Australian Government
Department of Defence
Defence Science and Technology Organisation

C-130H CW-1 Probabilistic Risk Analysis

Ribelito Torregosa and Weiping Hu

Presented by Dr. Ribelito Torregosa

Air Vehicles Division, DSTO

DSTO

Outline of the Presentation

- Objective of the research
- Risk model – the probability of failure
- Data development
- Implementation and verification
- Analysis of CW1
- Conclusion

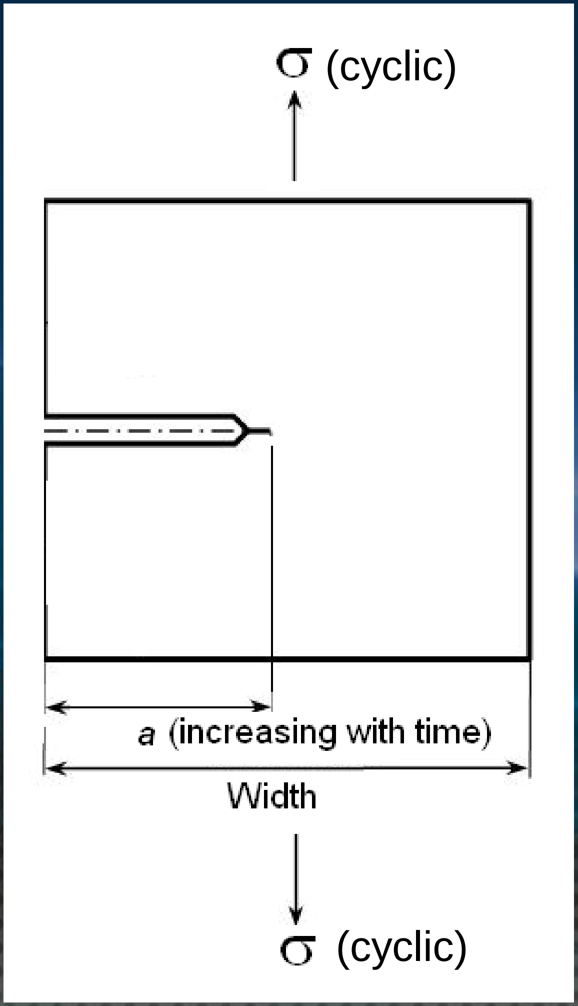
DSTO

Objective of the research

- Develop in-country capability for Probabilistic Risk Analysis
  - Develop Equivalent Initial Flaw Size distribution from tear down inspection data
  - Develop analysis tools for probabilistic risk analysis
  - Conduct a risk analysis on C130H
- Replicate the results of LM Aero CW-1 PRA

DSTO

What is Risk in the context of this paper?

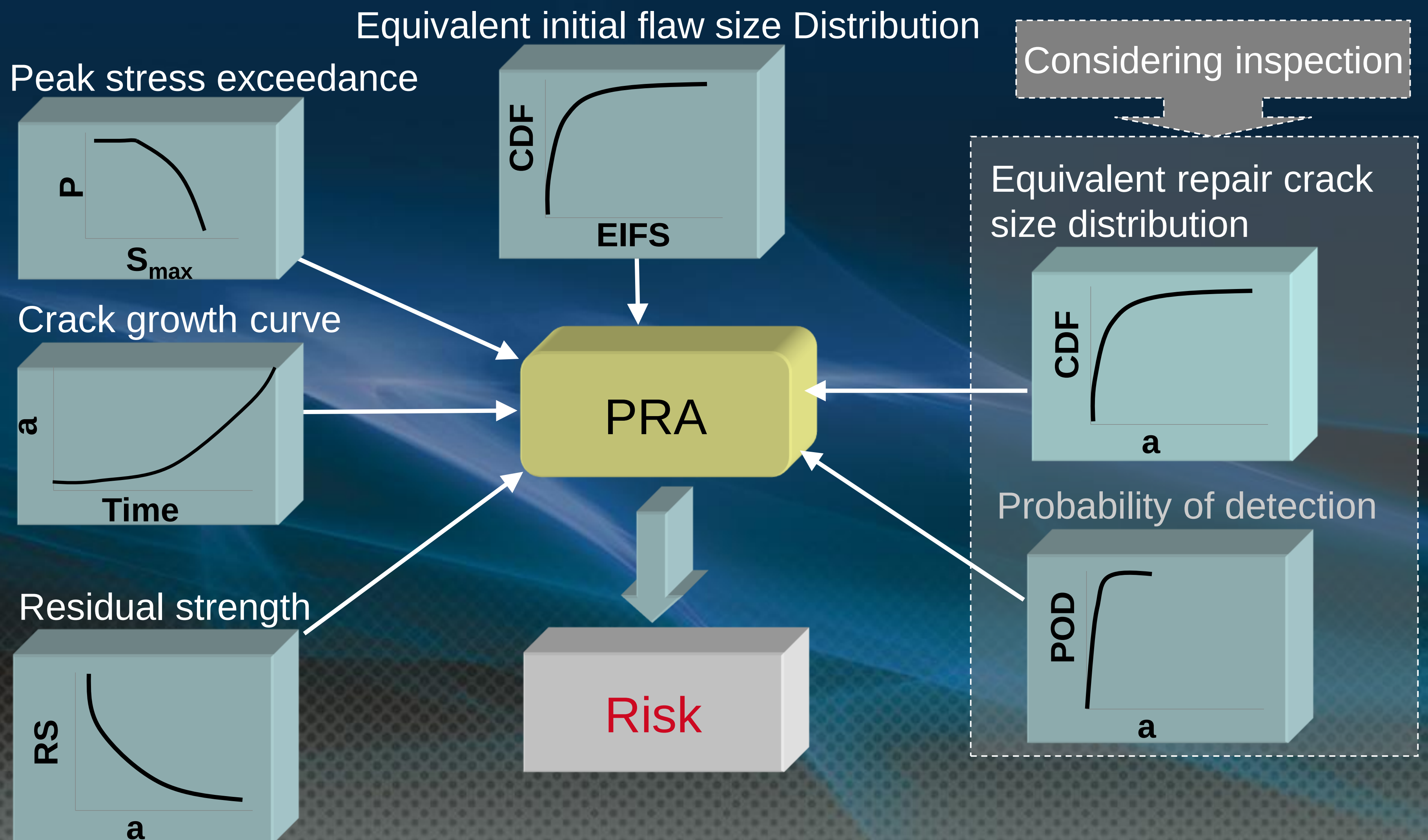


Risk - probability of failure or unstable fracture

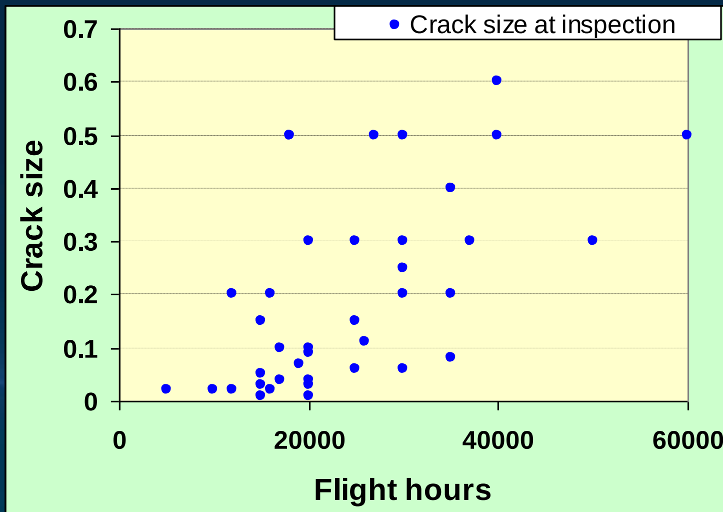
Failure occurs when;

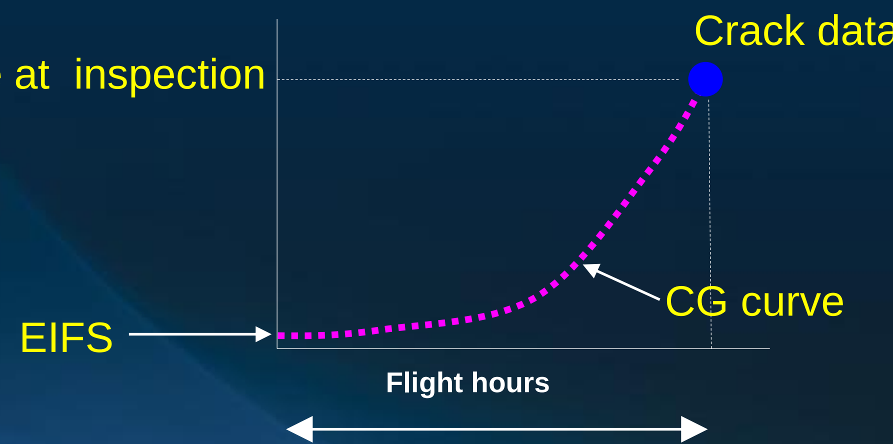
$$\sigma \geq \text{Residual strength}\ , RS$$

Schematic of Probabilistic Risk Analysis (PRA)



Equivalent Initial Flaw Size Distribution (EIFS)



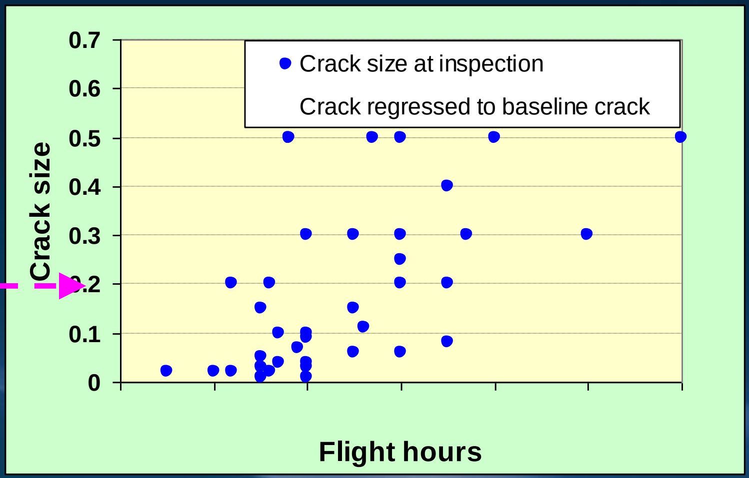


(EIFS concept)

- Fictitious crack size at time zero. ⇐ Regressed using CG curve
- Not a material property ⇐ Dependent on CG curve used

DSTO

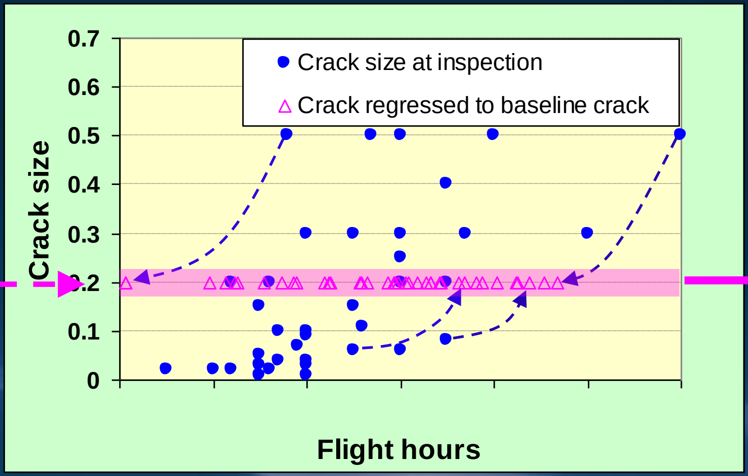
EIFS calculation procedure



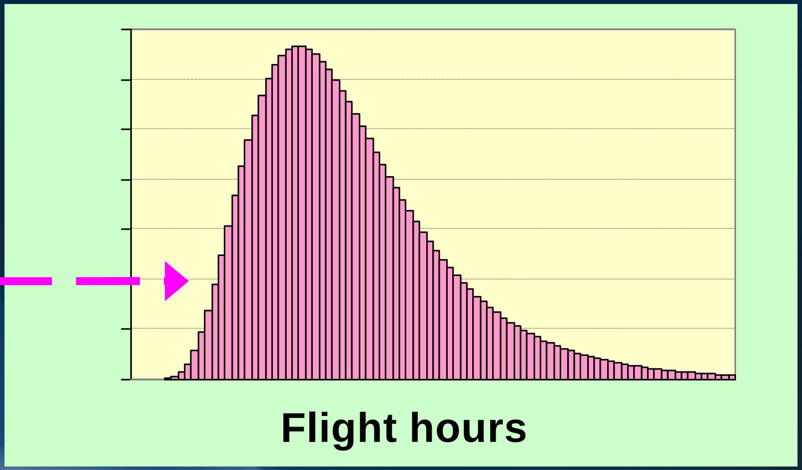
Mean of crack data = 0.20 in.

Assumed as baseline crack size

EIFS calculation procedure

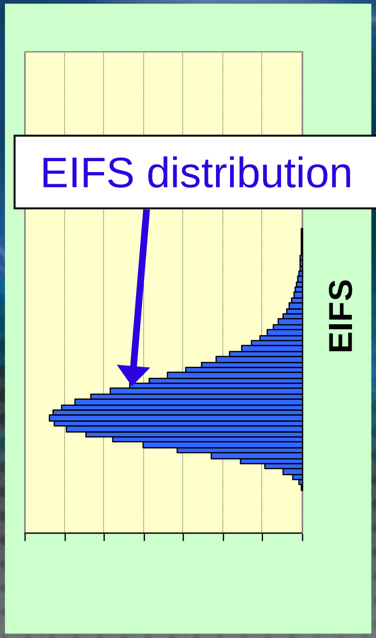


Life distribution at a=0.20 in



Mean of crack data = 0.20 in.

Assumed as baseline crack size



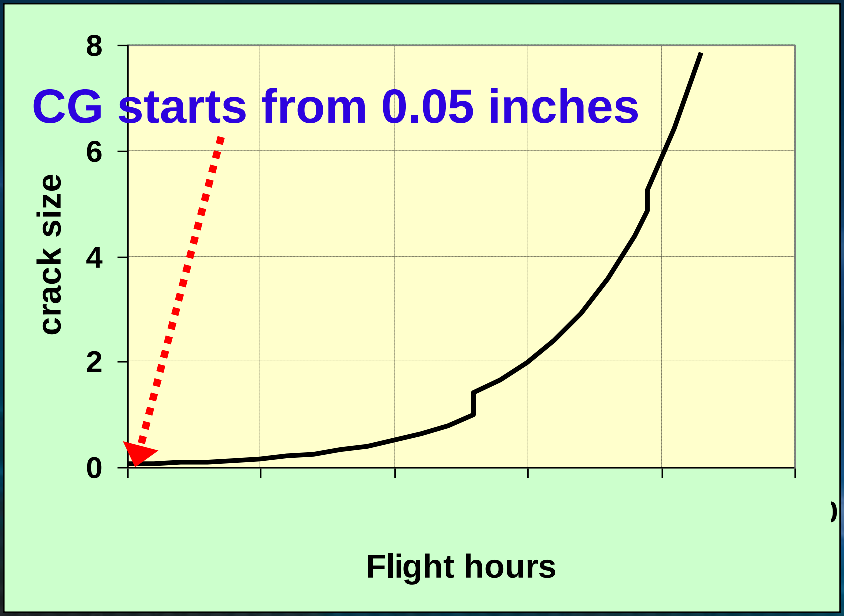
CG curve

Crack distribution at t=0

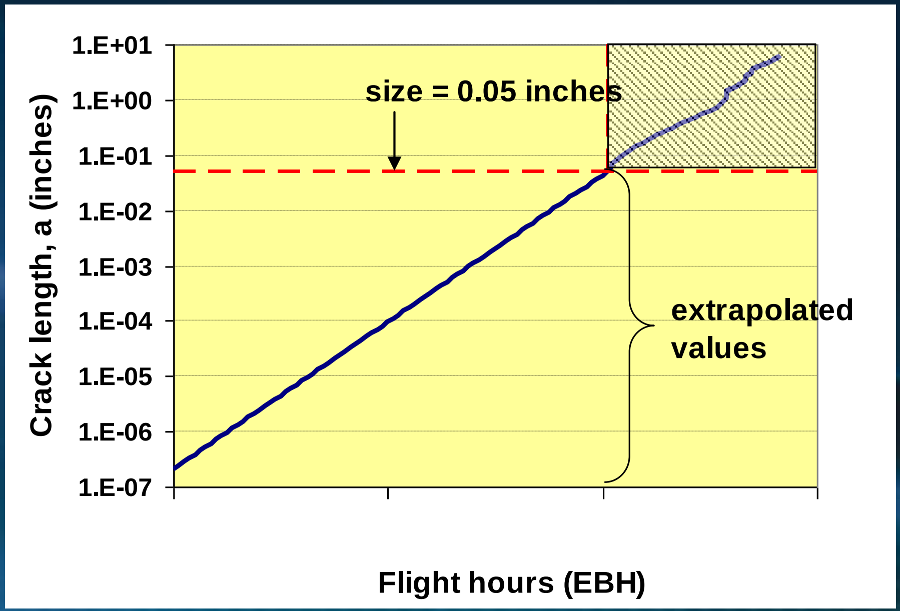
Master Crack Growth Curve

- CG curve back extrapolated

Original CG curve

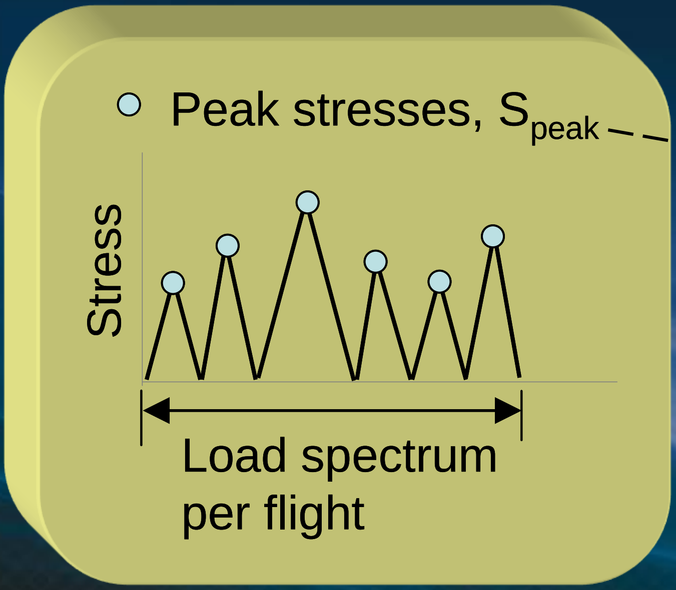


Extrapolated CG curve

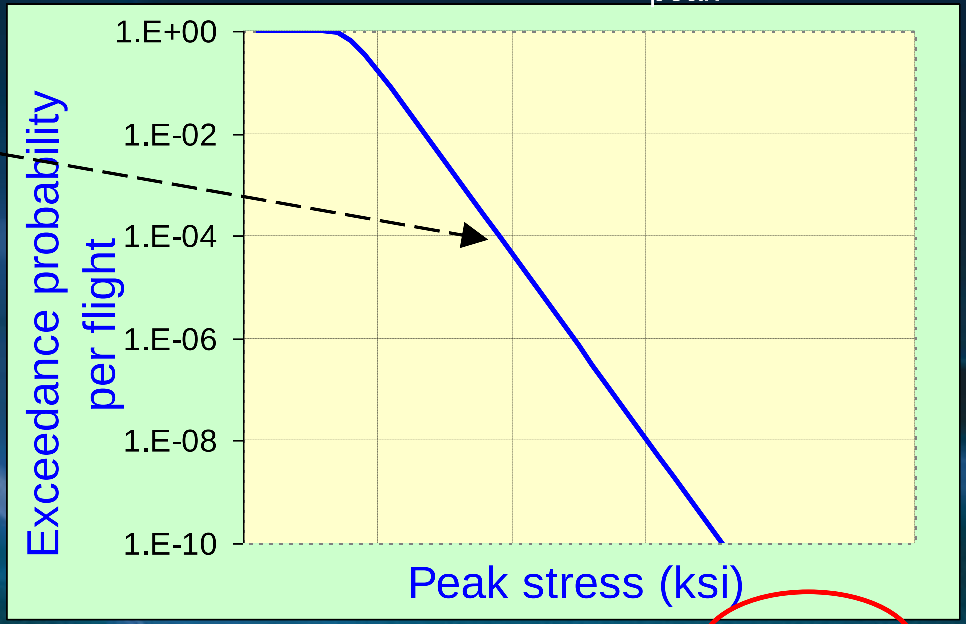


Peak stress distribution

☞The distribution of peak stresses of the cyclic load over a flight.



Exceedance curve of S_{peak}



Exceedance probability = 1 – F(s)

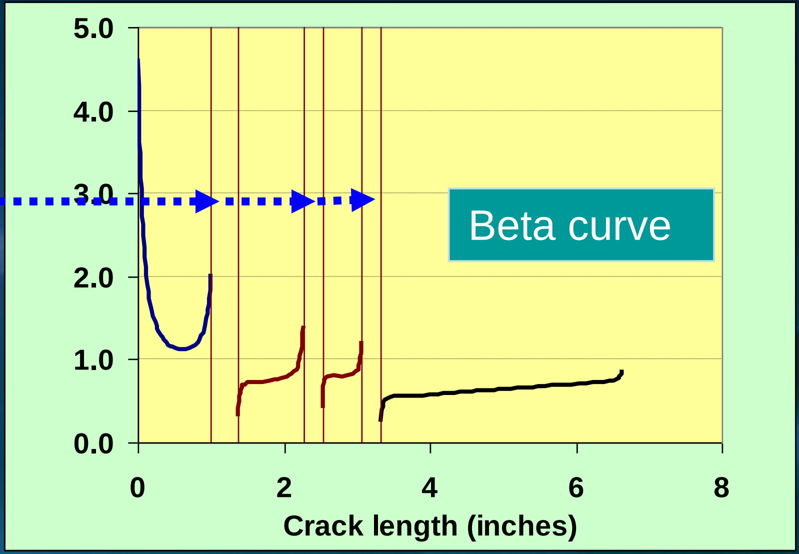
$$POF = \int_0^\infty f(a)\left(1 - \int_0^{s_{RS}(a)} f(s)\,ds\right)da$$

DSTO

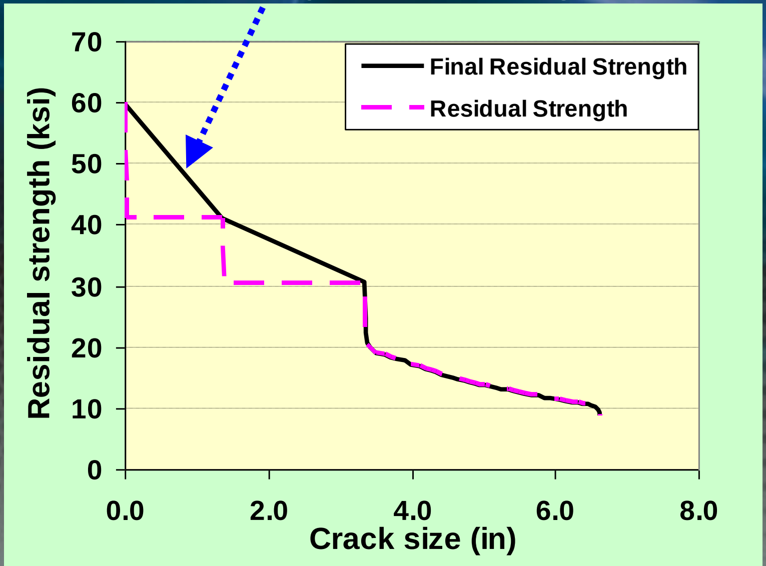
Residual strength, RS

$$\text{RS} = \text{Minimum}\left[\sigma_{cr} = \frac{K_c}{\sqrt{\pi a}\,\beta(a)}, \sigma_{ys}\right] \text{where} : \sigma_{ys} = \text{yield strength}$$

Holes

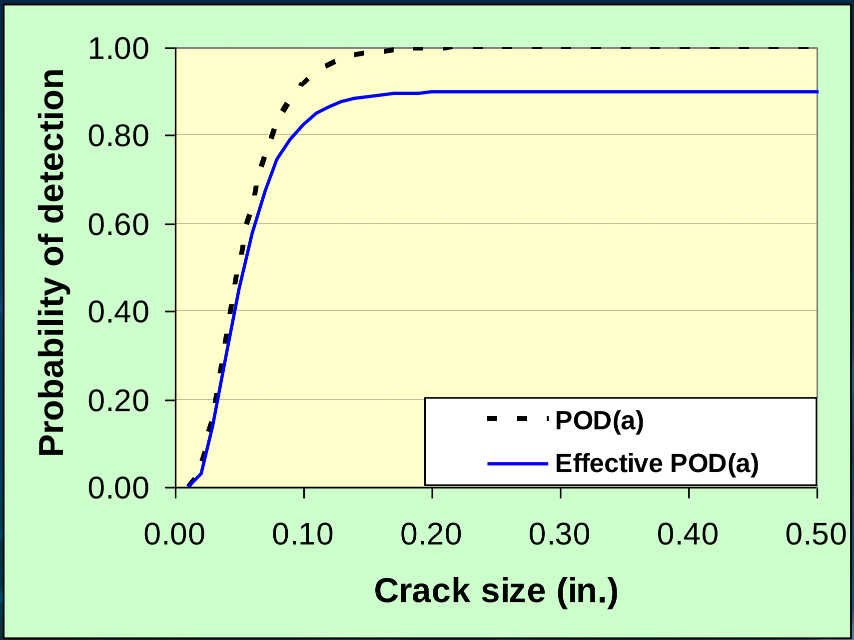


Monotonically decreasing



DSTO

Probability of detection



☞ POD a function of crack size

☞ POD influenced by many factors

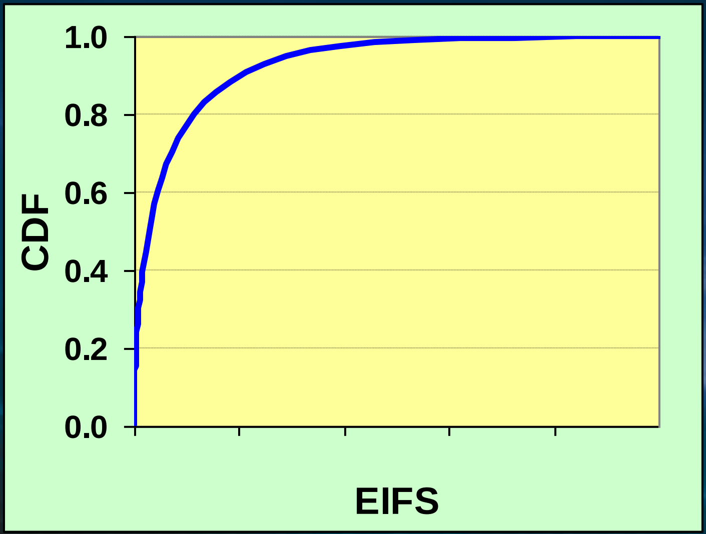
☞ *Eff. POD(a) = POI x POD(a)*

o Probability of inspection (POI) accounts for variability of inspection at various sites

DSTO

Equivalent repair crack size distribution

- when considering inspection effects
- crack distribution if inspection is *perfect*
- can be assumed identical to EIFS



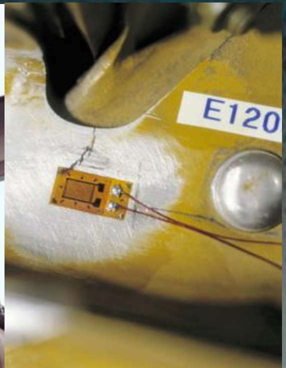
> ➢ *Perfect inspection* will only lead to equivalent repair crack size distribution *not zero cracks*

$$f_{\text{after}}(a) = P \cdot f_R(a) + [1 - POD(a)] \cdot f_{\text{before}}(a)$$

$f_R(a)$: equivalent repair crack distribution

$f_{\text{before}}(a)$: crack distribution before inspection

$f_{\text{after}}(a)$: crack distribution after inspection



Analysis Tools

- Tools : Risk Analysis Program options

PROF

- Distribution models are fixed
  - Peak stress can only be modelled as Gumbel type 1,
  - Fracture Toughness can only be modelled as Normal Distribution,
  - Probability of Detection (POD) can only be modelled by Lognormal Distribution

Does not have flexibility

DSTO

Analysis Tools

It was decided to use In-house analysis program for the following reasons :

- To develop a program that has more flexibility of the choice of distribution
- To develop a program that can be integrated with exising DSTO programs
- To gain more understanding and confidence on probabilistic risk analysis

Analysis Process

Probability of Fracture (POF)

$$POF = \int_0^{\infty} f(a)\big(POF(a)\big)da = \int_0^{\infty} f(a)\left(1 - \int_0^{s_{RS}(a)} f(s)ds\right)da$$

Where : s = stress , a = crack size, a_{rs}= critical crack size, s_{RS}= residual strength

$$POF = \int_0^{F_C} POF\left(F^{-1}(u)\right)du + (1 - F_C)$$

PROF program

➢Integration *about probability*, F_c

$$POF = \sum_{i=1}^{n_{CR}} PMF(a_i)\left[1 - \sum_{j=1}^{k_{RS}} PMF(s)\right] + [1 - F(a_{CR})]$$

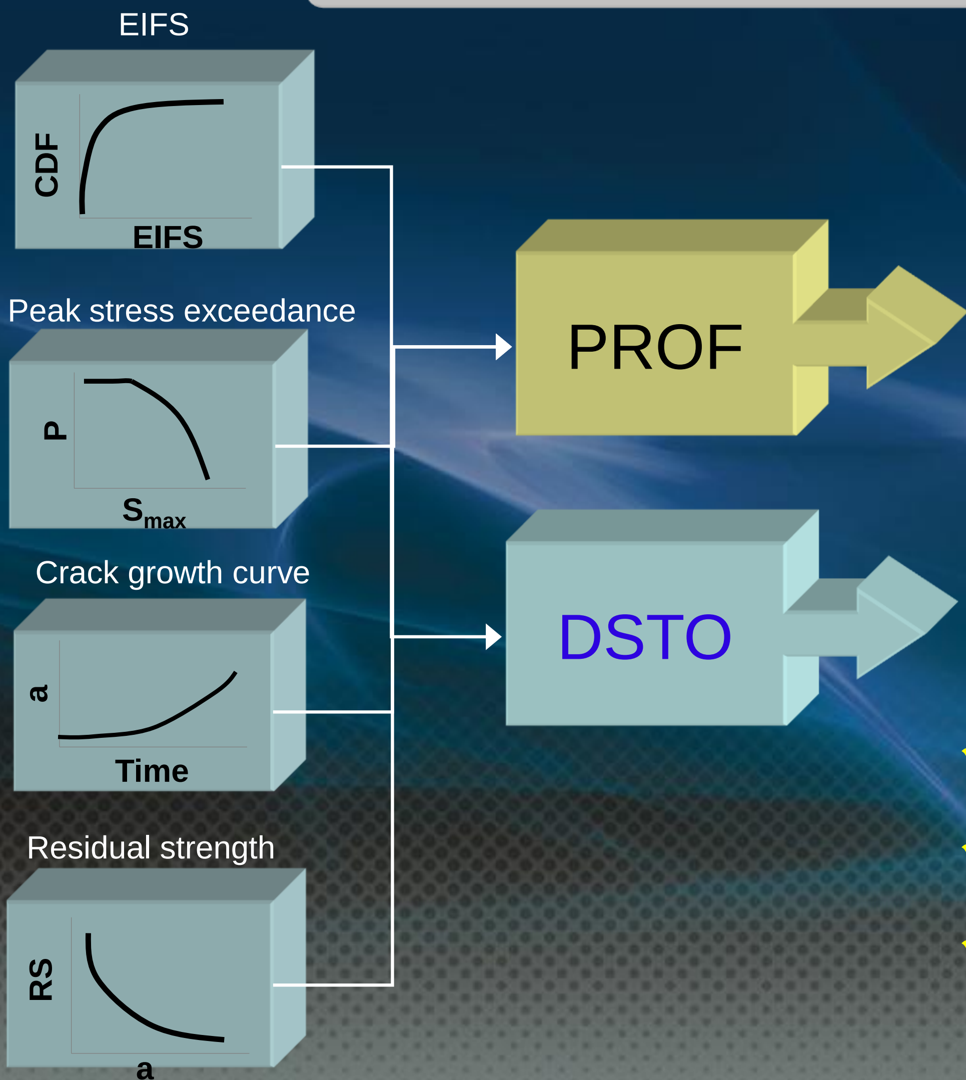
DSTO in-house program

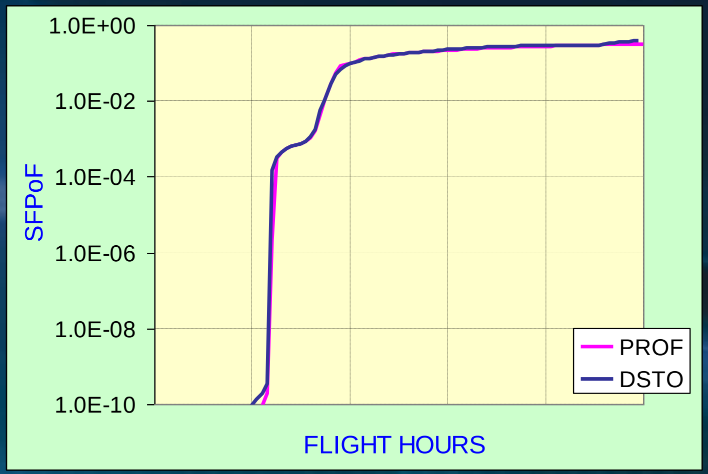
➢Integration about the *crack size, a*

DSTO

Verification of DSTO In-House Program

Sample problem 1 – Comparison with PROF

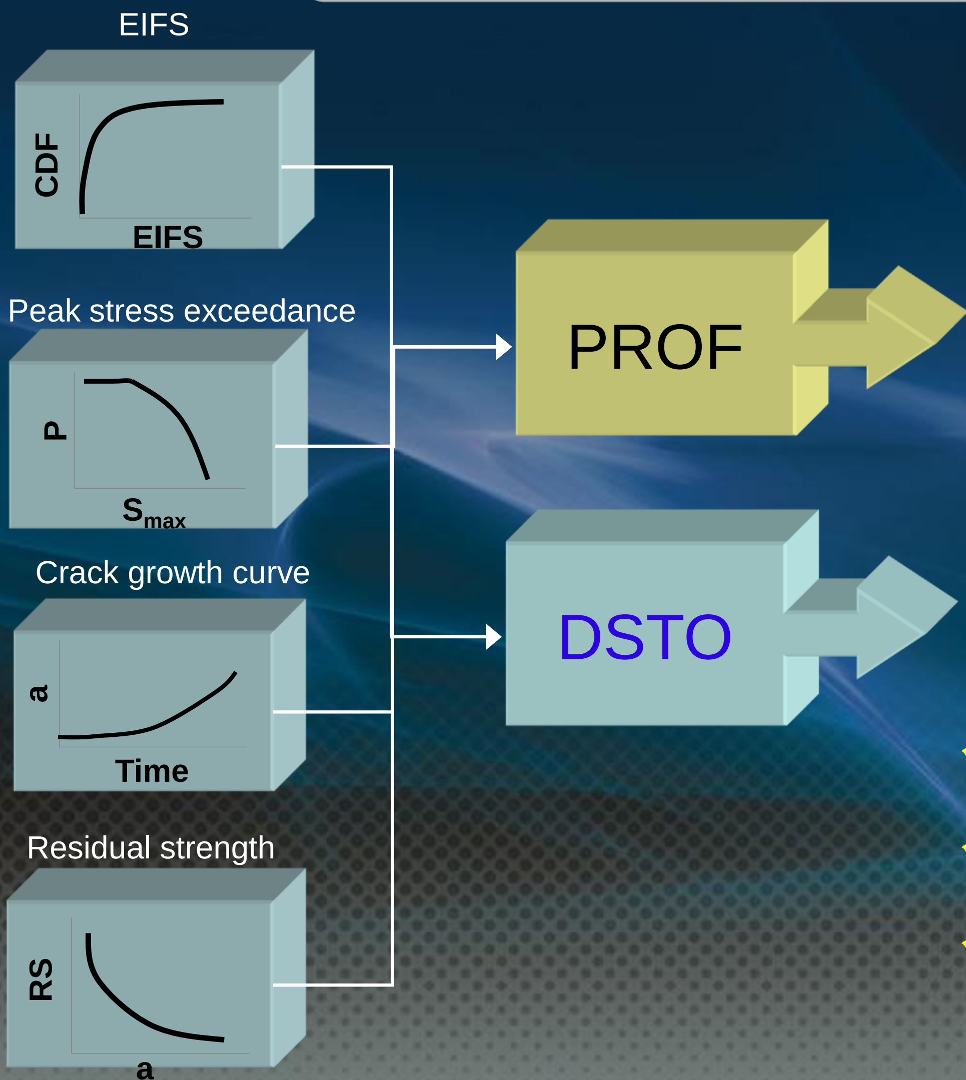


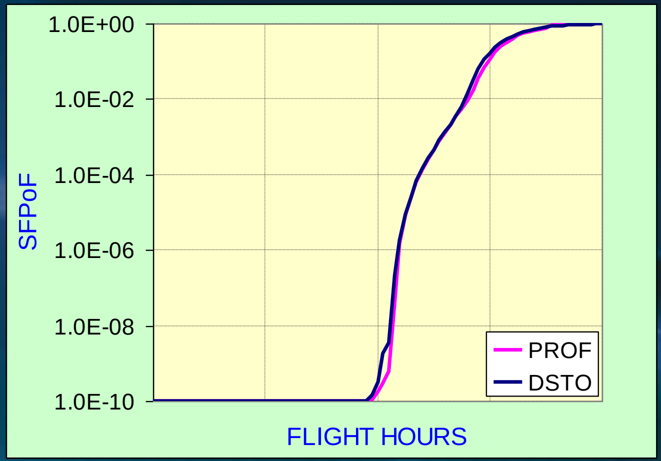


- ✓ Data used from *PROF*
- ✓ Results are compatible
- ✓ Validates the result from DSTO

Verification of DSTO In-House Program

Sample problem 2 – Comparison with PROF



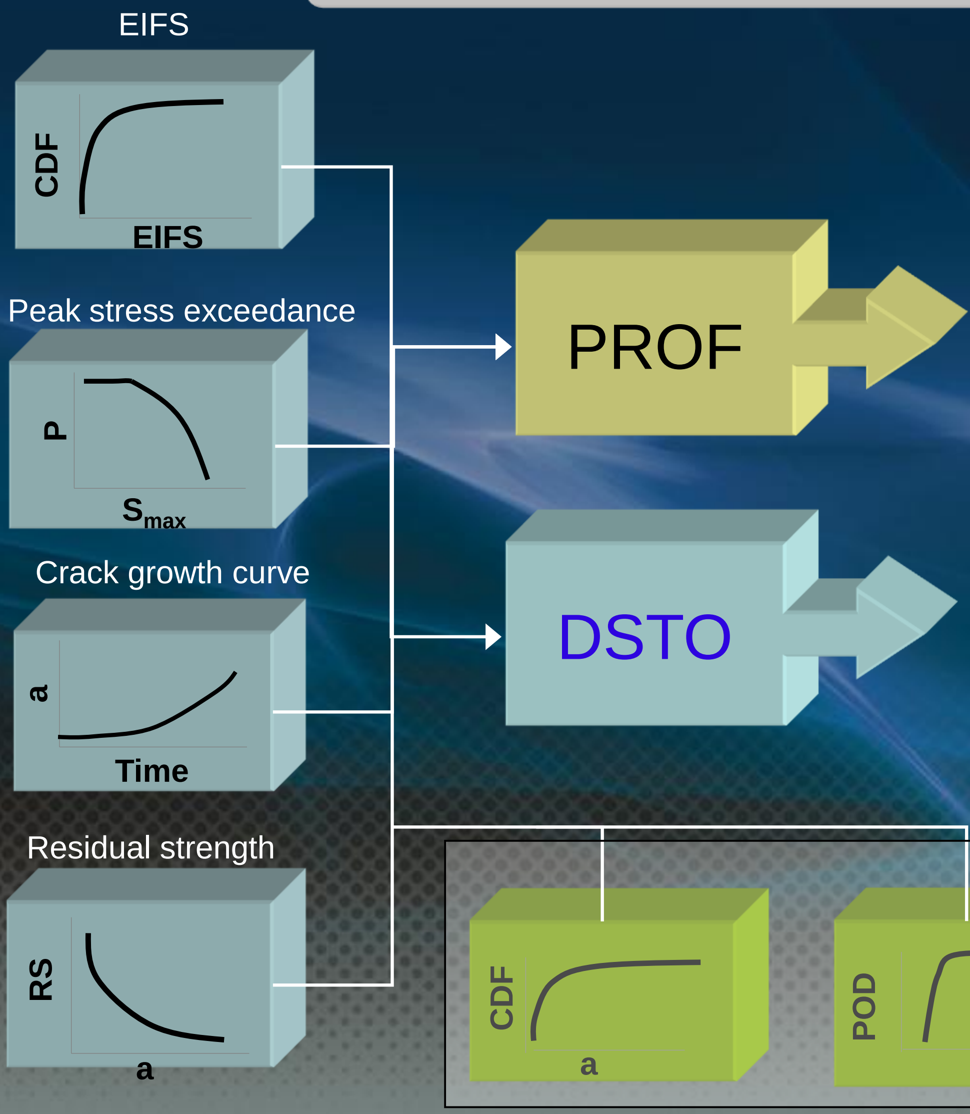


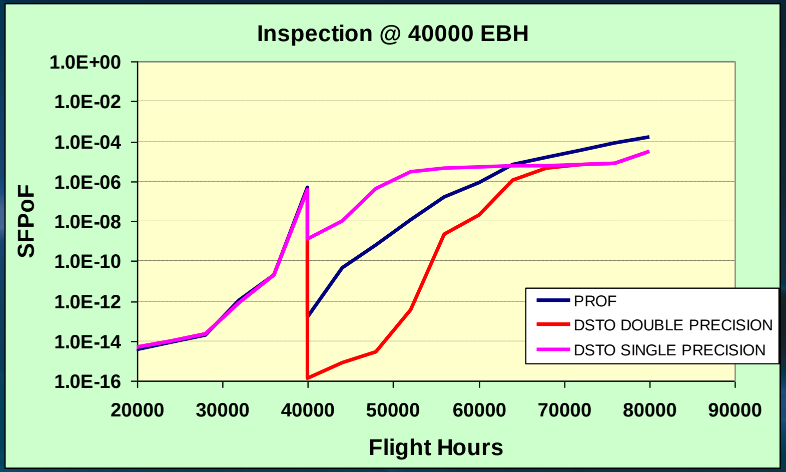
- ✓ Data used from *C130*
- ✓ Results are compatible
- ✓ Validates the result from DSTO

DSTO

Verification of DSTO In-House Program

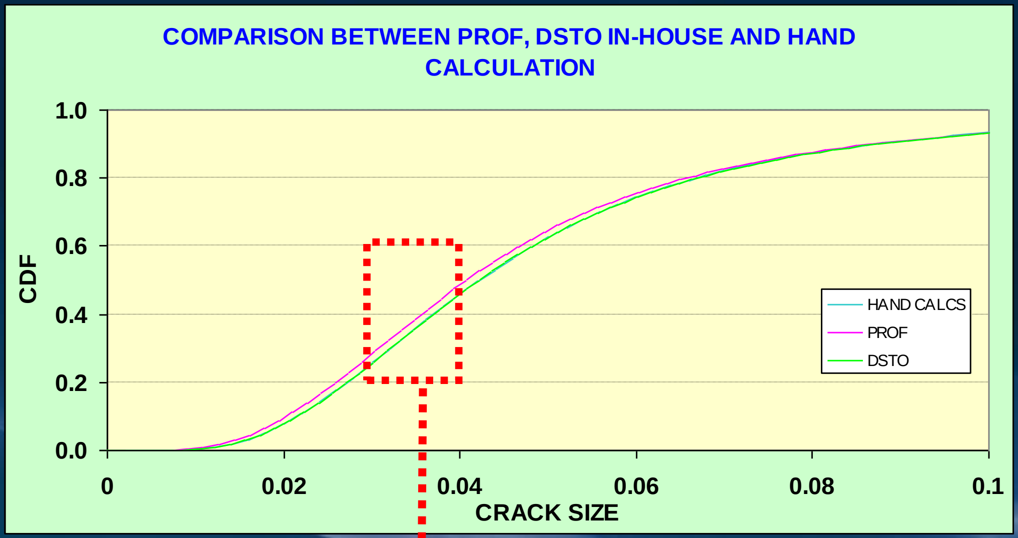
Sample problem 3 – Comparison with PROF

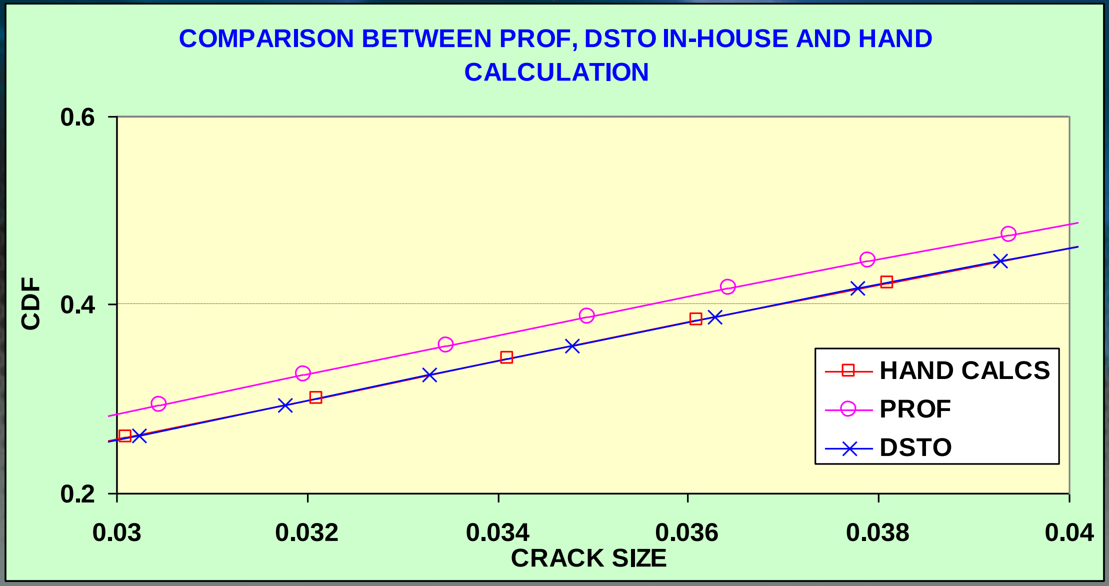




- ✓ Lower using double precision
- ✓ Higher using single precision

After inspection results checked against Sample Problem from Air Force Research Laboratory Report (AFRL-RB-WP-TR2010)





DSTO In-house program results much closer to 2010 Guidelines Risk and Reliability handbook

DSTO

AFRL-RB-WP-TR-2010-XXXX

STRUCTURAL TECHNOLOGY EVALUATION AND ANALYSIS PROGRAM (STEAP) FA8650-04-D-3346

Subcontract: F3346-09-43-SC01-01 (GDIT)

Aircraft Structural Risk & Reliability Analysis Handbook Phase 2

Robert P. Bell, Alan P. Berens,
Thomas Brussat, Joseph P. Gallagher,
Joseph W. Cardinal, James Rudd
Universal Technology Corporation

MAY 2010
Mid Year Report

Presently treat as FOUO. *(Final distribution to be evaluated by Air Force; intention is to be "Distribution Statement A: Approved for public release; distribution unlimited.)*

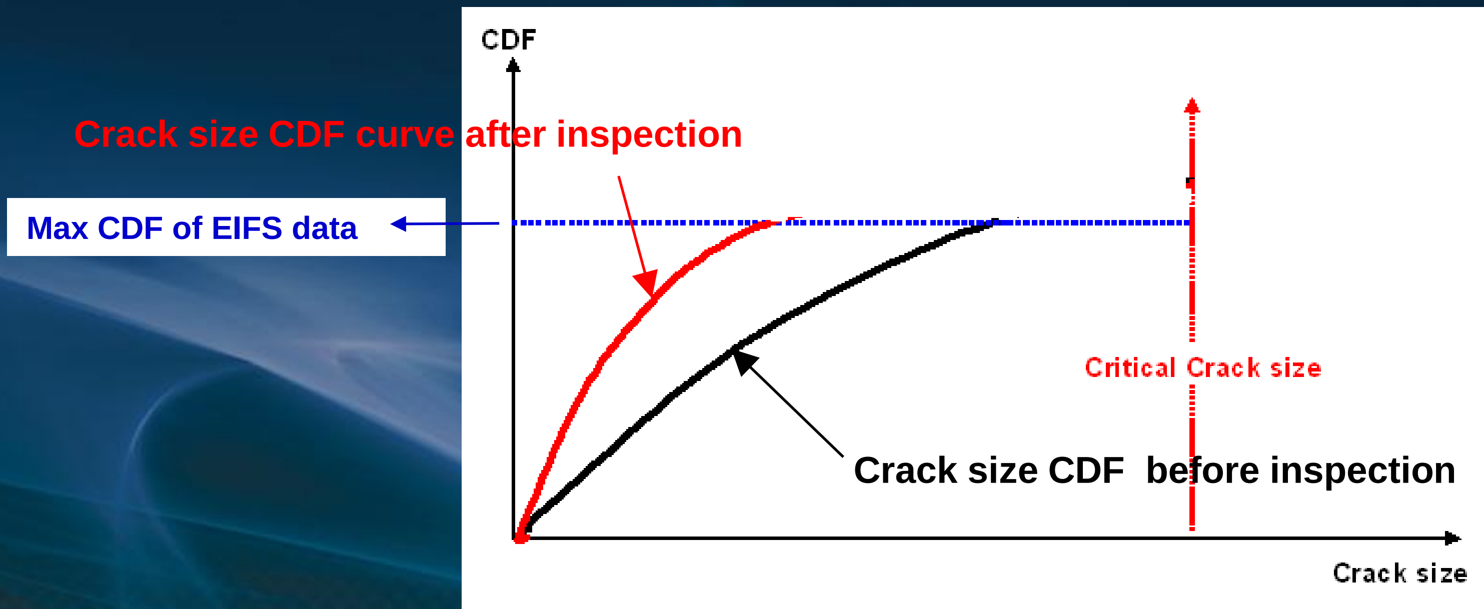
AIR FORCE RESEARCH LABORATORY
AIR VEHICLES DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7541
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

FOR OFFICIAL USE ONLY

DSTO

PROF and DSTO In-House Analysis Program

Why is there difference between PROF and DSTO results after inspection?

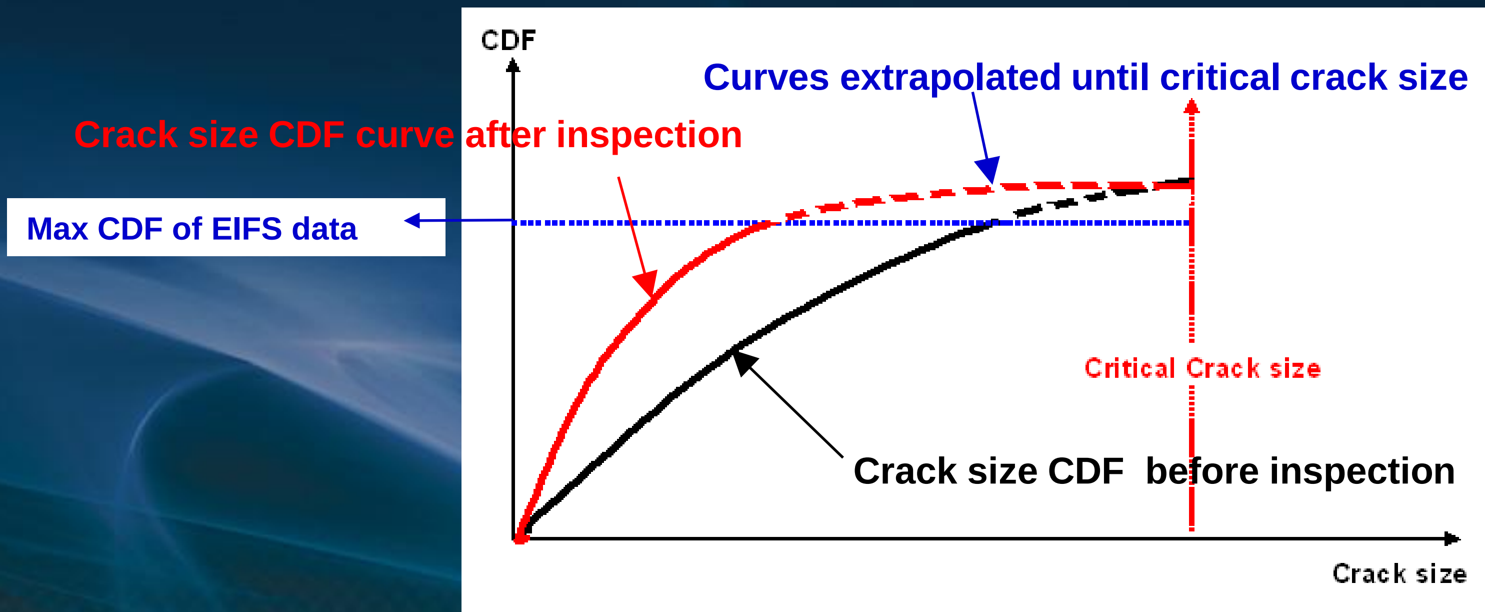


1) CDF curve is extrapolated until the critical crack size (*see dashed line)*

2) Extrapolation is based on exponential equation. Thus magnitude of error is also exponential.

PROF and DSTO In-House Analysis Program

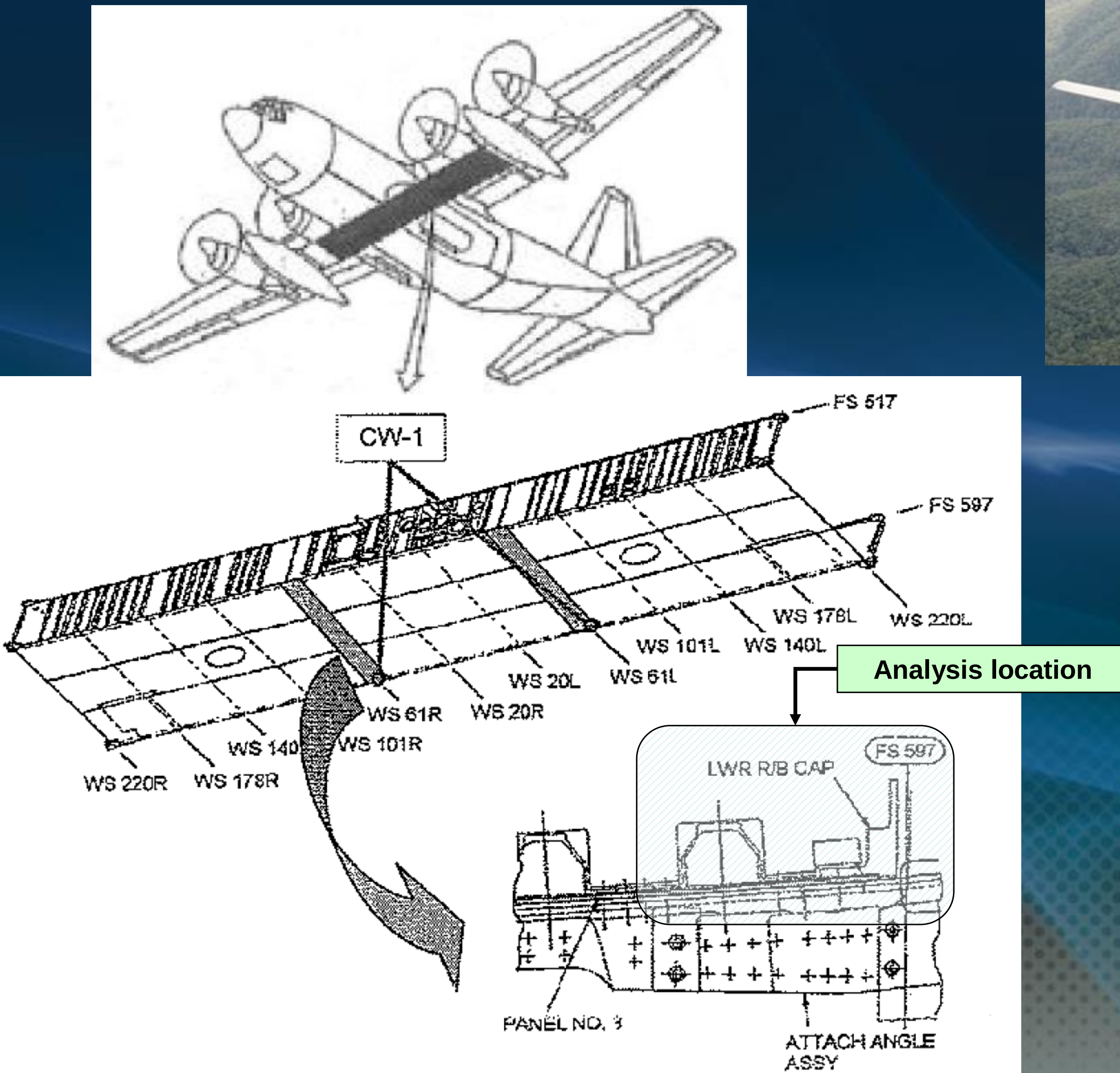
Why is there difference between PROF and DSTO results after inspection?



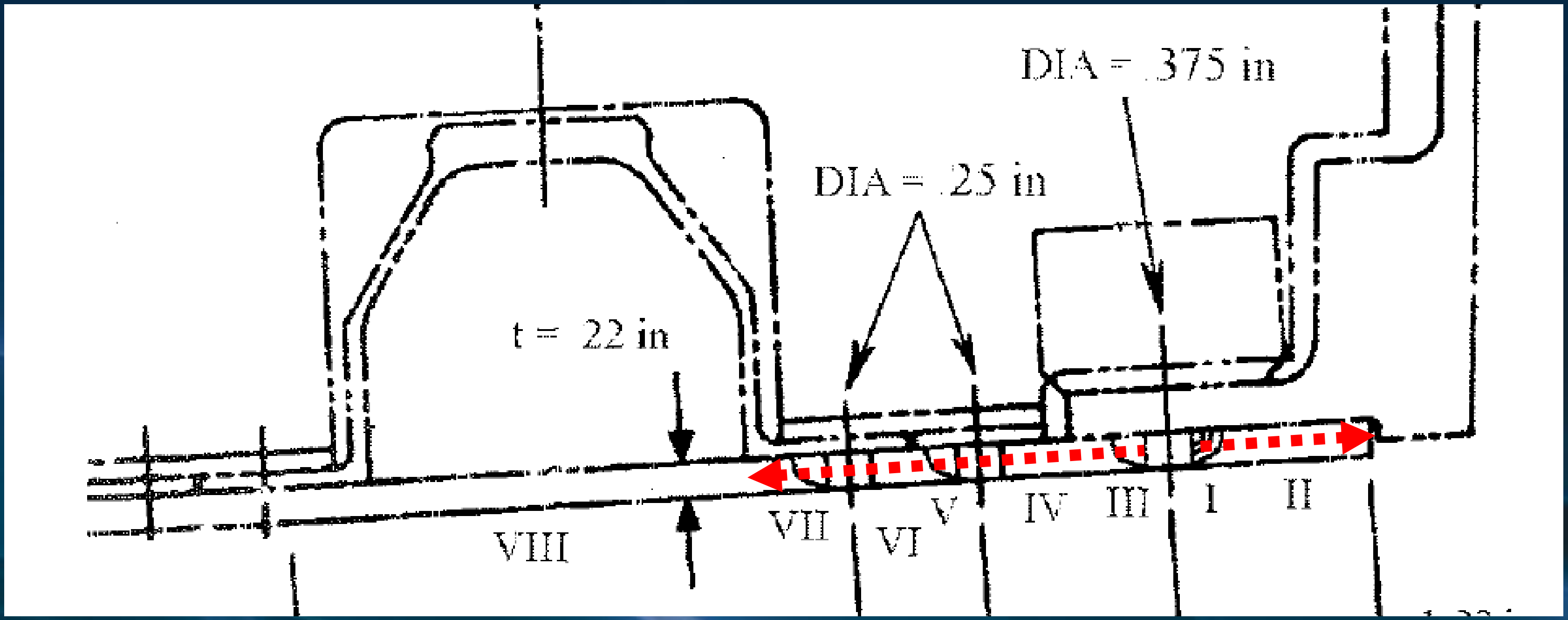
1) CDF curve is extrapolated until the critical crack size (*see dashed line)*
2) Extrapolation is based on exponential equation. Thus magnitude of error is also exponential.

DSTO

C130H CW-1 Risk Analysis



Crack Propagation Scenario Analysed

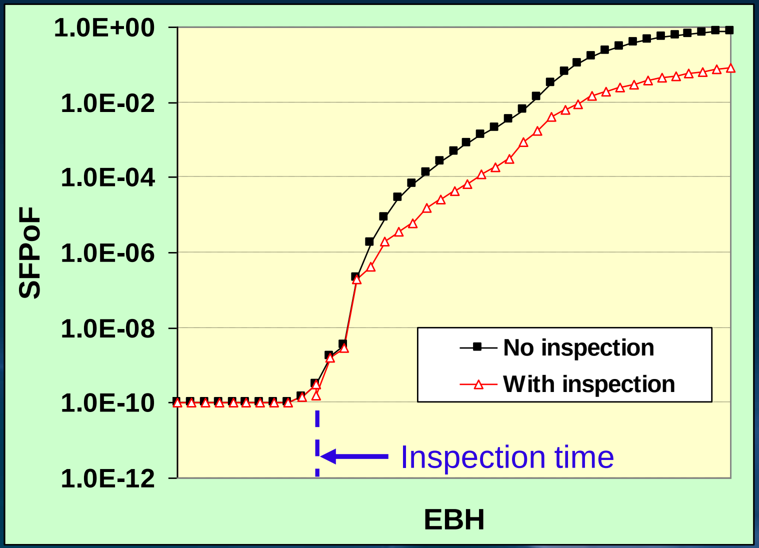


Crack propagation   I, II, III, IV, V, VI, VII

- Analysis assumes a crack phase by phase approach
- Multi site damage (MSD) not considered

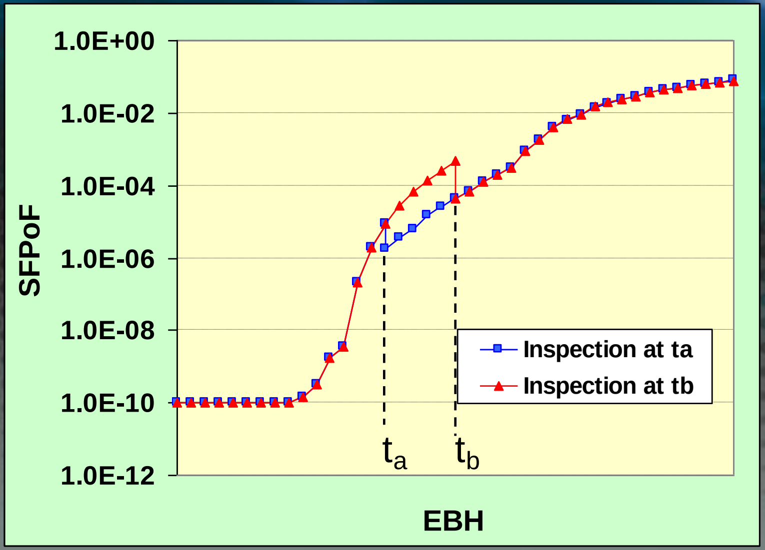
Comparison of Probability of Failures

- Effect of inspection



- Effect of inspection shows time lag

- Effect of varying inspection times



- Inspection more efficient when delayed
- Risk almost identical after second inspection

DSTO

Concluding Remarks

- Methodology to conduct a Probabilistic Risk Analysis has been developed
- DSTO's in-house PRA analysis software give identical results with PROF

➢ Effect of Inspection

- Reduction of failure probability from inspection is more effective when done later in its fatigue life
- When inspection is done early, the reduction of failure probability is not immediate.

DSTO

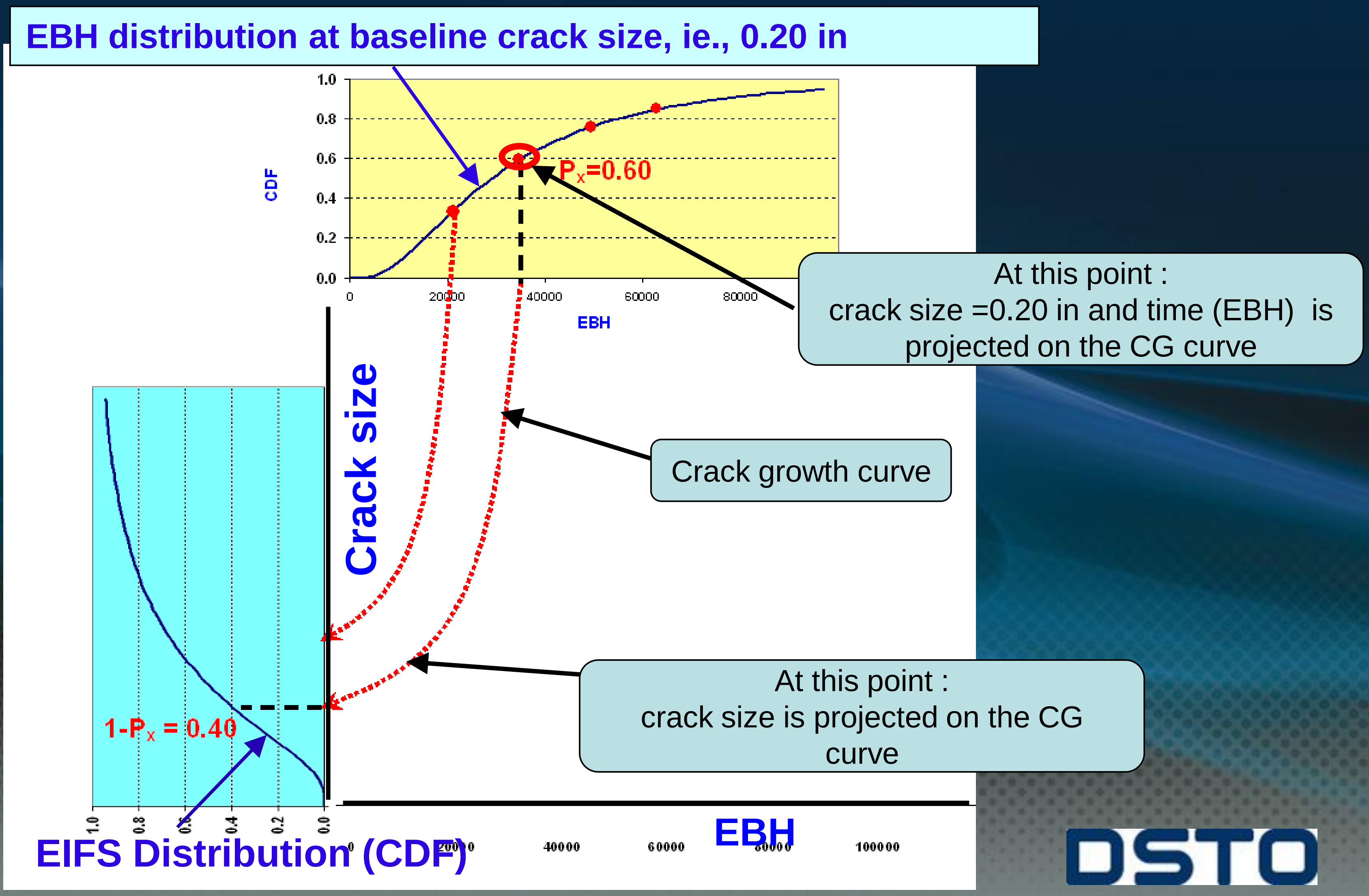
Concluding Remarks (cont.)

- ➢ Effect of varying inspection times
- o Inspection time needs to consider the risk level to optimize failure risk reduction.

DSTO

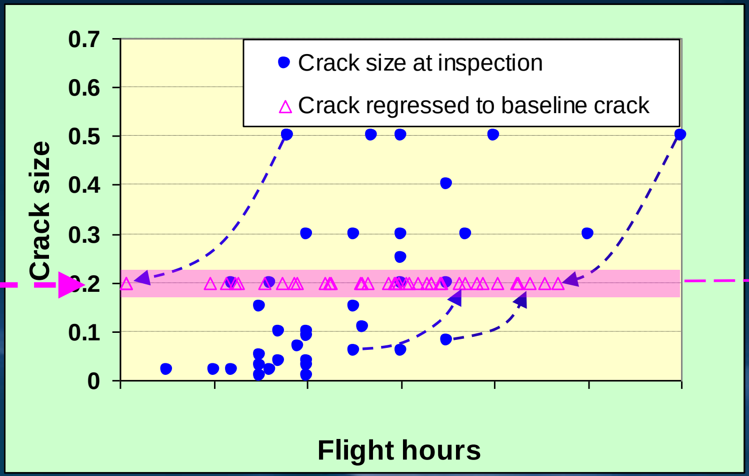
Any question?

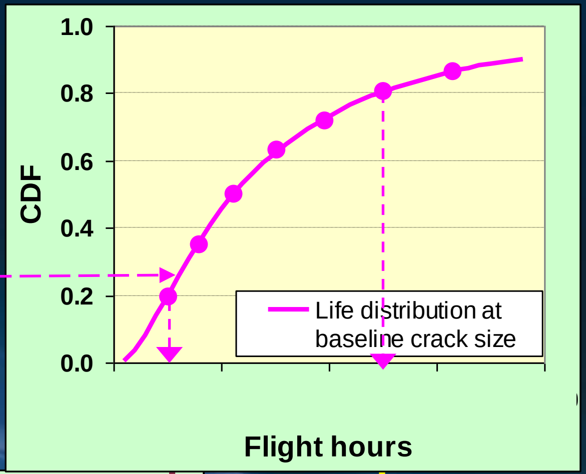
EIFS Regression Procedure



EIFS calculation procedure

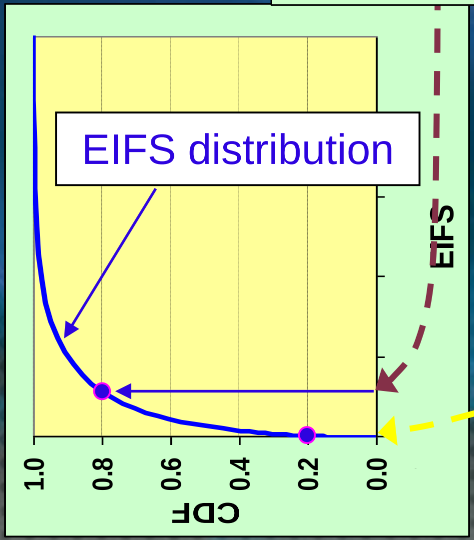
Life distribution at a=0.20 in





Mean of crack data = 0.20 in.

Assumed as baseline crack size



CG curve

Crack distribution at t=0
(i.e., EIFS)