## Fuselage Loads

- Pressurization
- **8,000-50,000 ft -5 to -57°C**
- $f = 0.00003-0.001$  Hz
- *Hunt; Wanhill, 2001*

## Wing Loads

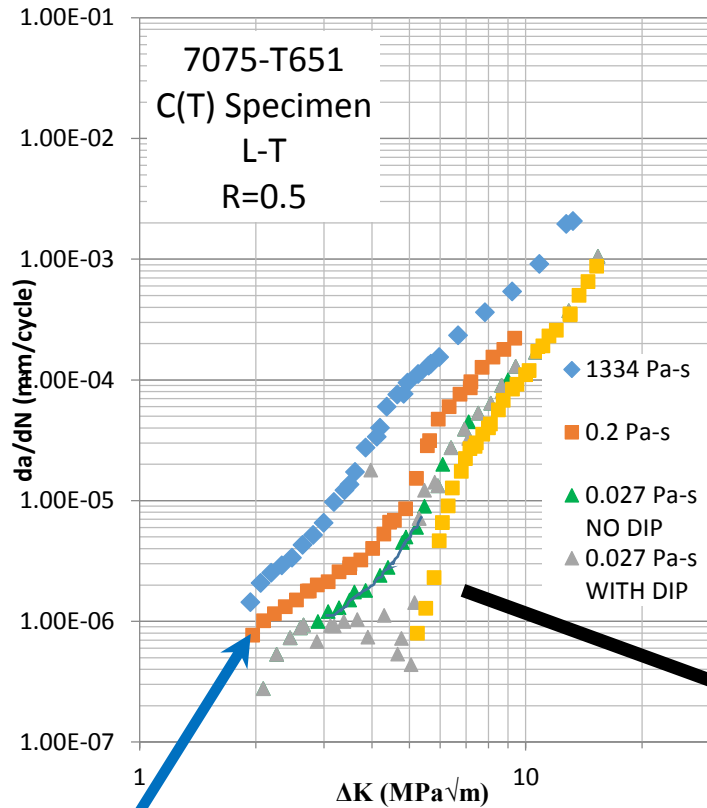
- Taxi/Take-off/Landing
- **Wind Gusts**
- **40% >10,000 ft; Thus < -5°C**
- $f = 0.1-10$  Hz
- *Jorge, 1979*

## Aerodynamic Loads

- Fuselage/Control Surfaces
- **0-50,000ft; Thus 0-60°C**
- $f = 0.0003-30$  Hz



# Preliminary LEFM Modeling Results

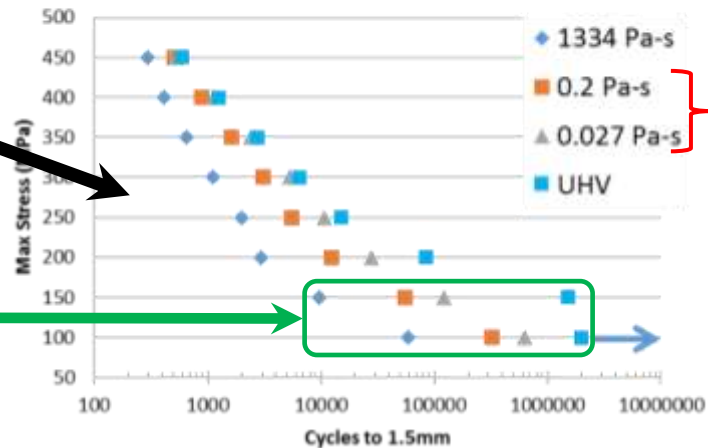


- Modeling Requirements
  - Environmental FCGR data
  - Defined environment by mission segment (taxi, takeoff, climb, cruise, descent, flaps, landing, etc.)
  - Known/assumed cycle frequency
- Software that can accept the above

## AFGROW

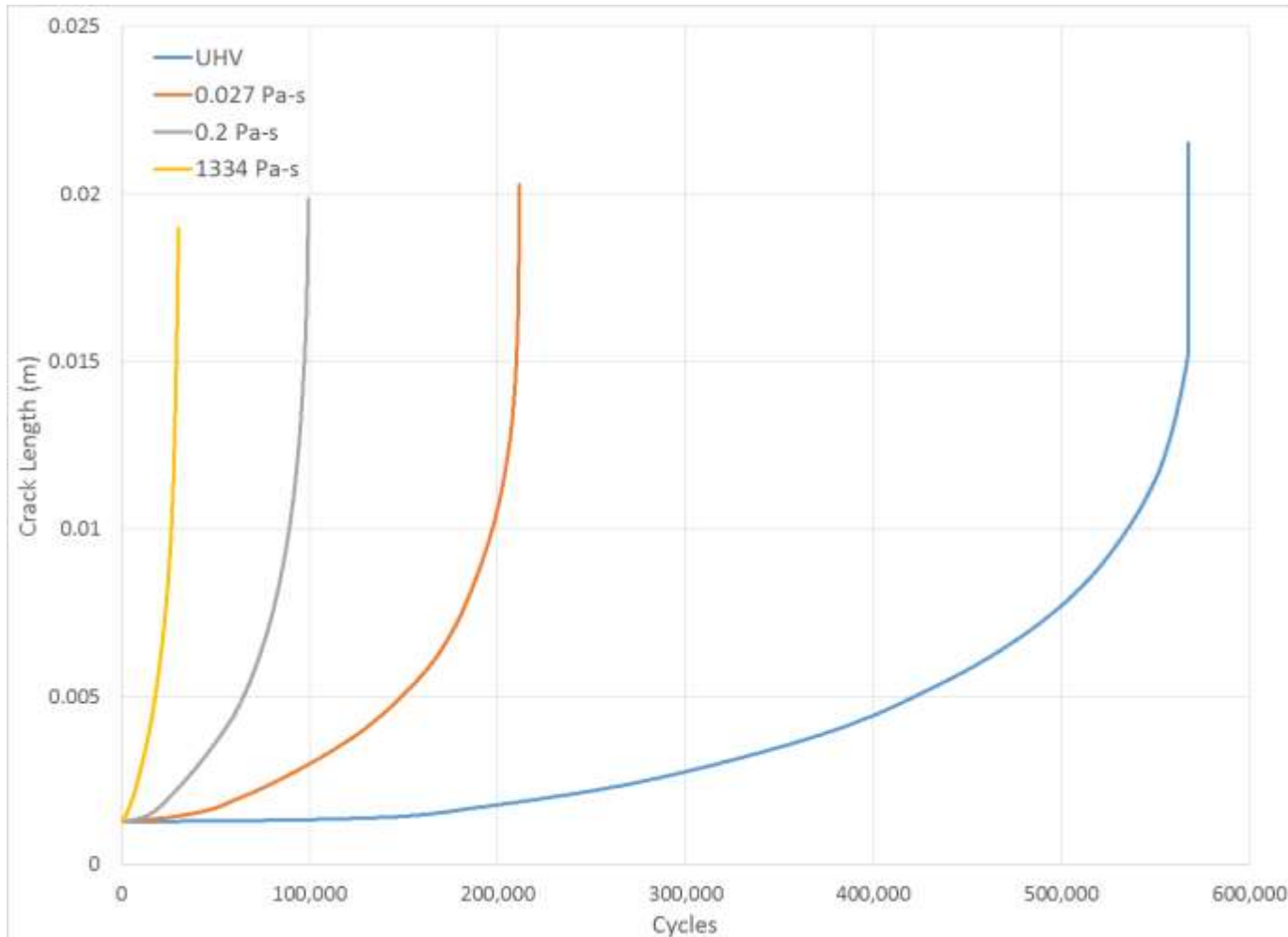
### AFGROW Predictions

Single Corner Crack at Hole  
R=0.5; a=250μm, c=250μm





# Crack Growth as a Function of Exposure

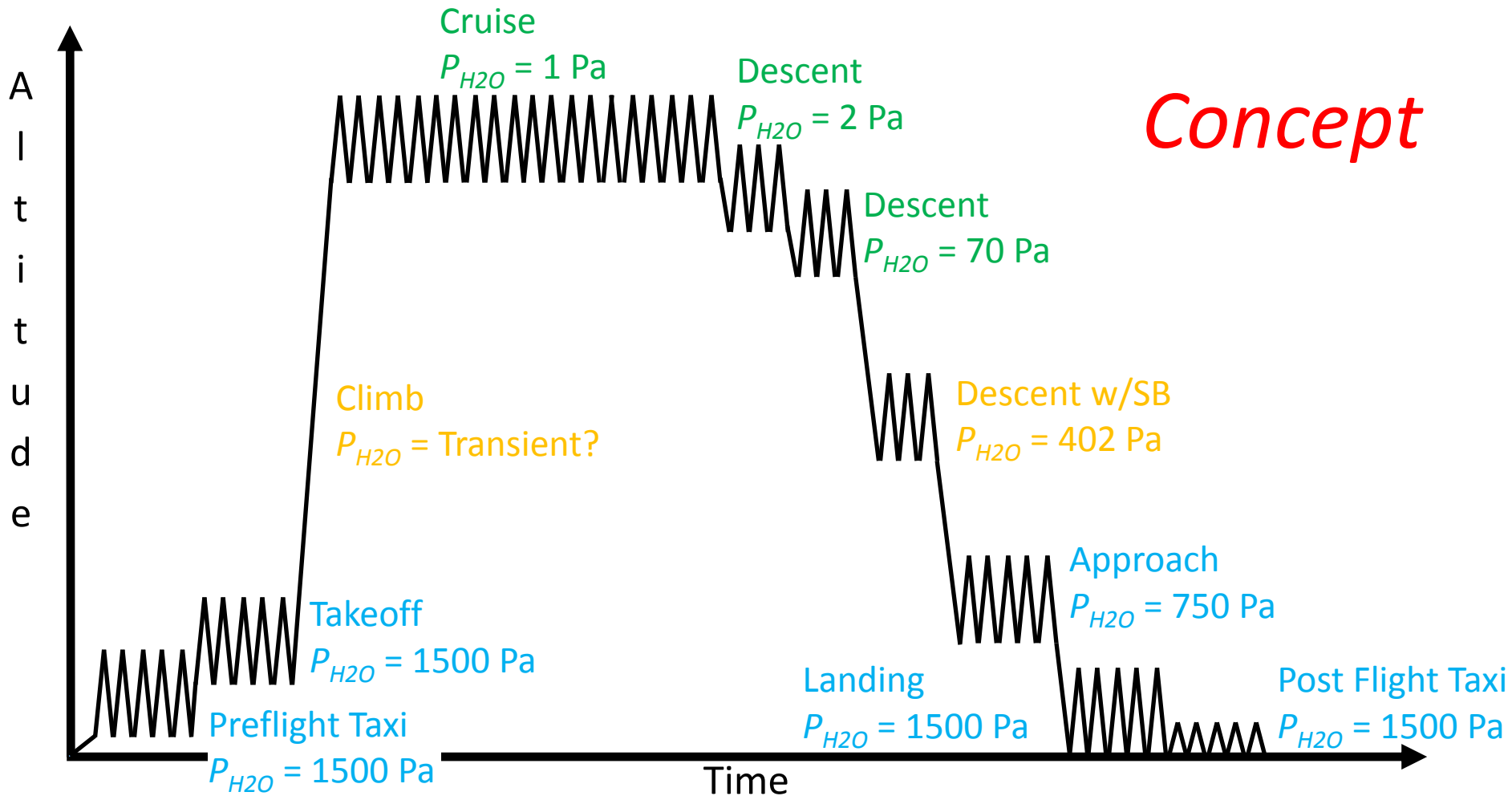


*Significant effect on fatigue life and inspection intervals*





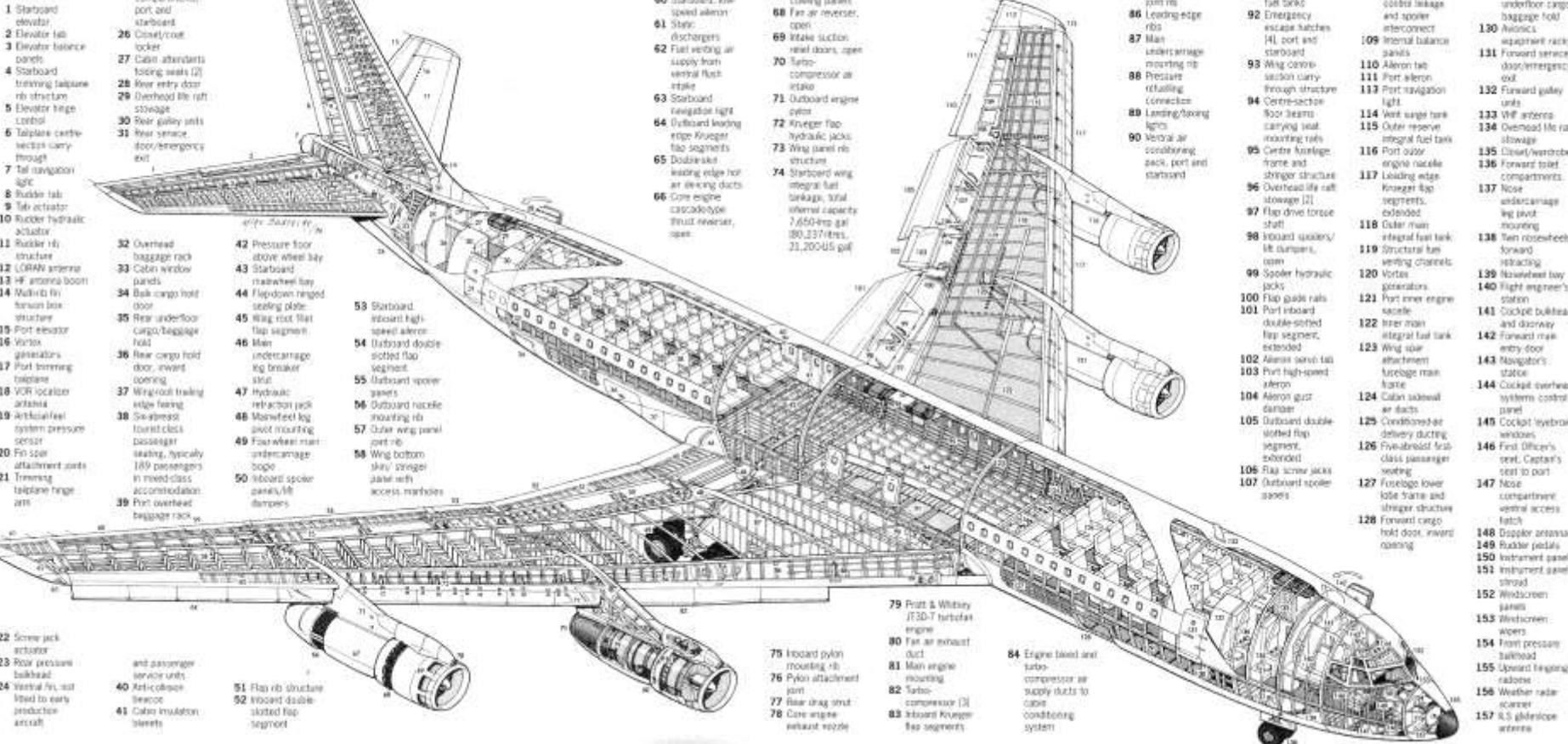
# Crack Growth Rate Data by Mission Segment





# Boeing 707 WS360 Example

**Boeing 707-320C**



- 1 Starboard elevator
- 2 Elevator tab
- 3 Elevator balance ponds
- 4 Starboard trailing tailplane rib structure
- 5 Elevator hinge control
- 6 Tailplane carburetors carry through
- 7 Tail navigation light
- 8 Rudder tab
- 9 Tab actuator
- 10 Rudder hydraulic actuator
- 11 Rudder rib structure
- 12 COMBAT antenna
- 13 HF antenna boom
- 14 Multi-rib fin fuselage box structure
- 15 Port elevator
- 16 Vortex generators
- 17 Port trimmer tabline
- 18 VOR locator antenna
- 19 Artificial feel system pressure sensor
- 20 Fin spar attachment joints
- 21 Trimming tailplane hinge arm
- 22 Screw jack actuator
- 23 Rear pressure bulkhead
- 24 Ventral fin, tied in to early production aircraft
- 25 Rear toilet compartments, port and starboard
- 26 Closet/trunk locker
- 27 Cabin attendant locking seats (2)
- 28 Rear entry door
- 29 Overhead life raft storage
- 30 Rear galley seats
- 31 Rear service door/emergency exit
- 32 Overhead baggage rack
- 33 Cabin window panels
- 34 Bulk cargo hold door
- 35 Rear underfloor cargo/baggage hold
- 36 Rear cargo hold door, inward opening
- 37 Wingroot trailing edge fairing
- 38 Six-armed forward class passenger seating, typically 189 passengers in mixed class accommodation
- 39 Port overhead baggage rack
- 40 Anti-collision beacon
- 41 Cabin insulation blanket
- 42 Pressure floor above wheel bay
- 43 Starboard mainwheel bay
- 44 Flipdown raged sealing plate
- 45 Wing root flat flap segment
- 46 Main undercarriage leg breaker strut
- 47 Hydraulic retraction jack
- 48 Mainwheel leg pivot mounting
- 49 Four wheel main undercarriage bogie
- 50 Inboard spool panels/fit dampers
- 51 Flap rib structure
- 52 Inboard double-skinned flap segment
- 53 Starboard inboard high-speed aileron
- 54 Outboard double-skinned flap segment
- 55 Outboard spool panel
- 56 Outboard nacelle mounting rib
- 57 Outer wing panel port rib
- 58 Wing bottom skin/ stringer access markholes
- 59 Aileron tab
- 60 Starboard, low-speed aileron
- 61 Static
- 62 Fuel venting air supply from ventral flush intake
- 63 Starboard navigation light
- 64 Outboard leading edge Krueger flap segments
- 65 Double-skinned leading edge hot air bleeding ducts
- 66 Core engine crocodile-type thrust reverser, open
- 67 Hinged engine cooling damper
- 68 Fan air reverser, open
- 69 Intake suction relief doors, open
- 70 Turbo-compressor air intake
- 71 Outboard engine cover
- 72 Krueger flap hydraulic jacks
- 73 Wing panel rib structure
- 74 Starboard wing integral fuel tankage, total internal capacity 7,650-imp gal (80,237 litres, 21,200 US gal)
- 75 Inboard pylon mounting rib
- 76 Pylon attachment joint
- 77 Rear drag strut
- 78 Core engine exhaust nozzle
- 79 Pratt & Whitney JT3D-7 turbofan engine
- 80 Fan air exhaust duct
- 81 Main engine mounting
- 82 Turbo-compressor (3)
- 83 Inboard Krueger flap segments
- 84 Engine bleed and turbo-compressor air supply ducts to cabin conditioning system
- 85 Inner wing panel port rib
- 86 Leading edge ribs
- 87 Main undercarriage mounting rib
- 88 Pressure refuelling connectors
- 89 Landing/dooring lights
- 90 Ventral air conditioning pack, port and starboard
- 91 Centre-section fuel tank
- 92 Emergency escape hatches (4), port and starboard
- 93 Wing control surface carry-through structure
- 94 Centre-section floor beams carrying seat mounting rails
- 95 Centre fuselage frame and stringer structure
- 96 Overhead life raft storage (2)
- 97 Flap drive torque shaft
- 98 Inboard spoilers/fit dampers, open
- 99 Spoiler hydraulic jacks
- 100 Flap guide rails
- 101 Port inboard double-skinned flap segment, extended
- 102 Aileron servo tab
- 103 Port high-speed aileron
- 104 Aileron gust damper
- 105 Outboard double-skinned flap segment, extended
- 106 Flap screw jacks
- 107 Outboard spool panels
- 108 Aileron hinge control linkage and spooler interconnect
- 109 Internal balance panels
- 110 Aileron tab
- 111 Port aileron
- 112 Port navigation light
- 114 Wing surge tank
- 115 Outer reserve integral fuel tank
- 116 Port outer engine nacelle
- 117 Leading edge Krueger flap segments, extended
- 118 Outer main integral fuel tank
- 119 Structural fan venting channels
- 120 Whistler generators
- 121 Port outer engine nacelle
- 122 Inner main integral fuel tank
- 123 Wing spar attachment fuselage main frame
- 124 Cabin sidewall air ducts
- 125 Conditioned-air delivery ducting
- 126 Five-abroad first class passenger seating
- 127 Fuselage lower lobe frame and stringer structure
- 128 Forward cargo hold door, inward opening
- 129 Forward underfloor cargo/baggage hold
- 130 Whistler nacelle squawbar racks
- 131 Forward service door/emergency exit
- 132 Forward galley units
- 133 VHF antenna
- 134 Overhead life raft storage
- 135 Outer/whistler engine nacelle
- 136 Forward toilet compartments
- 137 Nose undercarriage leg pivot mounting
- 138 Twin nosewheel, forward retracting
- 139 Nosewheel bay
- 140 Flight engineer's station
- 141 Cockpit bulkhead and doorway
- 142 Forward main entry door
- 143 Navigator's station
- 144 Cockpit overhead systems control panel
- 145 Cockpit 'eyebrow' windows
- 146 First Officer's seat, Captain's seat to port
- 147 Nose compartment ventral access hatch
- 148 Breaker antenna
- 149 Rubber pedals
- 150 Instrument panel
- 151 Instrument panel shroud
- 152 Windscreen panels
- 153 Windscreen wipers
- 154 Front pressure bulkhead
- 155 Upward flaring radome
- 156 Weather radar scanner
- 157 S.S. glint/ice antenna

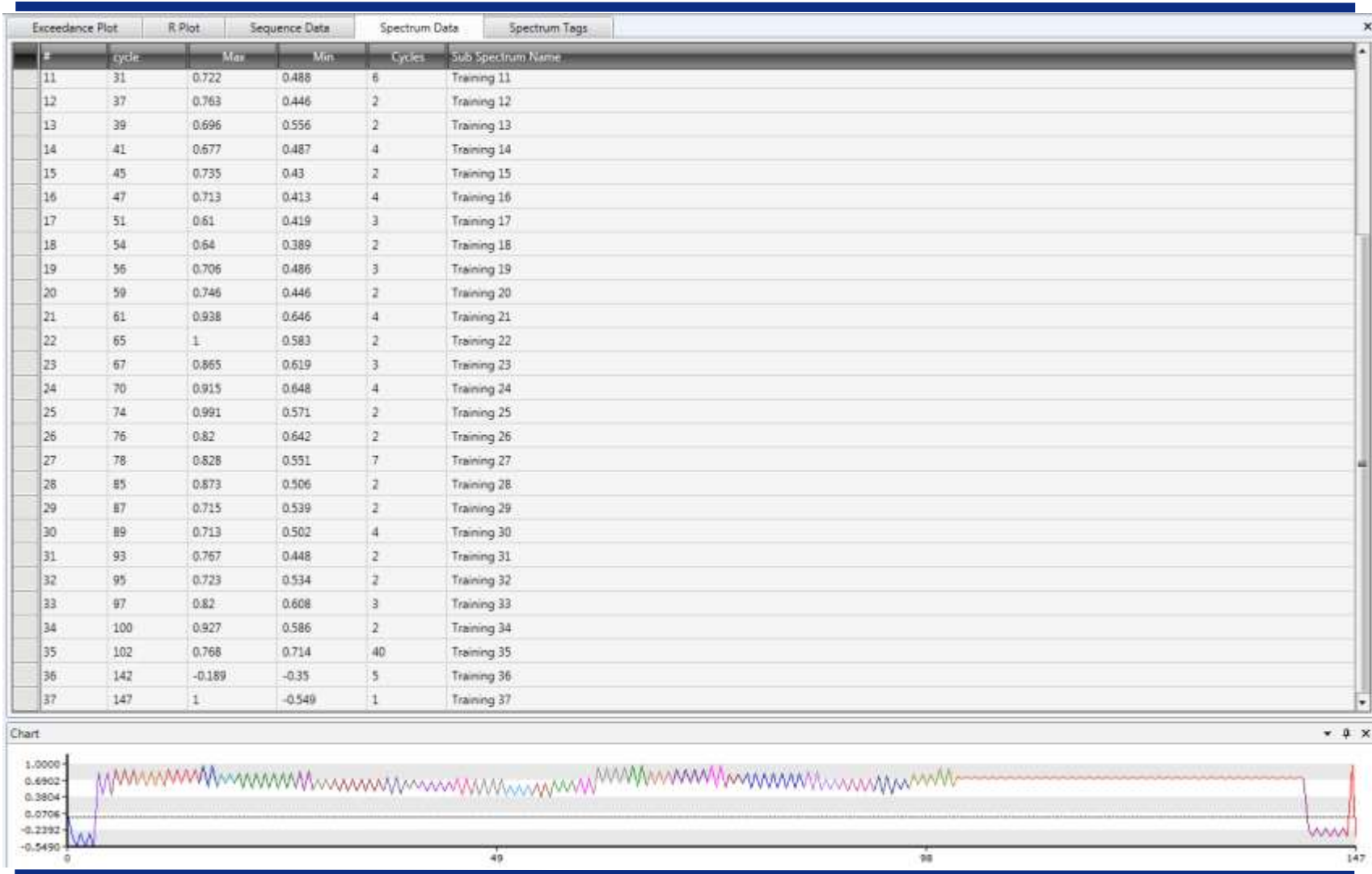


# Boeing 707 WS360 Enviro-Mechanical Spectrum

#	Segment	S <sub>max</sub> (ksi)	S <sub>min</sub> (ksi)	Cycles	Altitude (ft)	Actual (°C)	Binned (°C)
1	TAKEOFF	-5.55	-10.30	3	0	15.02	23
2	FLAPS DOWN DEPARTURE	15.82	7.89	2	1000	13.02	23
3	INIT CLIMB	17.12	11.57	3	3000	9.07	23
4	FINAL CLIMB	16.30	11.08	3	17000	-18.65	-15
5	CRUISE	17.17	12.16	4	34000	-52.26	-50
6	CRUISE	18.60	10.72	2	34000	-52.26	-50
7	FINAL CLIMB	15.38	12.02	2	34750	-52.26	-50
8	CRUISE	15.51	10.35	7	35500	-54.21	-57
9	CRUISE	16.37	9.50	2	35500	-54.21	-57
10	FINAL CLIMB	13.38	10.09	2	36750	-56.21	-57
11	CRUISE	13.55	9.15	6	38000	-56.48	-57
12	CRUISE	14.32	8.37	2	38000	-56.48	-57
13	FINAL CLIMB	13.06	10.43	2	39500	-56.48	-57
14	CRUISE	12.70	9.13	4	41000	-56.48	-57
15	CRUISE	13.78	8.06	2	41000	-56.48	-57
16	INIT DESCENT	13.38	7.74	4	33000	-50.26	-50
17	CRUISE	11.45	7.86	3	25000	-34.48	-37
18	CRUISE	12.01	7.30	2	25000	-34.48	-37
19	CRUISE	13.24	9.12	3	25000	-34.48	-37
20	CRUISE	13.99	8.37	2	25000	-34.48	-37
21	CRUISE	17.59	12.11	4	25000	-34.48	-37
22	CRUISE	18.76	10.94	2	25000	-34.48	-37
23	FINAL CLIMB	16.22	11.61	3	29500	-42.37	-37
24	CRUISE	17.16	12.15	4	34000	-52.26	-50
25	CRUISE	18.59	10.72	2	34000	-52.26	-50
26	FINAL CLIMB	15.38	12.05	2	34750	-52.26	-50
27	CRUISE	15.54	10.33	7	35500	-54.21	-57
28	CRUISE	16.37	9.50	2	35500	-54.21	-57
29	FINAL CLIMB	13.41	10.12	2	36750	-56.21	-57
30	CRUISE	13.38	9.41	4	38000	-56.48	-57
31	CRUISE	14.38	8.41	2	38000	-56.48	-57
32	INIT DESCENT	13.56	10.01	2	19000	-22.59	-30
33	FINAL DESCENT	15.38	11.41	3	3000	9.07	23
34	FLAPS DOWN APPROACH	17.39	10.99	2	1000	13.02	23
35	ROLL MANEUVER	14.41	13.39	40	1000	13.02	23
36	LANDING ROLLOUT	-3.54	-6.57	5	0	15.02	23
37	GAG	18.76	-10.30	1	Various	-34.28	-30

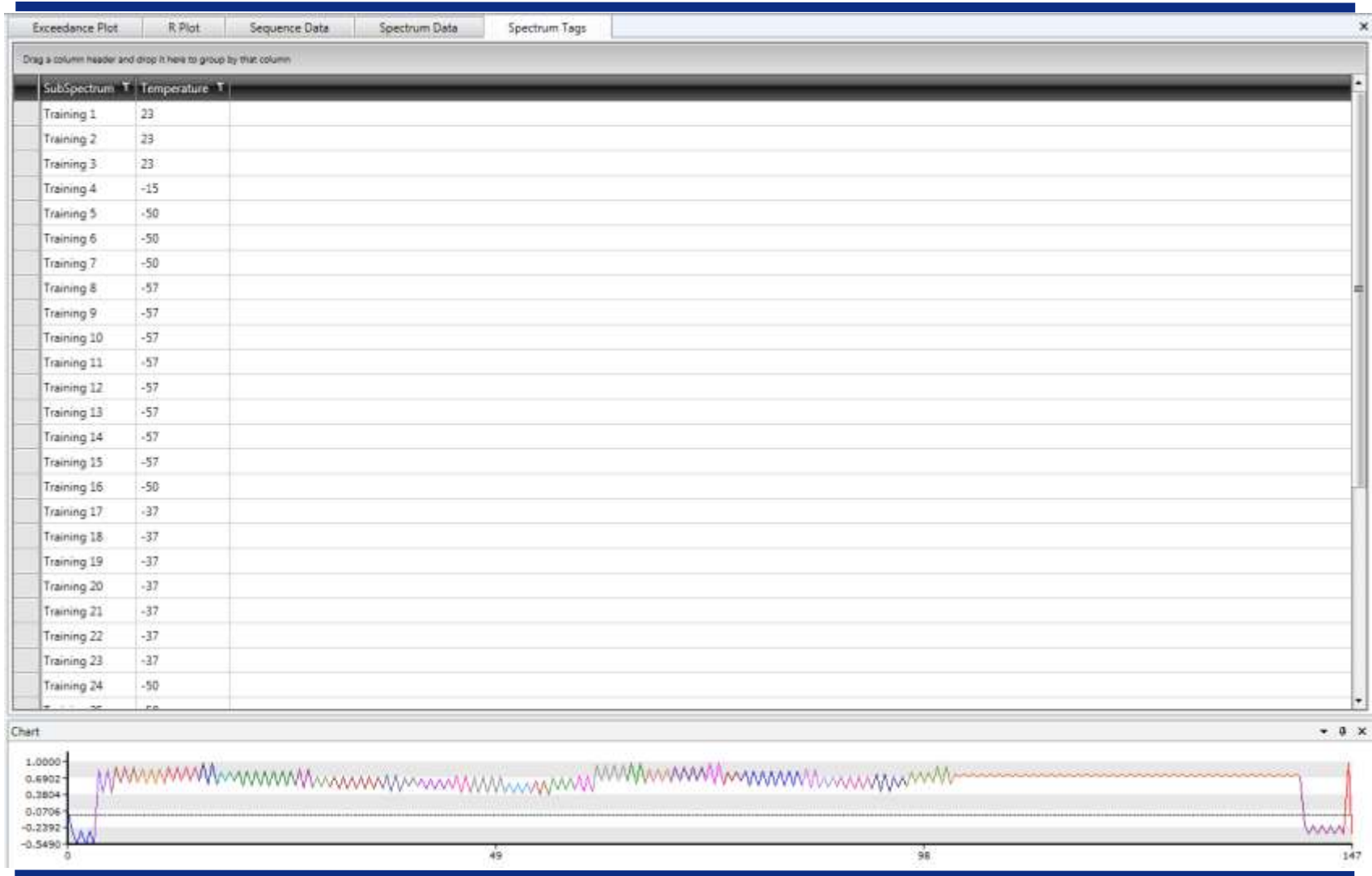


# SpectrumManager Mechanical Spectrum





# SpectrumManager Environmental Spectrum

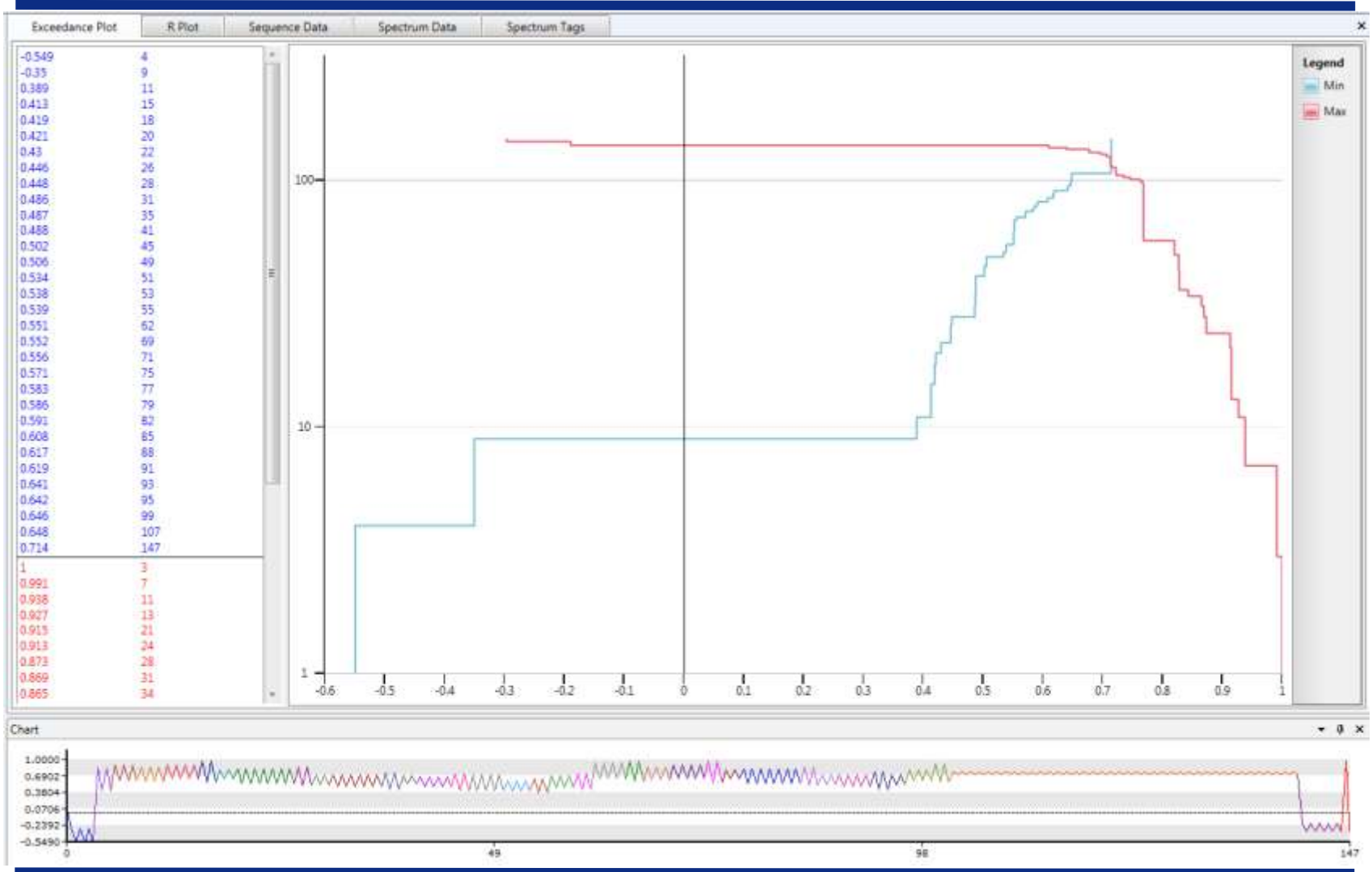






# SpectrumManager Metrics

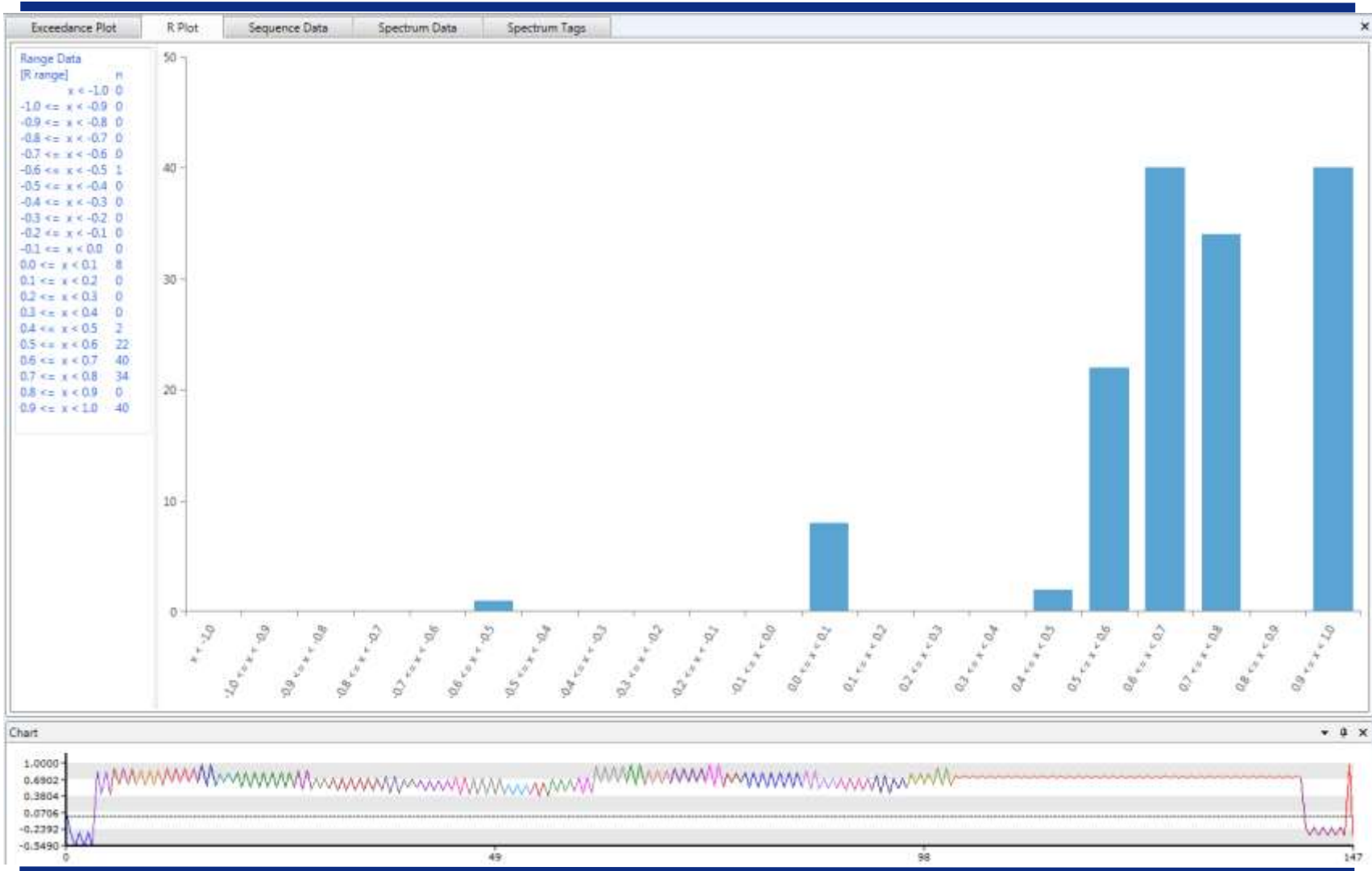
## Spectrum – Exceedance Plot





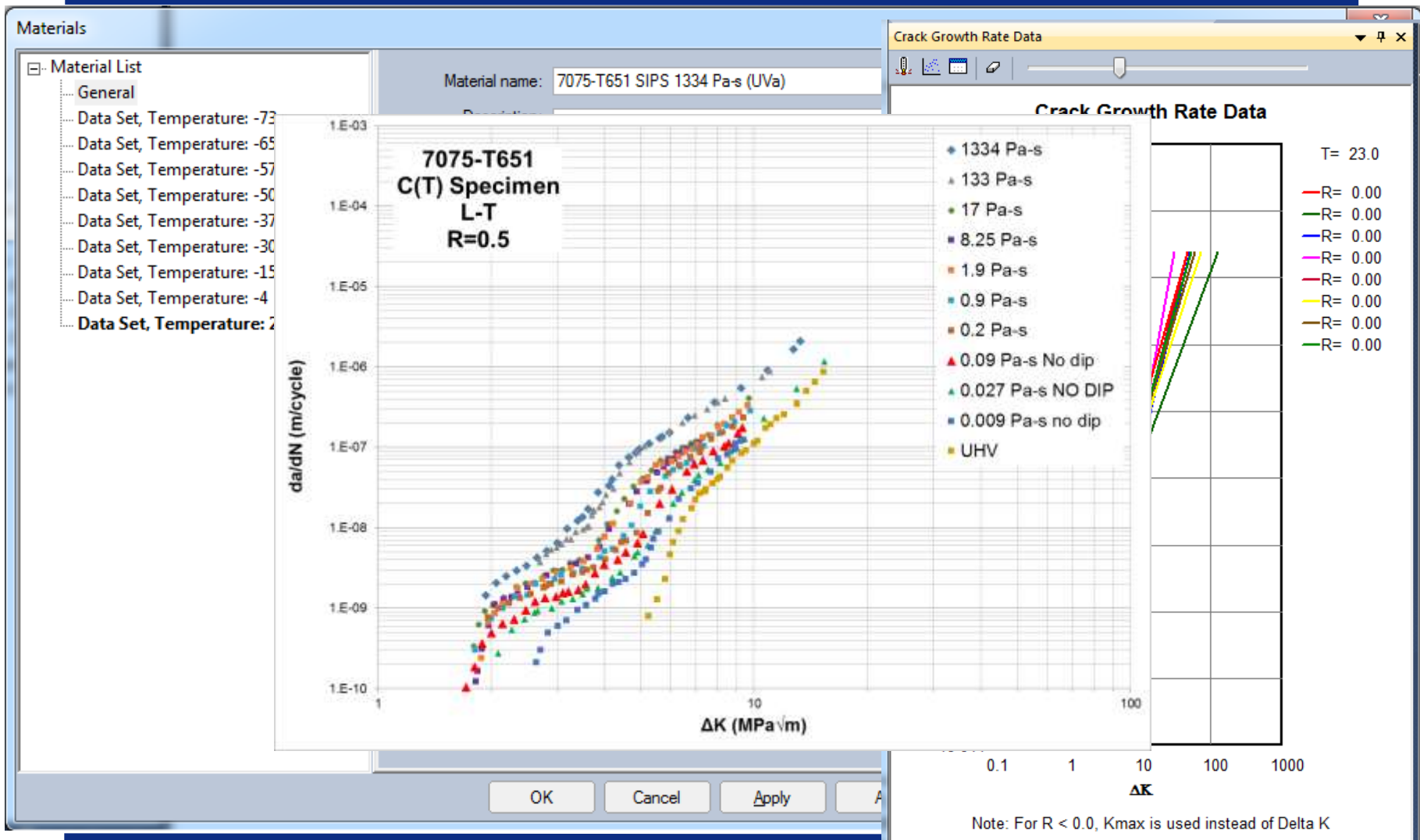
# SpectrumManager Metrics

## Spectrum – R Content





# AFGROW Input Multiple Tabular Look-up Data







# AFGROW Input

The screenshot displays the AFGROW software interface. At the top, a spectrum plot shows a blue line representing a stress spectrum. Below the plot, the main window is titled "Double Corner Crack at Hole - Standard Solution" and contains a diagram of a crack in a plate with a hole. To the left, a "Status" pane shows a tree view of the input parameters:

- 8707 WS 360
  - Double Corner Crack at Hole - Standard Solution
    - Load
      - Axial Stress Fractions: 1
      - Bending Stress Fractions: 0
      - Bearing Stress Fractions: 0
      - Crack length (C) = 0.00127
      - Crack length (A) = 0.00127
      - Width (W) = 0.0254
      - Thickness (T) = 0.00254
      - Hole Diameter (D) = 0.00390875
    - 7075-T651 SPS 1334 Pa-s (UVa) (Lookup Tabular Data)
      - 7075-T651 SPS 0.009 Pa-s (UVa) (Set), Temperature: -73
      - 7075-T651 SPS 0.027 Pa-s (UVa) (Set), Temperature: -65
      - 7075-T651 SPS 0.08 Pa-s (UVa) (Set), Temperature: -57
      - 7075-T651 SPS 0.2 Pa-s (UVa) (Set), Temperature: -50
      - 7075-T651 SPS 0.8 Pa-s (UVa) (Set), Temperature: -37
      - 7075-T651 SPS 1.9 Pa-s (UVa) (Set), Temperature: -30
      - 7075-T651 SPS 8.25 Pa-s (UVa) (Default Set), Temperature: -15
      - 7075-T651 SPS 17 Pa-s (UVa) (Set), Temperature: -4
      - 7075-T651 SPS 1334 (UVa) (Set), Temperature: 23
    - Stress State
      - Spectrum File - 18707\_WS360.sp3
        - N:\CAD\Task 5\AFGROW\8707\_WS360.sp3
        - SMF=129.390000
        - Pa=0.000000
        - SPL=0.000000
      - No Spectrum Filters
      - No Retardation
      - No K-Solution Filters
      - No Residual Stresses

At the bottom, an "Output" pane shows a grid of data, and a "Notification List" pane is empty. The status bar at the bottom indicates "Metric" and "PAUSE".

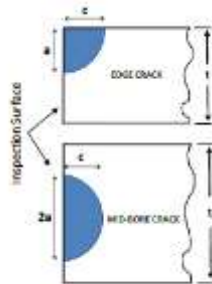


# AFGROW

## $a_{90/95}$ Results

### 1.2 Rotary Bolt Hole Eddy Current (BHEC) IAW TO-33B-1-2 (Figure 3)

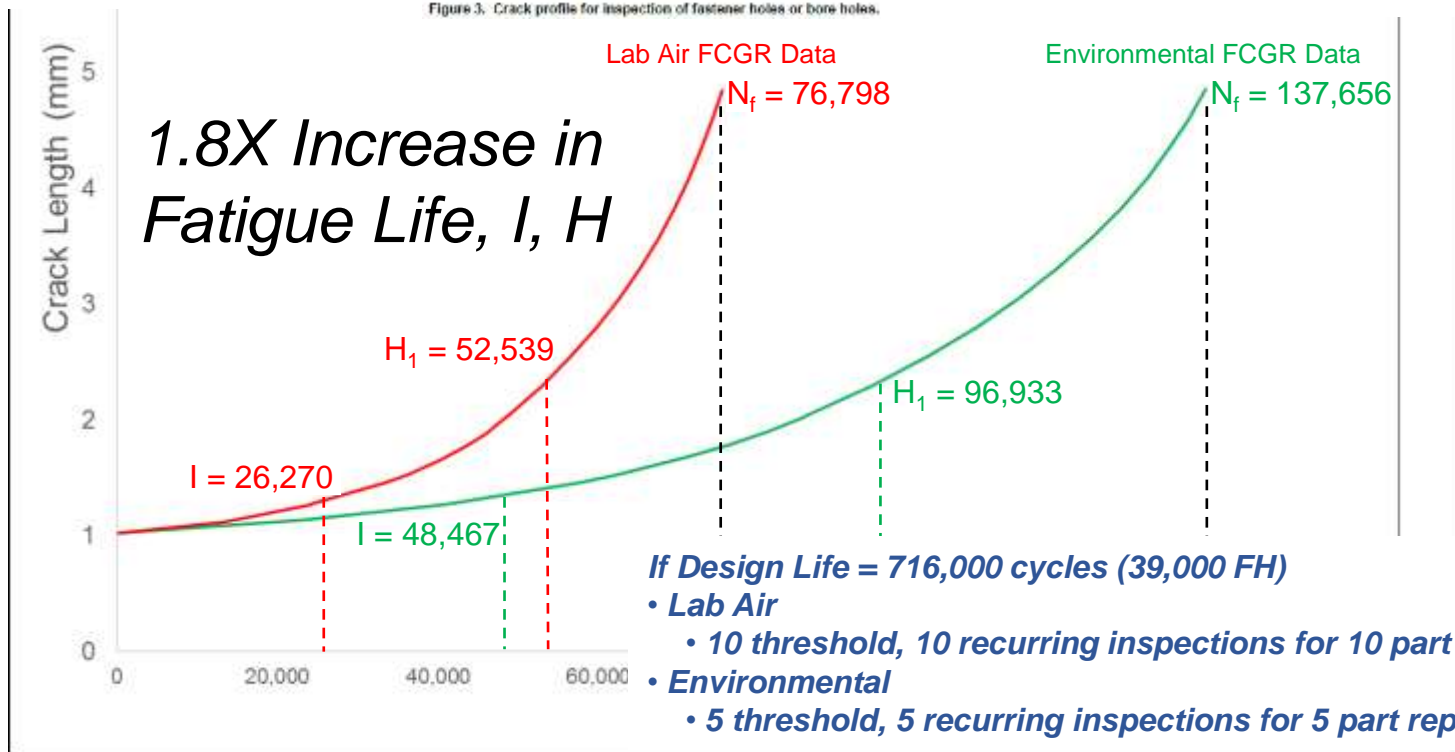
	$a_{90}$		$a_{90/95}$	
	Crack Length, $a$	Crack Depth, $c$	Crack Length, $a$	Crack Depth, $c$
<b>Edge Crack</b>				
Aluminum:	0.040 inch	0.040 inch	0.050 inch	0.050 inch
Titanium:	0.040 inch	0.040 inch	0.050 inch	0.050 inch
Steel:	TBD	TBD	TBD	TBD
<b>Mid Bore Crack</b>				
Aluminum:	0.080 inch	0.040 inch	0.100 inch	0.050 inch
Titanium:	0.080 inch	0.040 inch	0.100 inch	0.050 inch
Steel:	TBD	TBD	TBD	TBD



$$I = \frac{N_{a_{crit}} - N_{a_{init}}}{2} \quad \text{Initial Inspection}$$

$$H = \frac{N_{a_{crit}} - N_{a_{NDI}}}{2} \quad \text{Recurring Inspection}$$

Figure 3. Crack profile for inspection of fastener holes or bore holes.



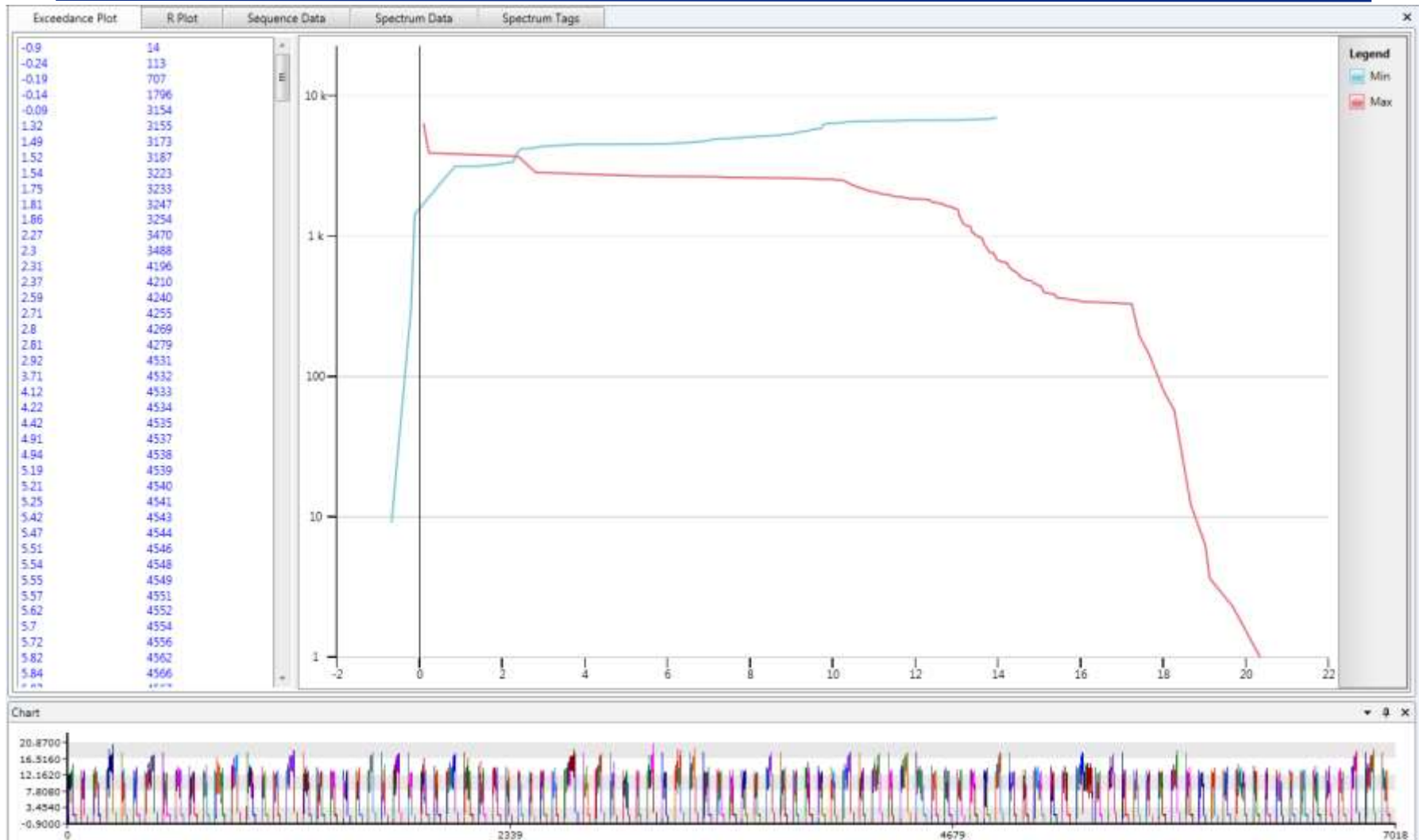


# Business Jet Example



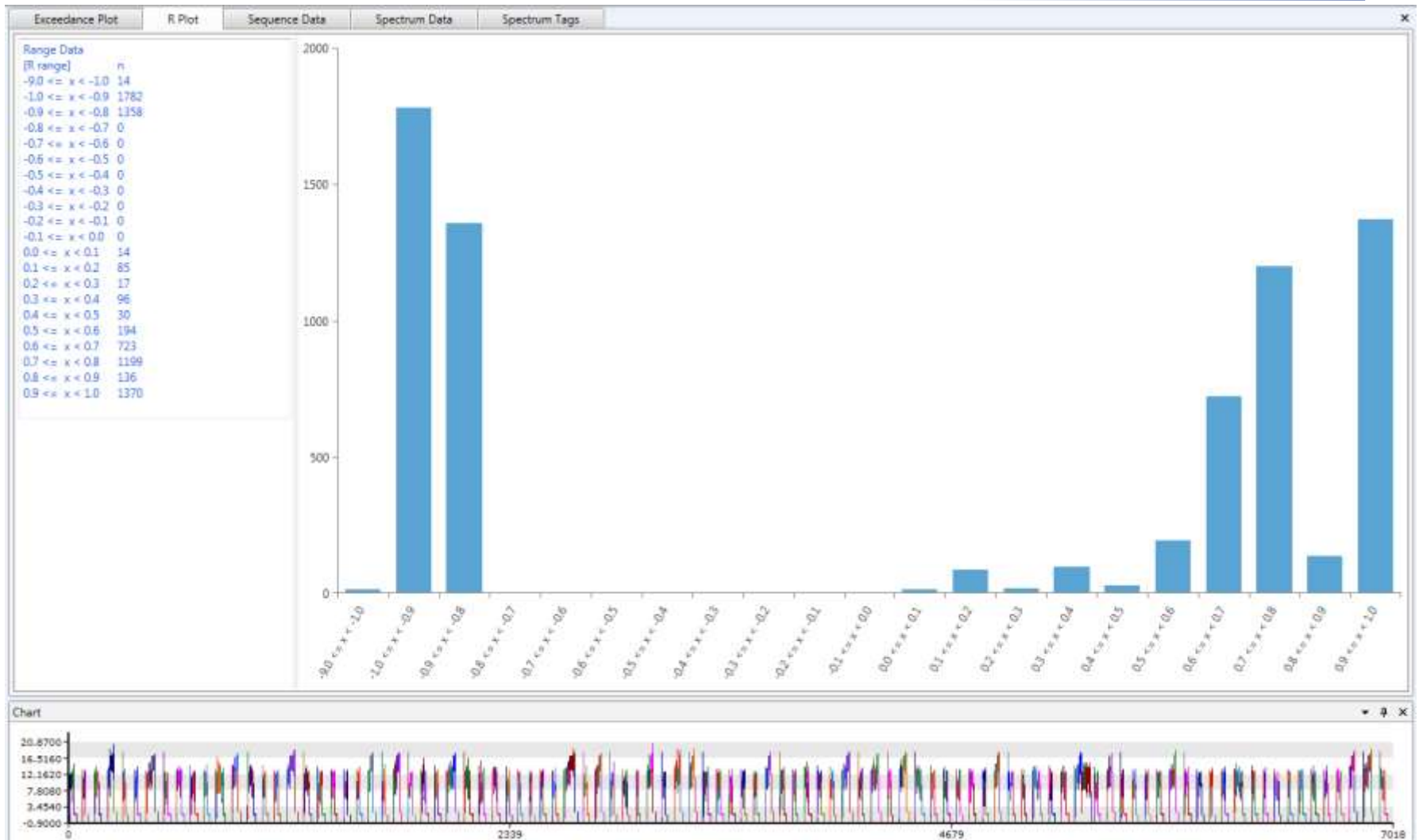


# SpectrumManager Metrics Spectrum – Exceedance Plot





# SpectrumManager Metrics Spectrum – R Content



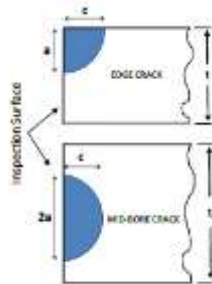




# AFGROW $a_{90/95}$ Results

## 1.2 Rotary Bolt Hole Eddy Current (BHEC) IAW TO-33B-1-2 (Figure 3)

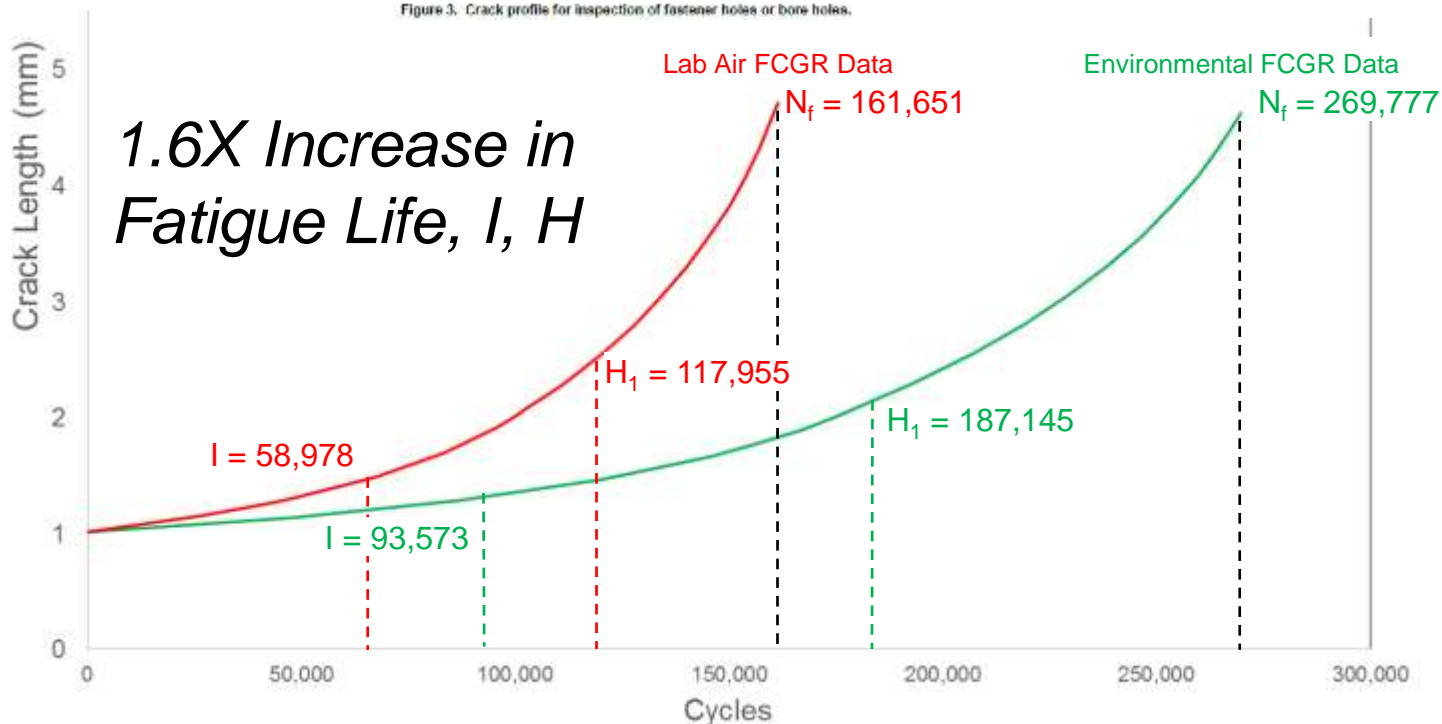
	$a_{90}$		$a_{90/95}$	
	Crack Length, $a$	Crack Depth, $c$	Crack Length, $a$	Crack Depth, $c$
<b>Edge Crack</b>				
Aluminum:	0.040 inch	0.040 inch	0.050 inch	0.050 inch
Titanium:	0.040 inch	0.040 inch	0.050 inch	0.050 inch
Steel:	TBD	TBD	TBD	TBD
<b>Mid Bore Crack</b>				
Aluminum:	0.080 inch	0.040 inch	0.100 inch	0.050 inch
Titanium:	0.080 inch	0.040 inch	0.100 inch	0.050 inch
Steel:	TBD	TBD	TBD	TBD



$$I = \frac{N_{a_{crit}} - N_{a_{init}}}{2} \quad \text{Initial Inspection}$$

$$H = \frac{N_{a_{crit}} - N_{a_{NDI}}}{2} \quad \text{Recurring Inspection}$$

Figure 3. Crack profile for inspection of fastener holes or bore holes.





# Next Steps

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- LexTech Capability Enhancements
  - Spectrum Manager
    - Each mission segment in the spectrum can have environmental parameters ( $T$ ,  $P_{H2O}$ , user, etc.) defined ✓
  - AFGROW
    - Accept multiple material data input ✓
- Verification - LexTech
- Validation - SAFE
  - Compare to lab test results
  - Can compare to in-service cracking results if the data is available