Australian Government
Department of Defence
Science and Technology

A comparative evaluation of a deterministic and probabilistic approach for determining safety inspection intervals of airframe structures

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Motivations of this research

"Purely deterministic criteria and methods were gradually supplemented or replaced with probabilistic approach"

- Rick Ryan, NAVAIR
  AASIS 2015

Economic pressure to extend fleet usage

Safety of aircraft

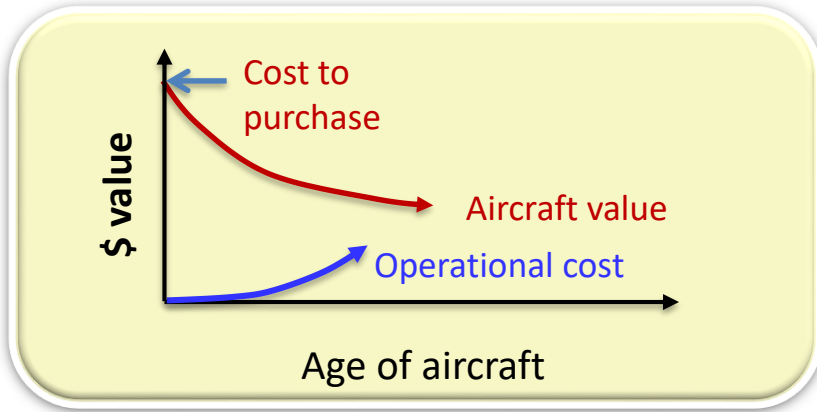# Motivations of this research

Which is ...

more accurate?

more economical?

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Fatigue failure risk analysis – what it brings to Defence

- Enhance safety
- Maximise availability
- Minimise cost of ownership

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Cost of ownership of military aircraft

Fatigue failure risk analysis :

- Operational life of an aircraft
- **Safety inspection interval**

US Data

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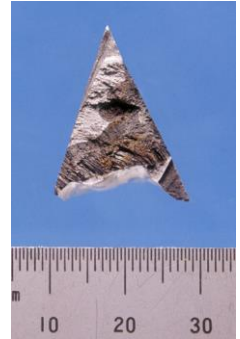
When does fatigue failure occur?
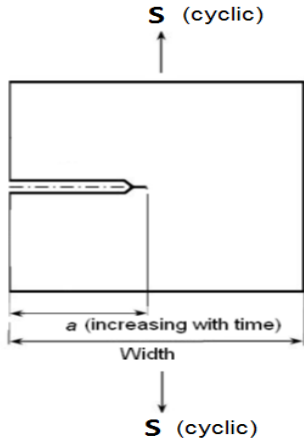
Fatigue failure occurs when :

$$K_C \leq S \cdot \beta(a)\sqrt{\pi a}$$

or

$$S > Residual\ Strength$$

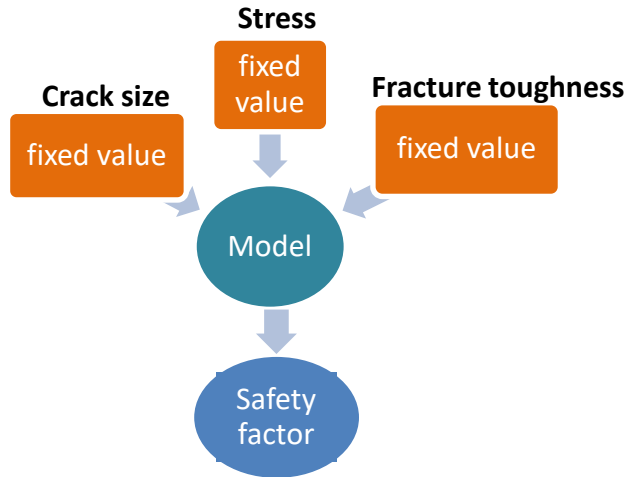Kc : stress intensity factor

S : cyclic stress applied

A: crack size

β(*a*) : geometry correction factor

There are infinite number of combinations of stresses (S) and crack sizes (*a*) that will cause failure

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Deterministic vs Probabilistic approach
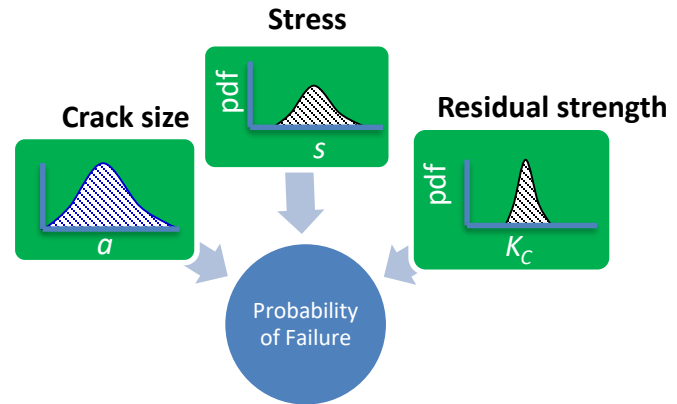
"Those who will begin with certainties, shall end in doubts;
but those who will be content to begin with doubts, shall end in certainty"   - Francis Bacon

Deterministic analysis

Stress

Crack size

fixed value

fixed value

Fracture toughness

fixed value

Model

Safety factor

$$K_C \leq S \cdot \beta(a)\sqrt{\pi a}$$

Probabilistic analysis

Stress

pdf

s

Crack size

pdf

a

Residual strength

pdf

K_C

Probability of Failure

$$PoF = \int_{0}^{\infty} f(a) \left(1 - \int_{0}^{S_{RS}(a_{cr})} f(s)\,ds \right)$$

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Deterministic approach – inspection interval
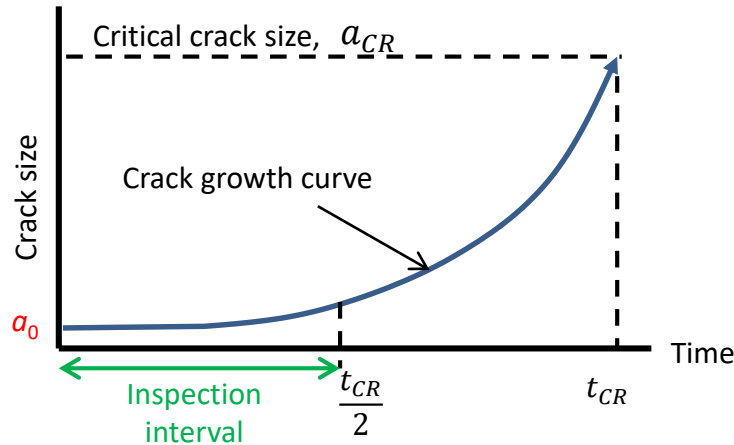
As per MIL-STD 1530D :

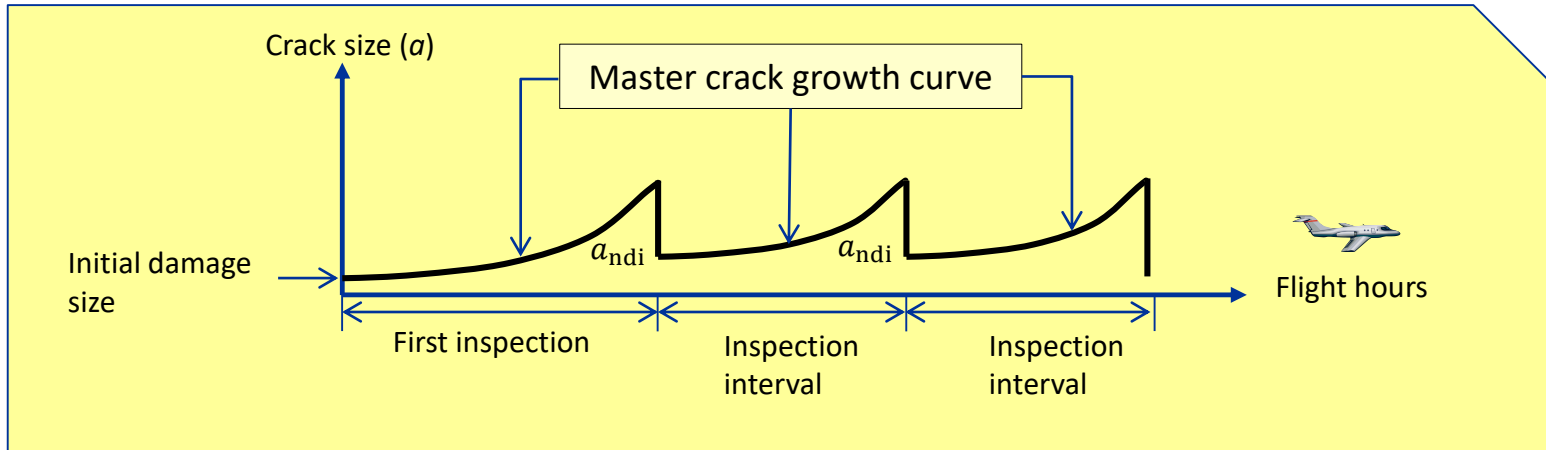**What does MIL-STD-1530D says?**

- ➢ **Initial inspection shall occur at one-half the life from max probable initial damage to the critical damage size**

- ➢ **Repeat inspections at or before one-half the life from minimum detectable size to the critical damage size**

a_0 = maximum probable initial damage size (**first inspection**)

OR

a_0 = maximum detectable damage size (**repeat inspections**)

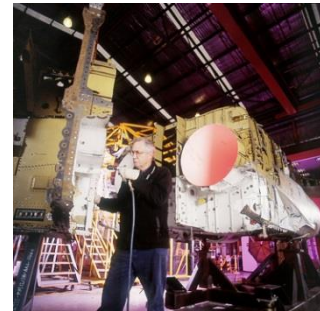DST GROUP   Science and Technology for Safeguarding Australia

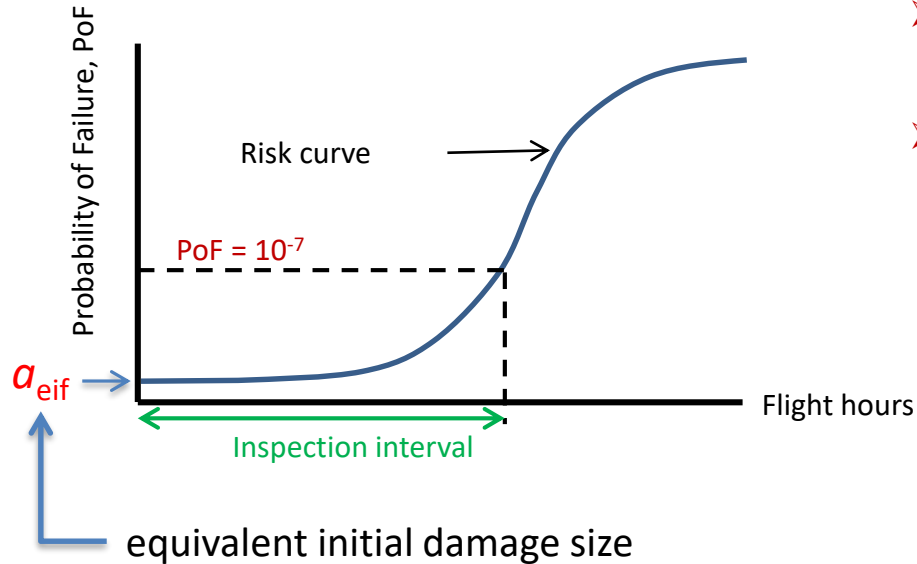# Inspection interval - Deterministic approach

- 👍 Well understood
- Assuring

- 👎 Can not be used to predict the operational life limit, OLL
- How many inspections before retiring an aircraft?

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Probabilistic approach – inspection interval

As per MIL-STD 1530D :

Probability of Failure, PoF

Risk curve

PoF = 10^{-7}

a_{eif}

Flight hours

Inspection interval

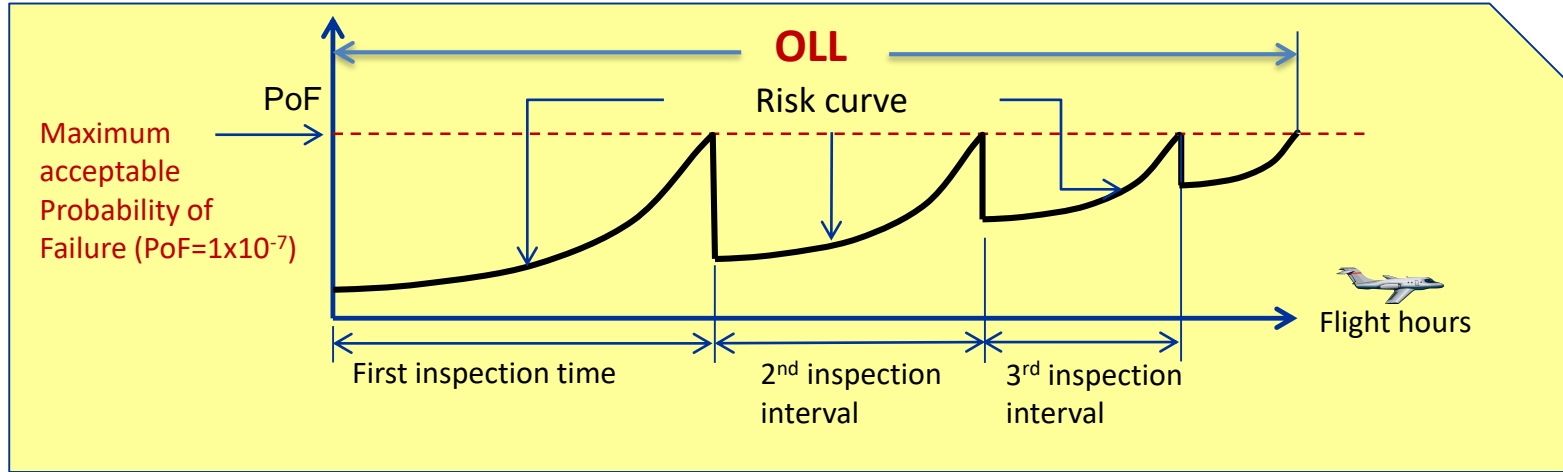equivalent initial damage size

What does MIL-STD-1530D says?

➢ **Risk analysis shall be used to determine if reduction in inspection intervals required,**

➢ **PoF=10^{-7} (acceptable risk)**

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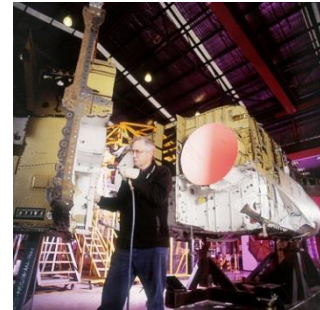
Inspection interval - Probabilistic approach

- 👎
  - Not well understood
  - Not assuring
- 👍
  - Can predict Operational Life Limit (OLL)

Comparison of Probabilistic and Deterministic Predictions using Coupon Test Results

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Coupon test

Notch Detail
(All dimensions in mm)
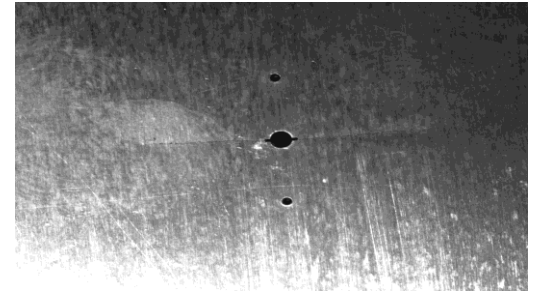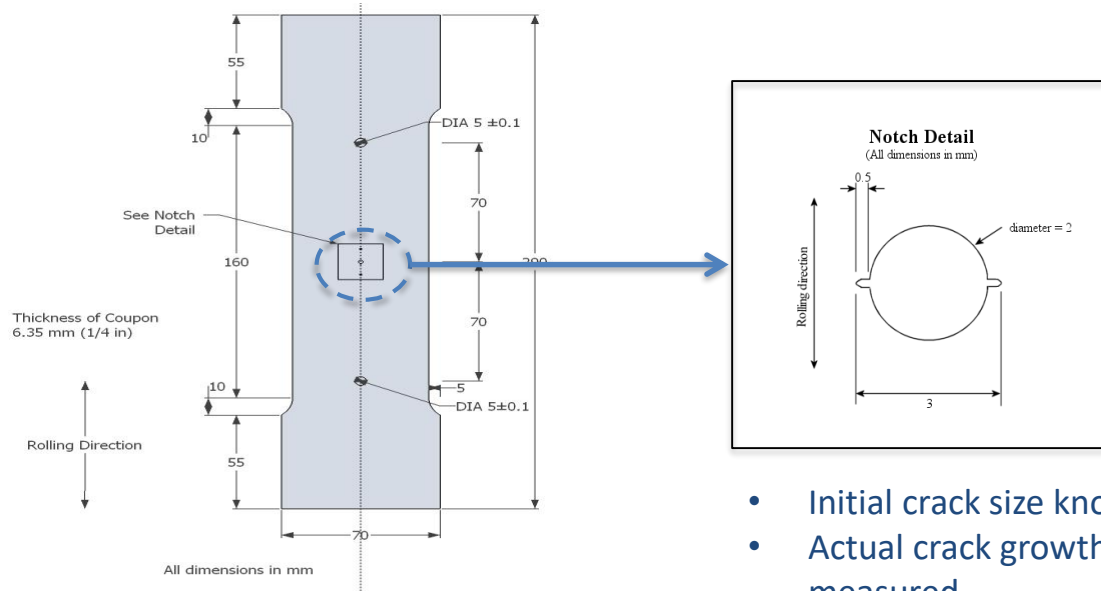
- Initial crack size known
- Actual crack growth curve measured

Material: Aluminium 7075 T7351
No. of coupons tested : 85

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Validation of Probabilistic and Deterministic Fatigue Life Predictions

1. Virkler Data – 68 Sets

Loading: Constant amplitude
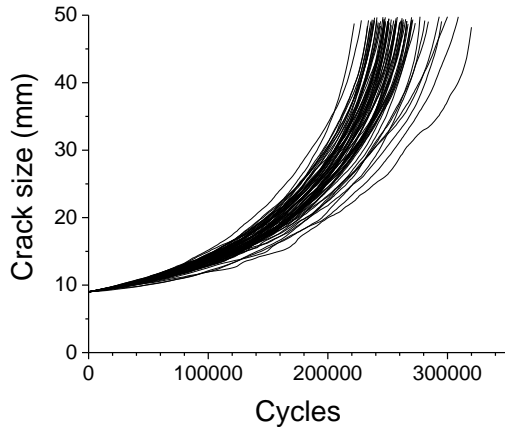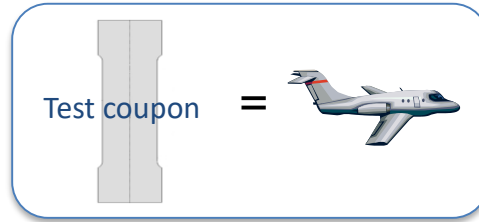
2. DSTG Data – 85 Sets

Loading: Variable amplitude

Analogy :

Test coupon =

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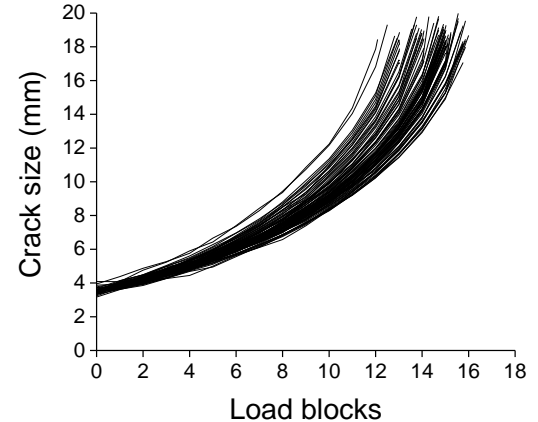
Probabilistic prediction

Using DSTG test coupons

Constant Kc=32

Variable Kc, mean =32 Stdev=1.0
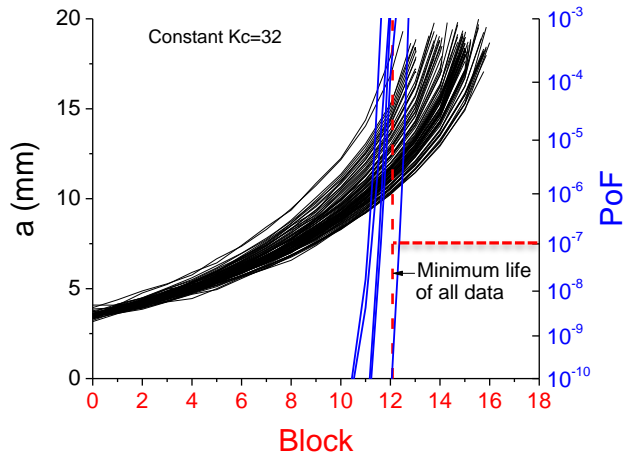
- Fixed fracture toughness, K_C
  Accuracy: **4 out of 5**
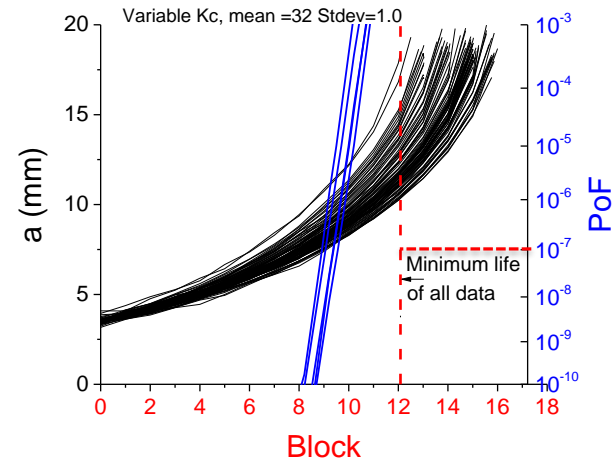
- Variable fracture toughness, K_C
  Accuracy: **5 out of 5**

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Deterministic vs Probabilistic prediction

DST Group test coupons

Test coupon fatigue lives (Load blocks)	Independent Trials	Deterministic analysis (FS=2.0)	Deterministic analysis	Probabilistic analysis (Fixed K_C)	Probabilistic analysis (Variable K_C)
		Predicted safe hours (Load blocks)			
	1	7.7	15.4	11.5	9.9
	2	7.6	15.2	12.4	10.4
12.1 (min) 16.1 (max)	3	7.3	14.6	11.1	9.7
	4	7.8	15.6	11.2	10.2
	5	7.5	15.0	11.6	10.2

Note: Safe prediction < 12.1

- **Probabilistic prediction closer to test results**
- **Probabilistic fracture toughness safer prediction**
- **Deterministic more (over?) conservative**

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Deterministic vs Probabilistic prediction

- **Using Virkler test data**
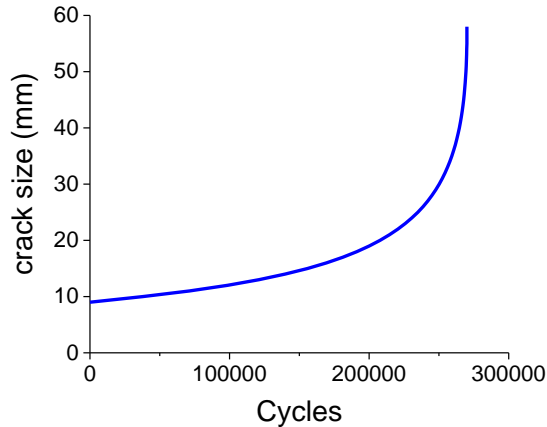
Master crack growth curve
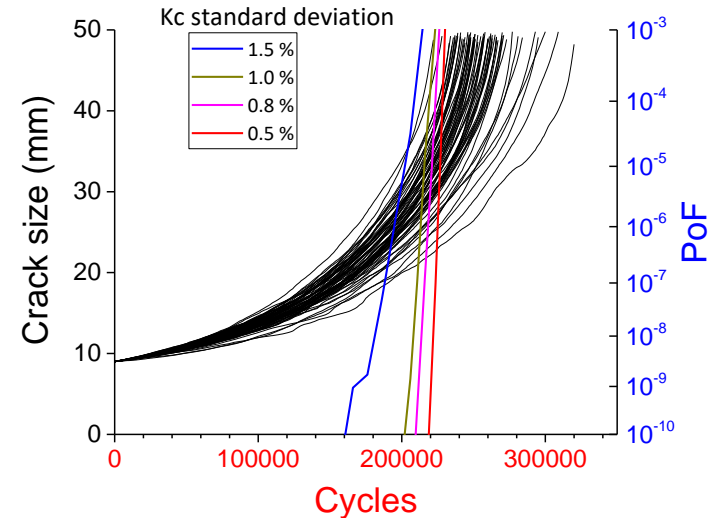
Black curve – **crack growth curves**

Other colours– **risk curves**

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Deterministic vs Probabilistic prediction

Using Virkler data

Test coupon fatigue lives (Cycles)	Deterministic prediction safe life FS=2.0 (Cycles)	Deterministic prediction safe life (Cycles)	Probabilistic prediction Fixed K_C value	Probabilistic prediction Mean K_C = 25 Mpa-m$^{1/2}$	
			Safe life (Cycles)	St. dev.	Safe life (Cycles)
222000 (min) 320000 (max)	129700	259400	231117	1.5	188101
				1.0	210649
				0.8	215851
				0.5	223529

Note: Safe prediction < 222000

Higher assumed fracture toughness (Kc) variability leads to safer prediction

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Inspection Interval Comparison - Lessons Learned

- **Deterministic only** ⟶ **Safe**

- **Probabilistic only** ⟶ **Safe**

- **Deterministic + Probabilistic =**
  - **Conservative**
  - OR
  - **Safe and economical**

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Conclusions:

1. Both the deterministic and probabilistic approach gave conservative predictions but the probabilistic approach predicts a life closer to the actual safe life

2. Without the use of a factor of safety, probabilistic prediction is more conservative

3. The application of both deterministic and probabilistic approach in predicting the safe fatigue life and inspection interval provides increased confidence in the prediction

Future work:

- Application of both deterministic and probabilistic analysis to C-130J test interpretation

- Application of probabilistic to FA-18 structural integrity assessment to supplement the deterministic analysis

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Questions?

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Safety inspections requirements

What does MIL-STD-1530D says?

a. **Initial inspection shall occur at one-half the life from max probable initial damage to the critical damage size**

b. **Repeat inspections at or before one-half the life from minimum detectable size to the critical damage size**

Deterministic

c. **Risk analysis shall be used to determine if reduction in inspection intervals required, etc... PoF=10^{-7} (acceptable risk)**

Probabilistic

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Inspection Interval Comparison - Lessons Learned

Deterministic only =

Probabilistic only =

Both Deterministic and Probabilistic = +

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