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Application of the Holistic Structural Integrity Process to Canadian Forces Challenges

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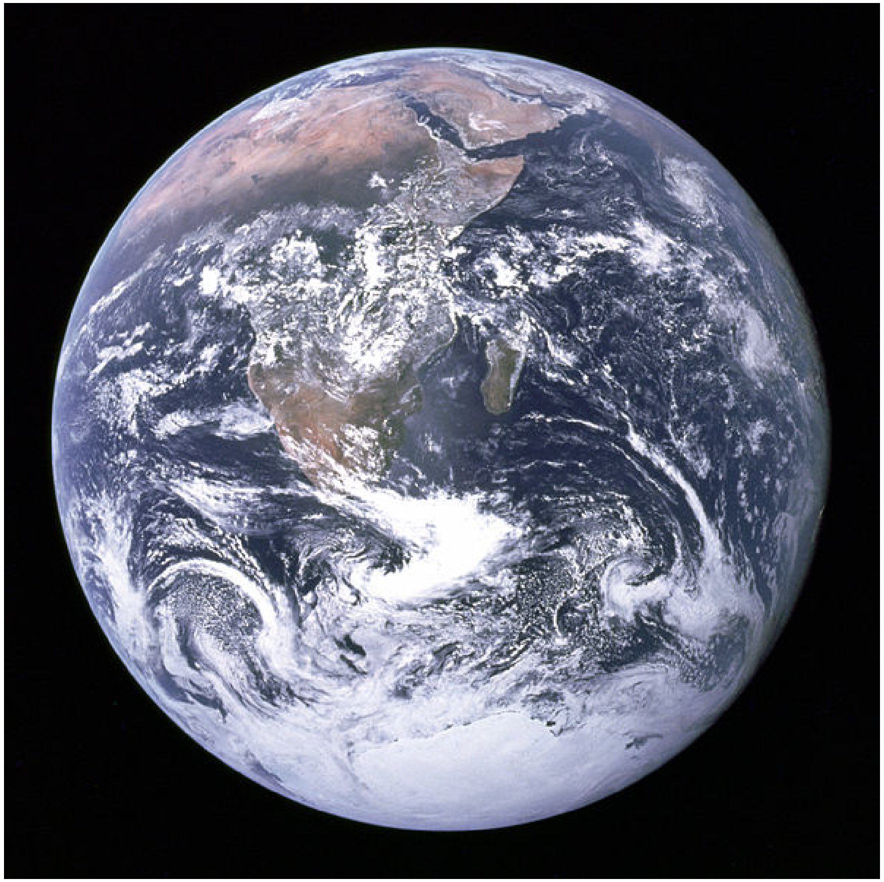
HOLISTIC



The Earth seen from Apollo 17.

From a **holistic** perspective, the universe exists in and forms integrated webs of wholeness, often beyond our direct perception. [Wikipedia]

Opening Remarks

- Introducing new tools to the evaluation and support of Aircraft Structural Integrity is a slow process as safety of flight is at stake.
- The approach we have taken is to test the new tools by using real examples in parallel with existing tools.
- The new tools described in this presentation have the potential to provide new decision basis for better management of aircraft structure in the future, they are not yet used for decision making by Canadian Forces at this time.

Outline of Presentation

- Background
- Current Canadian Forces (CF) Lifing Methodologies
- Challenging Issues with Existing Lifing Methods
- Holistic Structural Integrity Process (HOLSIP) Framework
  - Case Study: CF-18 Corrosion Fatigue Analysis
- HOLSIP Based Risk Assessment
  - Case Study: CFCW-1 Lower Surface Panel
  - Case Study: Risk Analysis on CP140 (P3)
- Concluding Remarks
- Future Work

Background

- CF military aircraft have been certified using diverse standards.
- Uniquely “Canadian” service usage:
  - significantly different from Certification Spectrum,
  - affects Certification defined Safe Life, Crack Growth and Residual Strength.
- Prior service history (> 20 years!) missing on most fleets before concerted loads monitoring efforts begun.

Background

CF Legacy Aircraft Problems

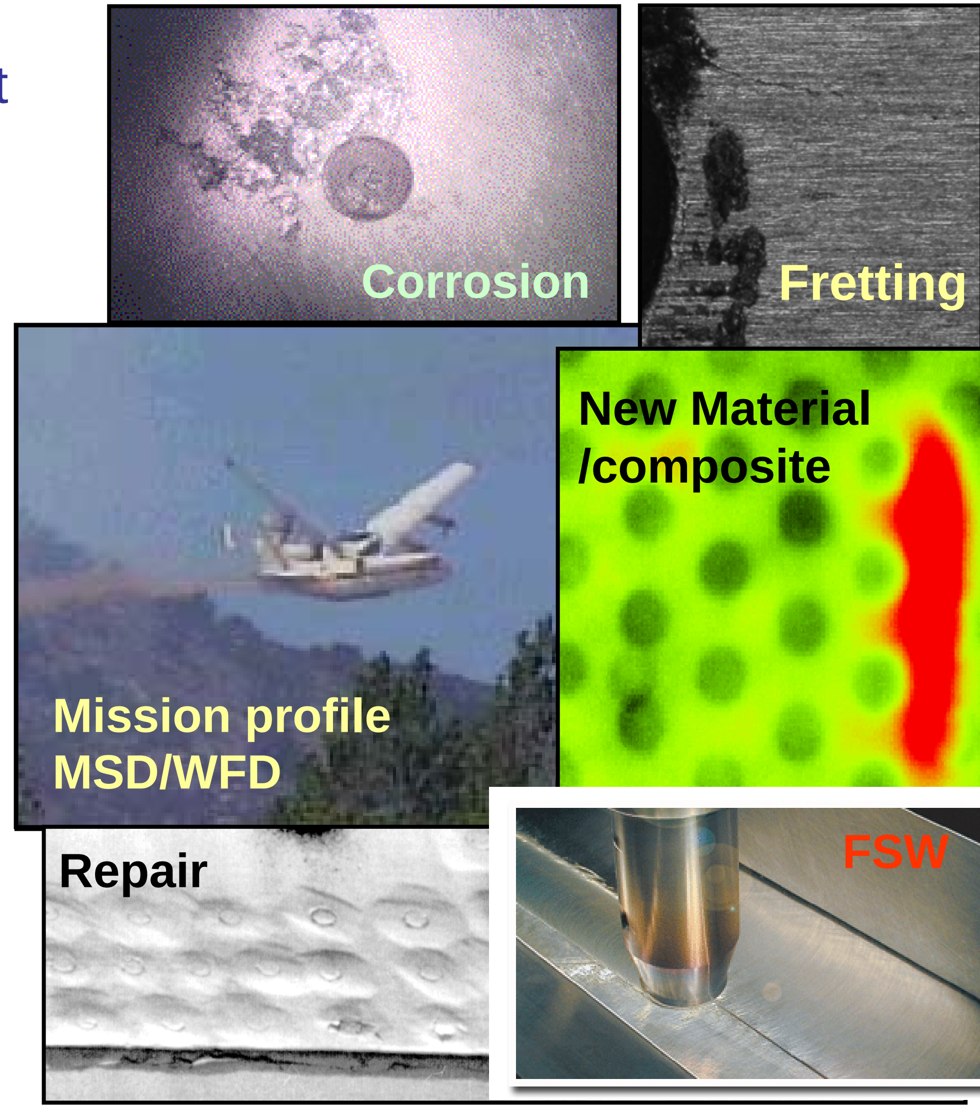
- Lack of:
  - spectrum / design criteria / historical usage info,
  - component tracking (components interchanged between aircraft) & incomplete component history cards.
- Aircraft operated in “unknown territory”:
  - no demonstrated lives in accordance with actual usage.
- Damage is occurring on aircraft where it did not occur in original Full Scale test and vice versa.

Current Lifing Methodologies

- **Safe Life (SL):**
  - Originally used to life CF188 Hornet, CT114 Tutor (Snowbirds)
    - How to extend the life after ‘Safe Life’?
- **Damage Tolerance (DT):**
  - Originally used to life CC144 Challenger, CT142 Dash 8, CT156 Harvard II
  - Currently being used on the CT114 Snowbirds, CF118 Hornet and repairs for the CC130 Hercules
    - Difficulty analyzing fail safe structures
    - Load redistribution not taken into account

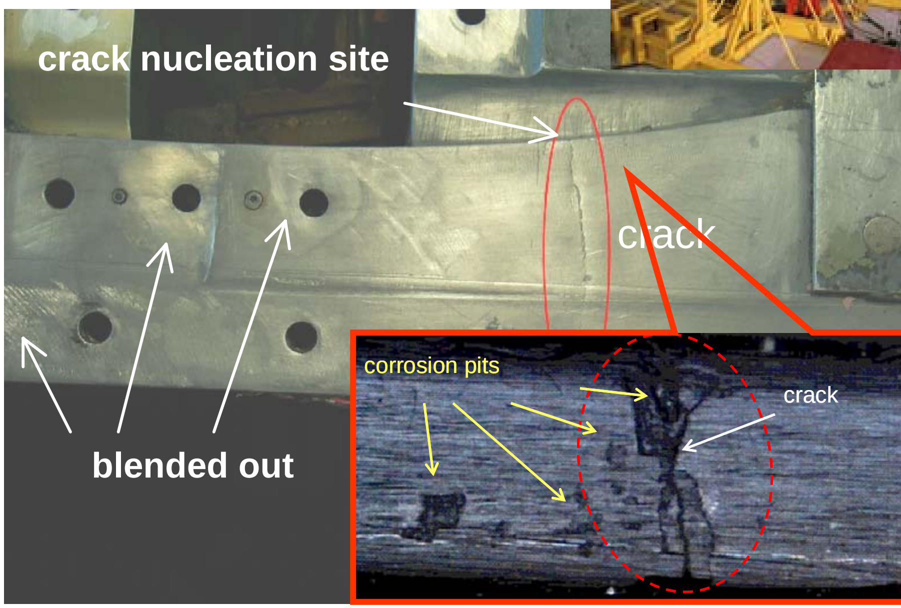
Issues ….??

- **Challenging issues** - the current lifing paradigms, do not adequately take into account:
  - Complex damage scenarios (MSD/MED/WFD…)
  - Repair damage
  - Environmental and age degradation modes (corrosion pitting/SCC, fretting/wear…)
  - Difficulty with new materials (composites) and manufacturing techniques (i.e. friction stir welding)
  - Changes/unknown in mission profiles

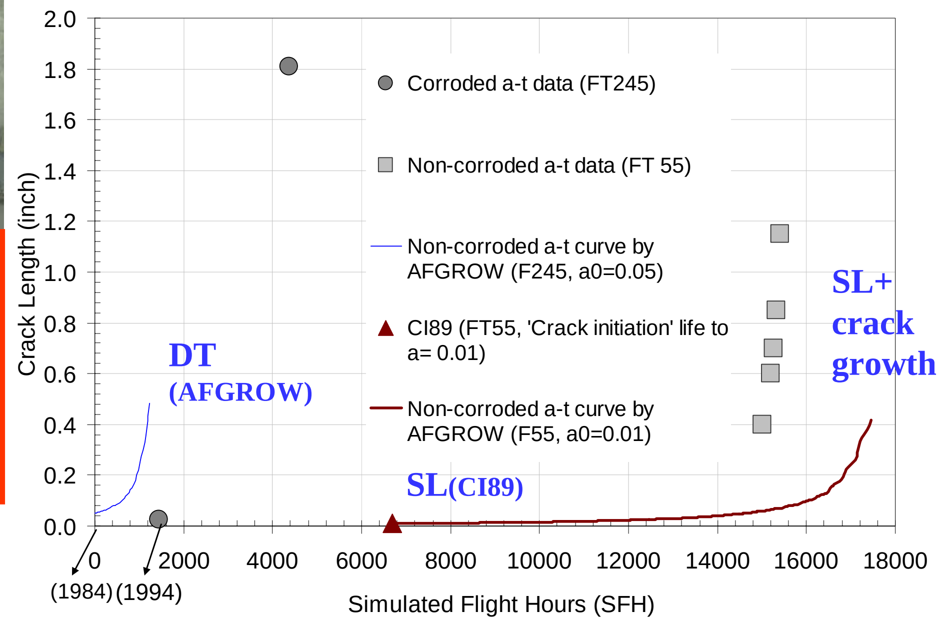


Example Issue 1 : CF-18 Corrosion Fatigue

Full Scale Wing Test



Fatigue Life Analysis



Crack (1.81 inch) found at 2932 simulated FH in the longeron.

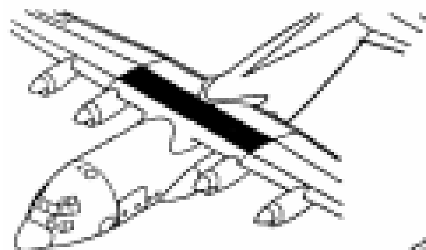
Crack nucleated from corrosion pits on upper outboard longeron

DT life is too short.
SL life is conservative
SL+ crack growth is not conservative

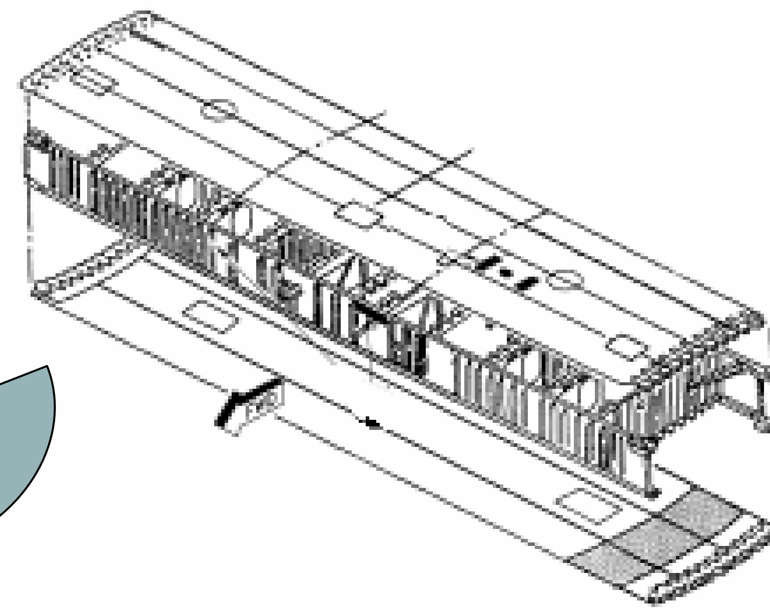
Example Issue 2: CC130 Center Wing MSD/WFD

- **CW-1:**10 of 30 A/C inspected had cracked Lower Aft Wing Panels
- CW-12: 11 cracked/severed Corner Fittings
- CW-14: 12 cracked/severed Lower Forward Spar Caps
- CW-9: 13 cracked Rainbow Fittings
- CW-11: 14 cracked Lower Forward Wing Panels

What is the risk of getting there?



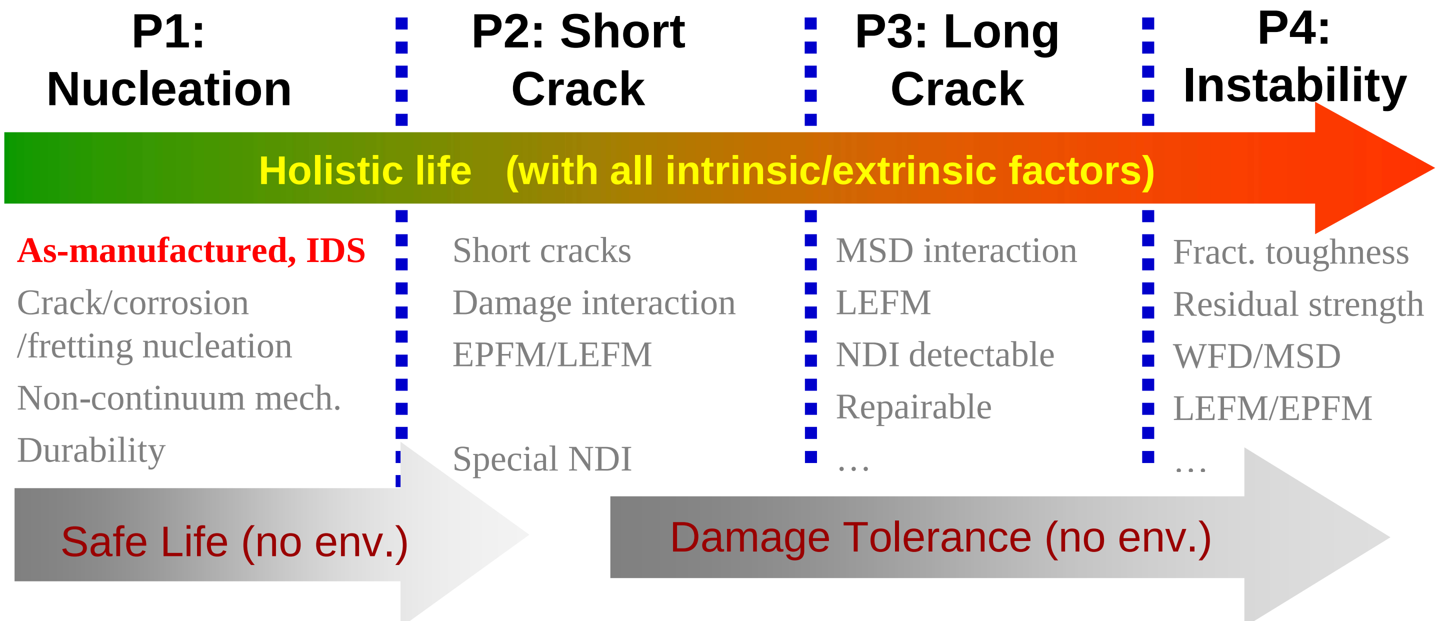
With these In-service damages



Holistic Structural Integrity Process

- The ever-growing demands on aircraft availability and sustainment is resulting in a significant increase in the cost of maintaining existing aircraft due to the detection of unanticipated damage.
- Physics-based models have recently been developed to predict structural degradation and failure modes to enhance life assessment methodologies. It is now possible to quantify the internal state of a material as well as the external influences that drive the life of a component.
- These advancements have led to the development of a new lifing paradigm that will permit the CF to retain the positive aspects associated with both the safe life and damage tolerance approaches while quantifying the risks associated with all sources of damage. This paradigm is known as the Holistic Structural Integrity Process (HOLSIP), which is capable of positively impacting all aspects of safety, cost and availability through risk management.
- Can also be effectively applied in SHM (DPHM) and elsewhere.

Holistic structural integrity Process (HOLSIP) Development

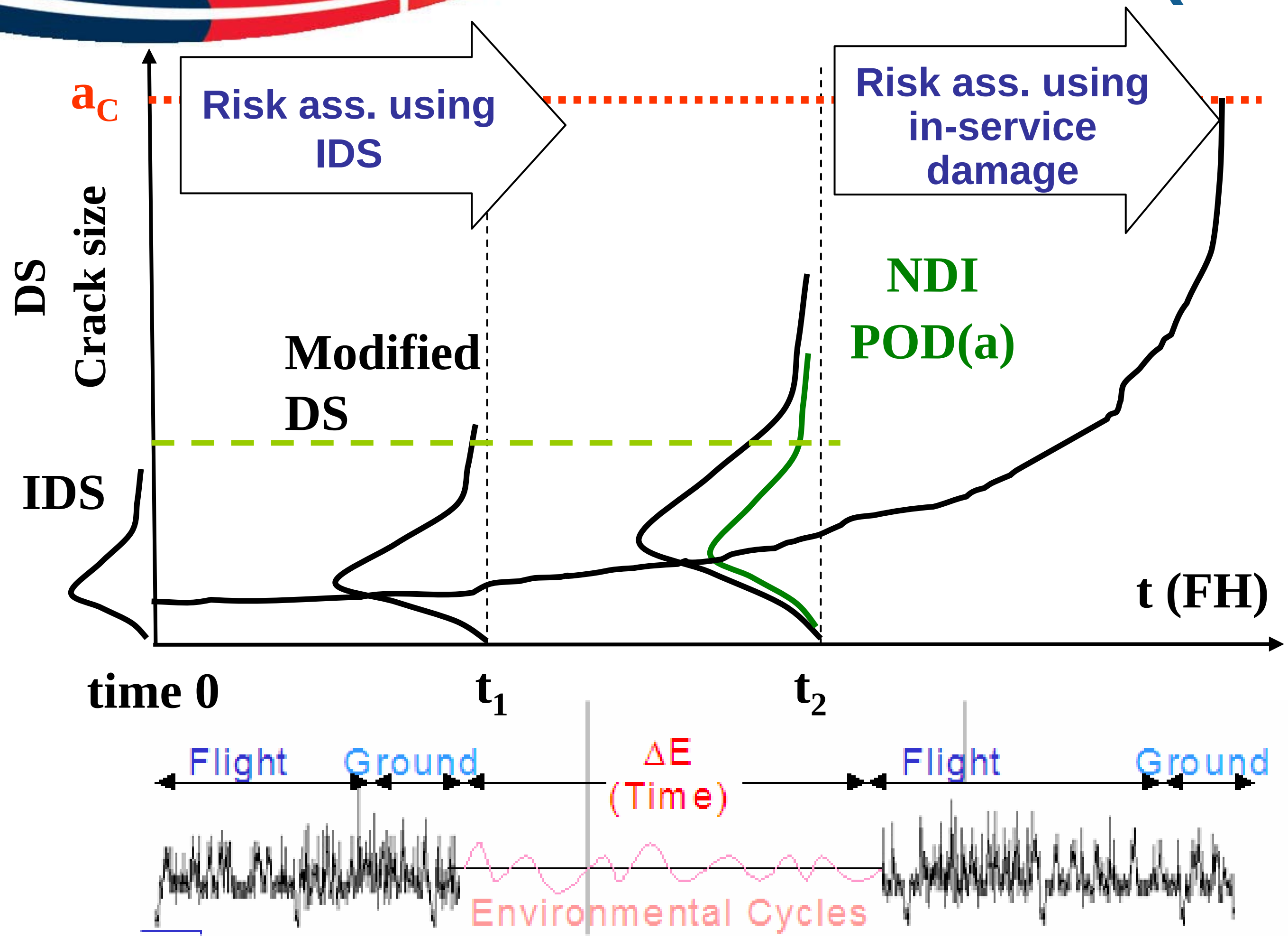


Motivation: augment safe-life and damage tolerant paradigms with the *ultimate* goal to evolve HOLSIP into a new paradigm for both design and sustainment stages.

Key elements: physics based models, probabilistic modeling, health monitoring, advanced NDE and risk assessment…

Developers: NRC, APES, U. of Utah, Tri/Austin, AFRL/USAF,…

HOLSIP: Discontinuity States (DS) Evaluation



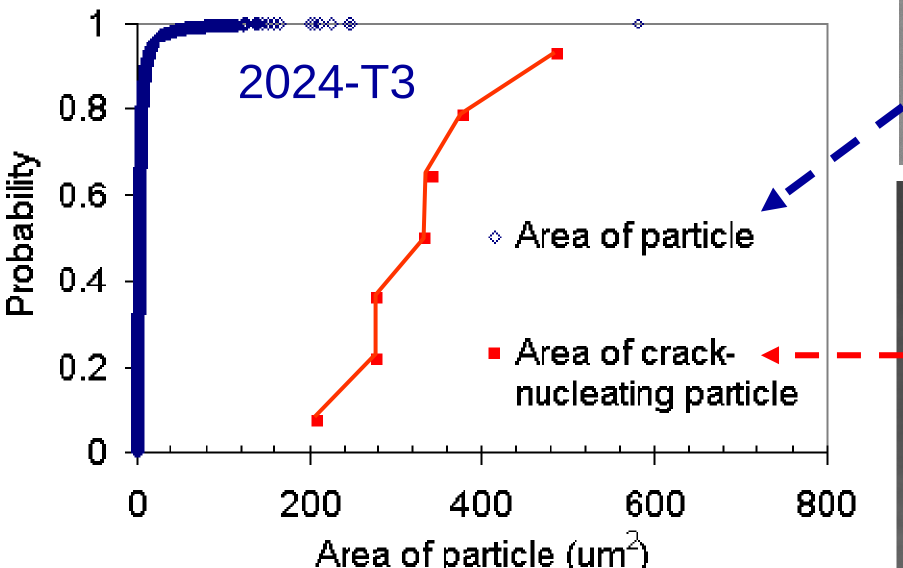
HOLSIP Fundamental Tasks:

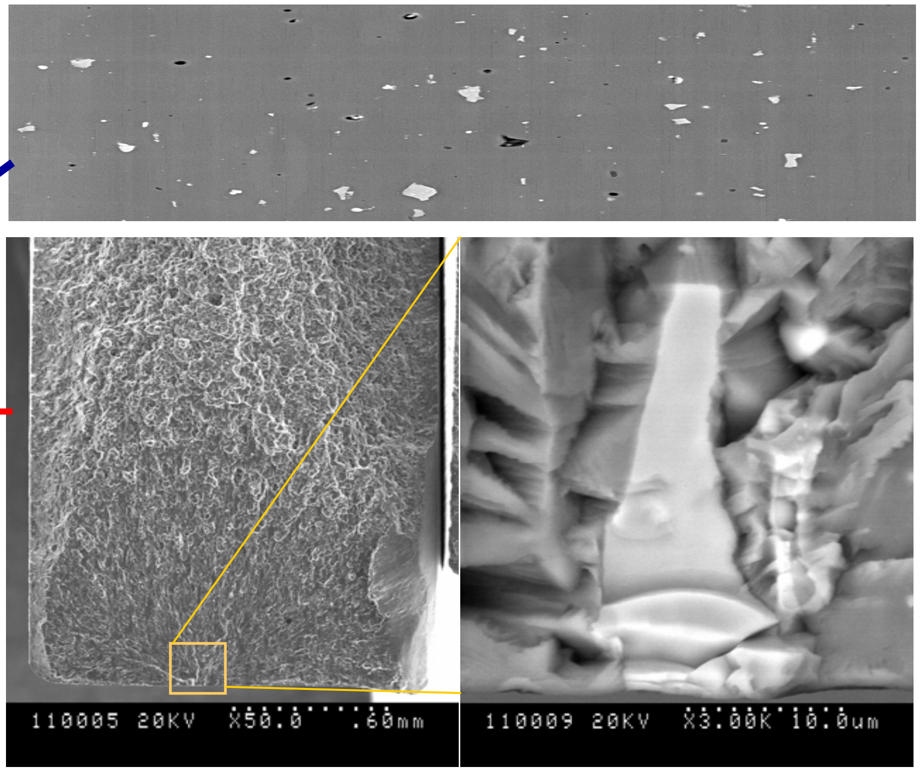
- physically characterize IDS,
- physically model external effects (cyclic and environmental) on IDS.
- …

- Presently, HOLSIP is developing IDS database and physics models to 'evolve' the IDS for *future lifing technology*.

Initial Discontinuity States
(Material Characterization for Future Lifing Technology)

Initial discontinuity states (IDS): The *initial population of discontinuities that are in a structure made of a given material as it was manufactured in a given geometric form*. The IDS is a geometric and material characteristic that is a function of composition, microstructure, phases and phase morphology, and the manufacturing process used to process the material.





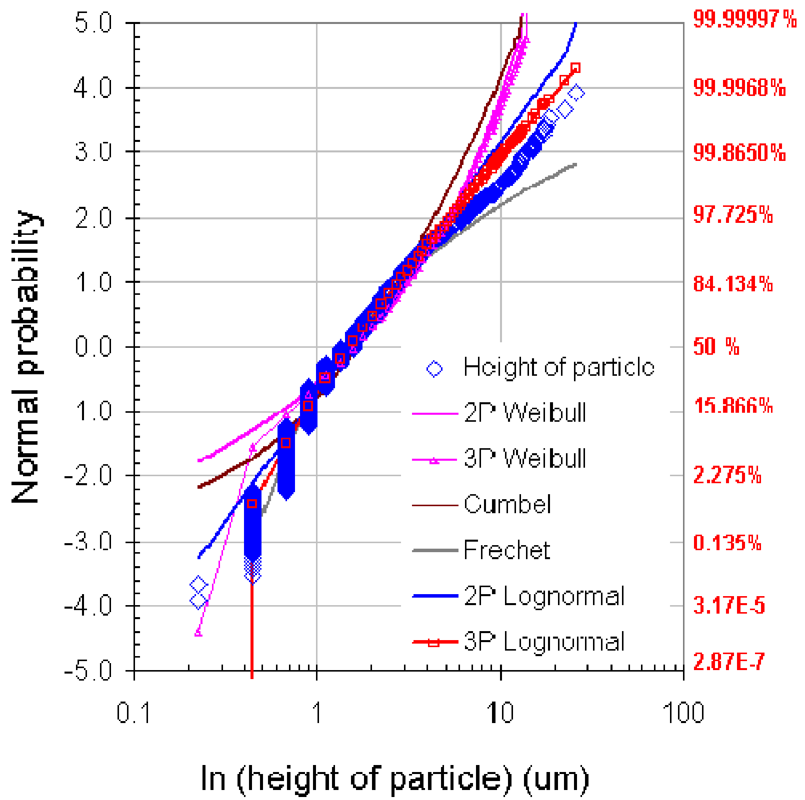
IDS examples: particles, pores, scratches.

IDS Distributions

(Research for Future Lifing Technology)

IDS/particle and pore distribution

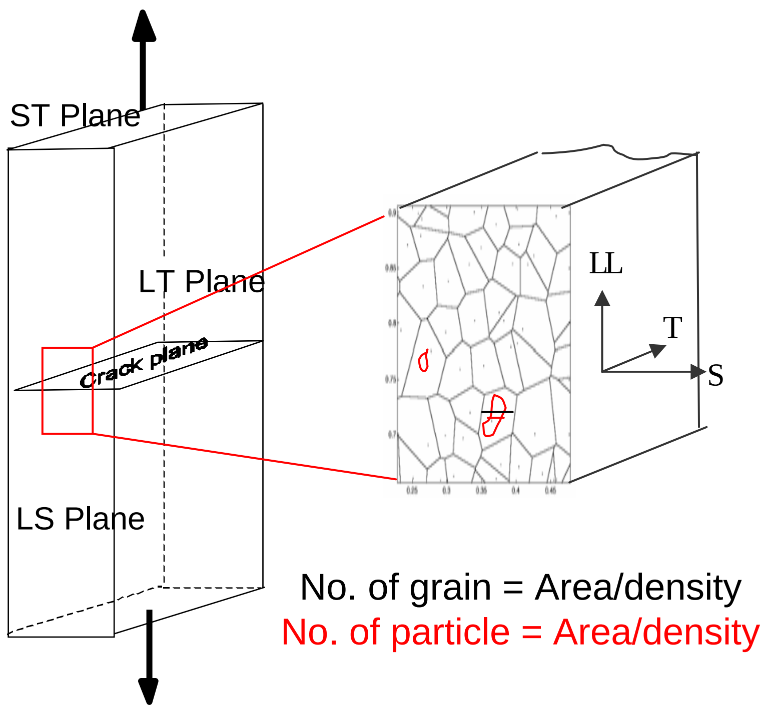
- **<u>A 3 Parameter Lognormal</u>** – best-fit distributions for all material IDS/particle and pores.
- **<u>Weighted 3P Lognormal</u>**: best fit to the ***right tail*** of the distributions.
- **<u>Distribution parameters</u>** were obtained for
  2024-T3
  7075-T6
  7050-T7452
  7079-T6
  7178-T6
  for future HOLSIP application.



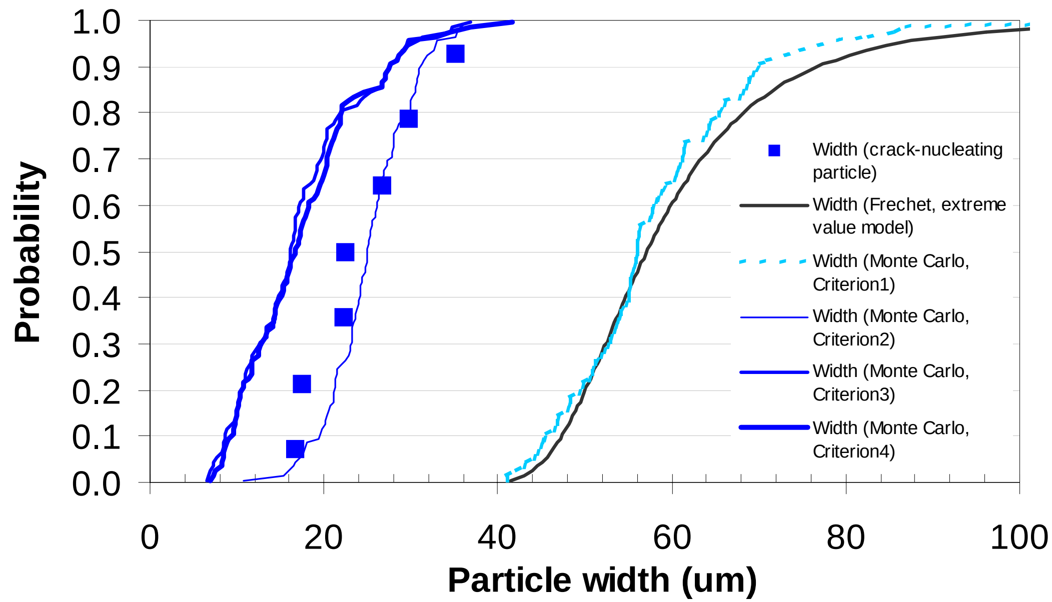
Ex. Goodness-of-fit plot on Normal probability paper (<u>height of particle</u> on ST plane, bare 2024-T3,0.063”CFSD)

IDS Fatigue Subset
(Research for Future Lifing Technology)

Developed a new *Monte Carlo simulation* to correlate material IDS distributions to its fatigue subsets based on material science and micromechanics.



Schematic particle and grain structure on fatigue critical area.

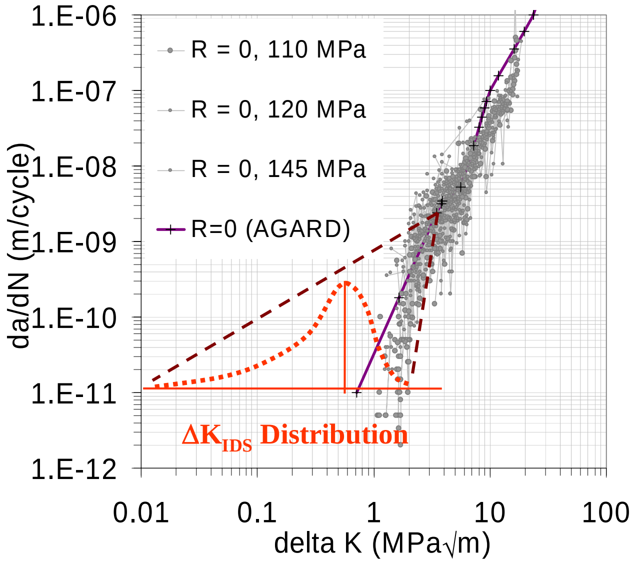


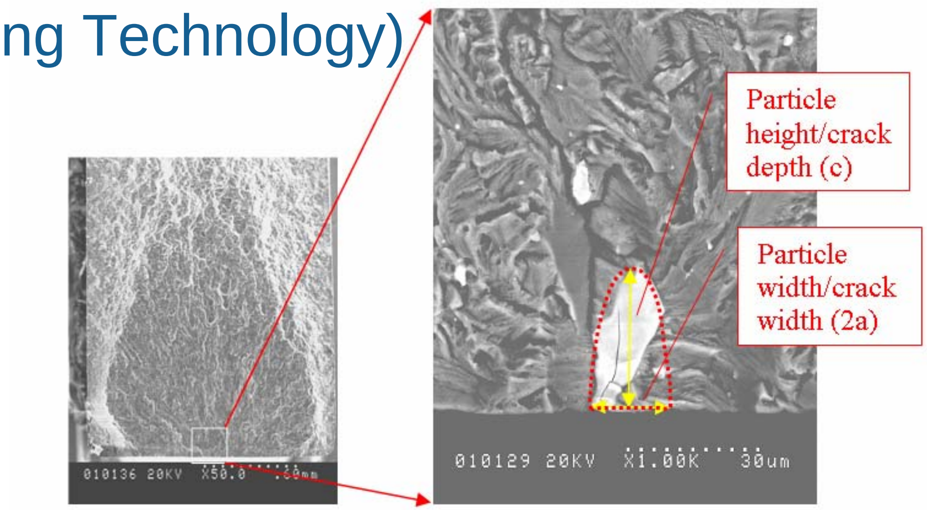
IDS fatigue subsets, prediction and test (2024-T3/0.063”,S_{max}44 ksi,R0.1)

- Particle size, grain size and orientation are considered in the Simulation.

IDS based Short Crack Model

(Probabilistic Modeling for Future Lifing Technology)



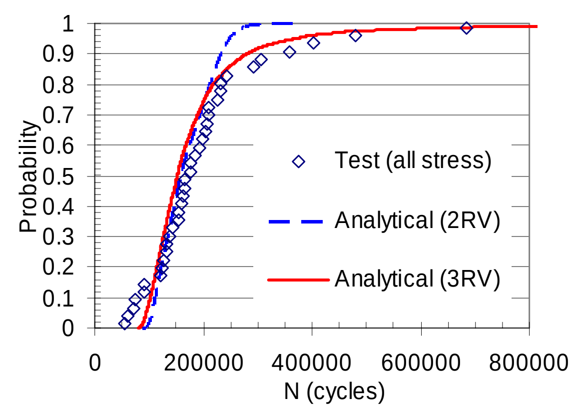


IDS/particle based fatigue model variables, 1) particle width, 2) height,

3) ΔK_{IDS} - combined microstructural effects (particle, grain size, orientation..)

Physics-based short crack model can,

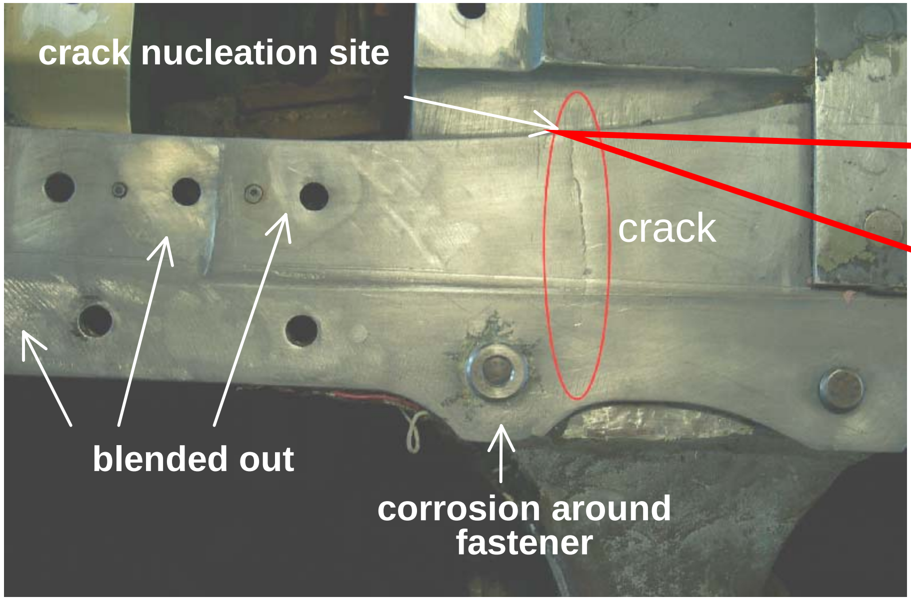
- correlate IDS/particle with individual fatigue life
- estimate a better fatigue life distribution



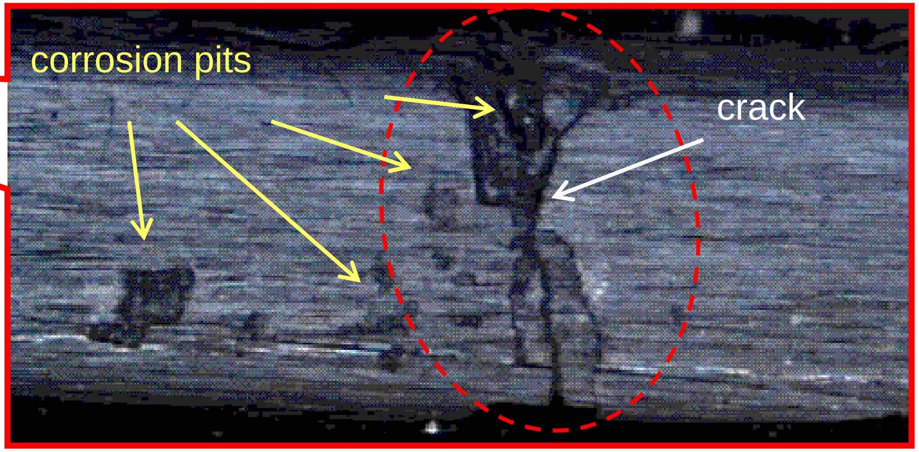
Fatigue life distribution of 2024-T3

Case Study: CF-18 Corrosion Fatigue Analysis

- Fuselage/transition structure, 3644 hours service in US Navy (1984-1994)
- Crack (1.81 inch) found at 2932 simulated flight hours in the right hand upper outboard longeron (UOL).

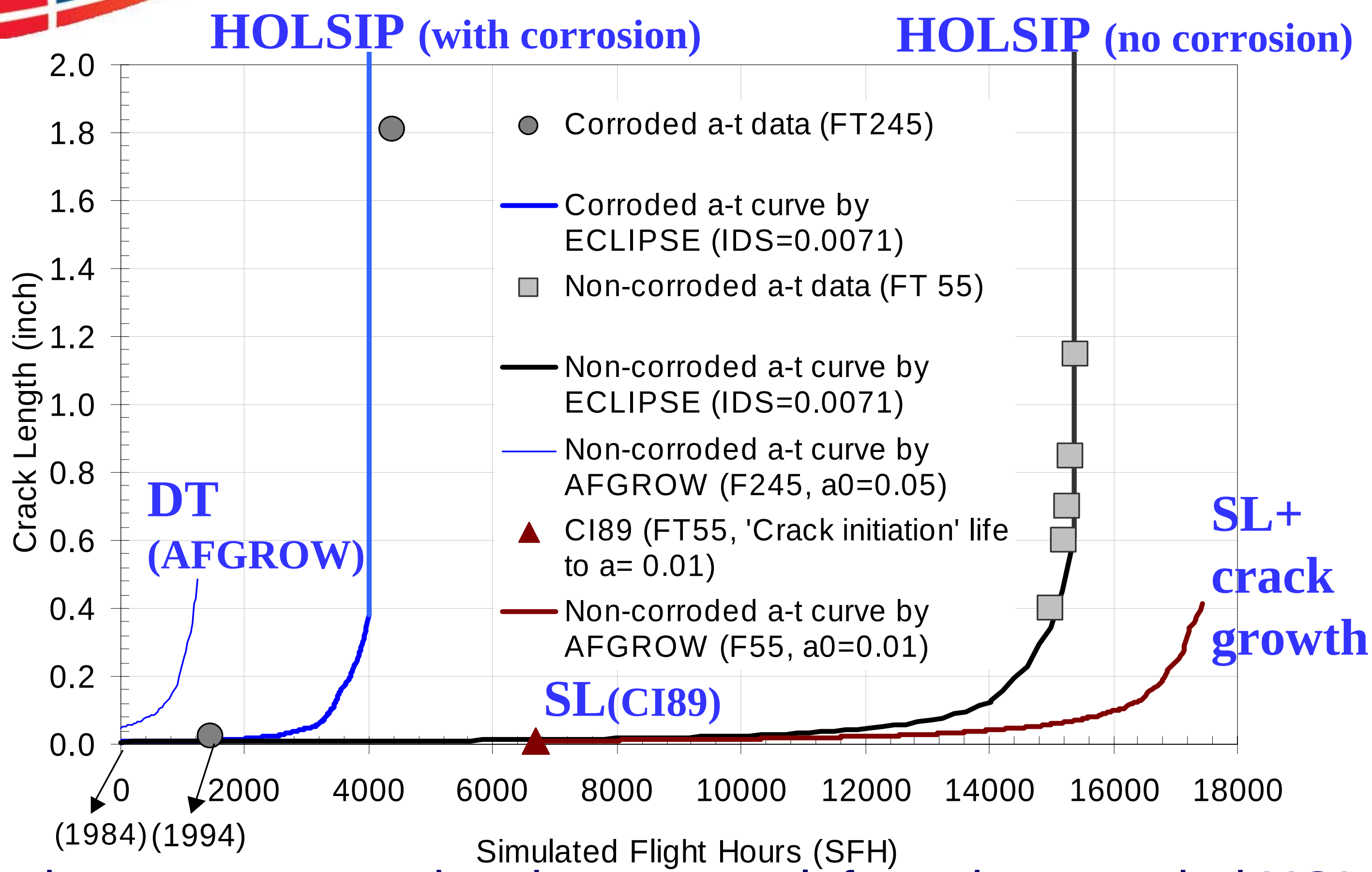


Crack nucleated from corrosion pits on upper outboard longeron



Side view of upper outboard longeron at crack nucleation site

HOLSIP vs. Safe-Life (SL), Damage Tolerant (DT)



- DT life is too short as compared to the test result from the corroded UOL.
- SL life is conservative and SL+ crack growth is not conservative when compared to the pristine test results.
- HOLSIP life is close to reality for both cases.

Risk Management for CF Fleets

CF ASIP managers need:

- New structural integrity assessment capabilities to deal with the new materials and joining technologies used in the newly acquired platforms as well as the increase in occurrences in age related degradation (such as WFD) that are occurring in existing platforms.
- This new structural integrity analysis has to be combined with a risk assessment capability.

Quantitative Risk Assessment for CF ASIP

- **RARM** (Record of Airworthiness Risk Management): "*the single most critical decision making tool in the air force*" (DND).
- Qualitative risk assessment (RA) and Quantitative RA in RARM.

Qualitative Definitions

Description	Level	Qualitative Definitions	Individual Aeronautical Product (1)	Entire Fleet (2)	Individual Aircrew Career (3)	All Exposed DND Aircrew (4)
Frequent	A	Likely to occur frequently.	Expected to occur frequently during the operational life of an individual aircraft	Occurs continuously to the entire fleet	Expected to frequently during each individual's career	Occurs continuously to the entire population
Reasonably Probable	B	Expected to occur one or more times	Expected to occur one or more times during the operational life of an individual aircraft	Likely to occur several times per year to the entire fleet	Expected to occur one or more times during each individual's career	Likely to occur several times to the population per year
Remote	C	Unlikely, but possible to occur	Unlikely, but possible to occur during the operational life of an individual aircraft	May occur once or more times per year to the entire fleet	Unlikely but possible to occur during each individual's career	May occur once or more times per year to the aircrew population
Extremely Remote	D	Not expected to occur	Not expected to occur during the operational life of an individual aircraft	May occur one or more times during the entire operational life of the entire fleet	Not expected to occur during each individual's career	May occur once or more times to the entire aircrew population
Extremely Improbable	E	So unlikely, it may be assumed that it will never occur	So unlikely, it may be assumed that it will never occur during the entire operational life of all aircraft of the type or to the aircrew flying the type			

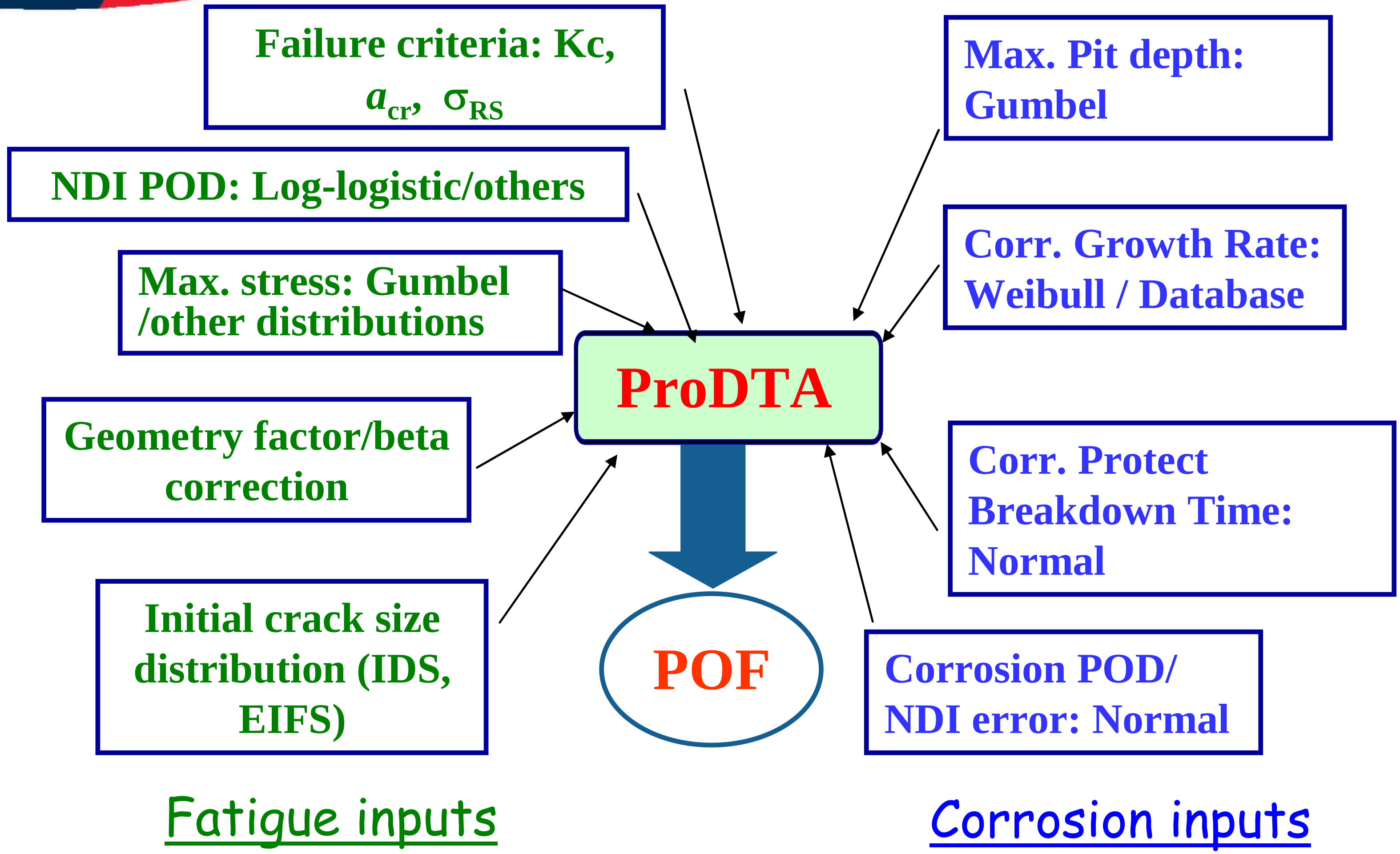
Quantitative Definitions

Hazard Probability Level	Hazard Probability Thresholds (Per Flight Hour)			
	DND Passenger Carrying Aircraft (Derived from FAR 25.1309 Civil Design)	Military Aircraft		
		Military Aircraft	Military Aircraft - Ejection Seat Equipped	Unmanned Aerial Vehicles (UAVs) * [illegible]
Frequent	Greater than 1	Greater than	Greater than	Greater than
Reasonably Probable	Le 1			
Remote	Le 1			
Extremely Remote	Le 1			
Extremely Improbable	Le 1 x 10[illegible]	1 x 10[illegible]	1 x 10[illegible]	1 x 10[illegible]

For all military aircraft, fixed wing, UAV, and helicopters

When "sufficient" data is available, Quantitative RA substantiates the assignment of a risk number (ex. frequent→10^{-3}, remote →10^{-5}, extremely remote → 10^{-7} …)

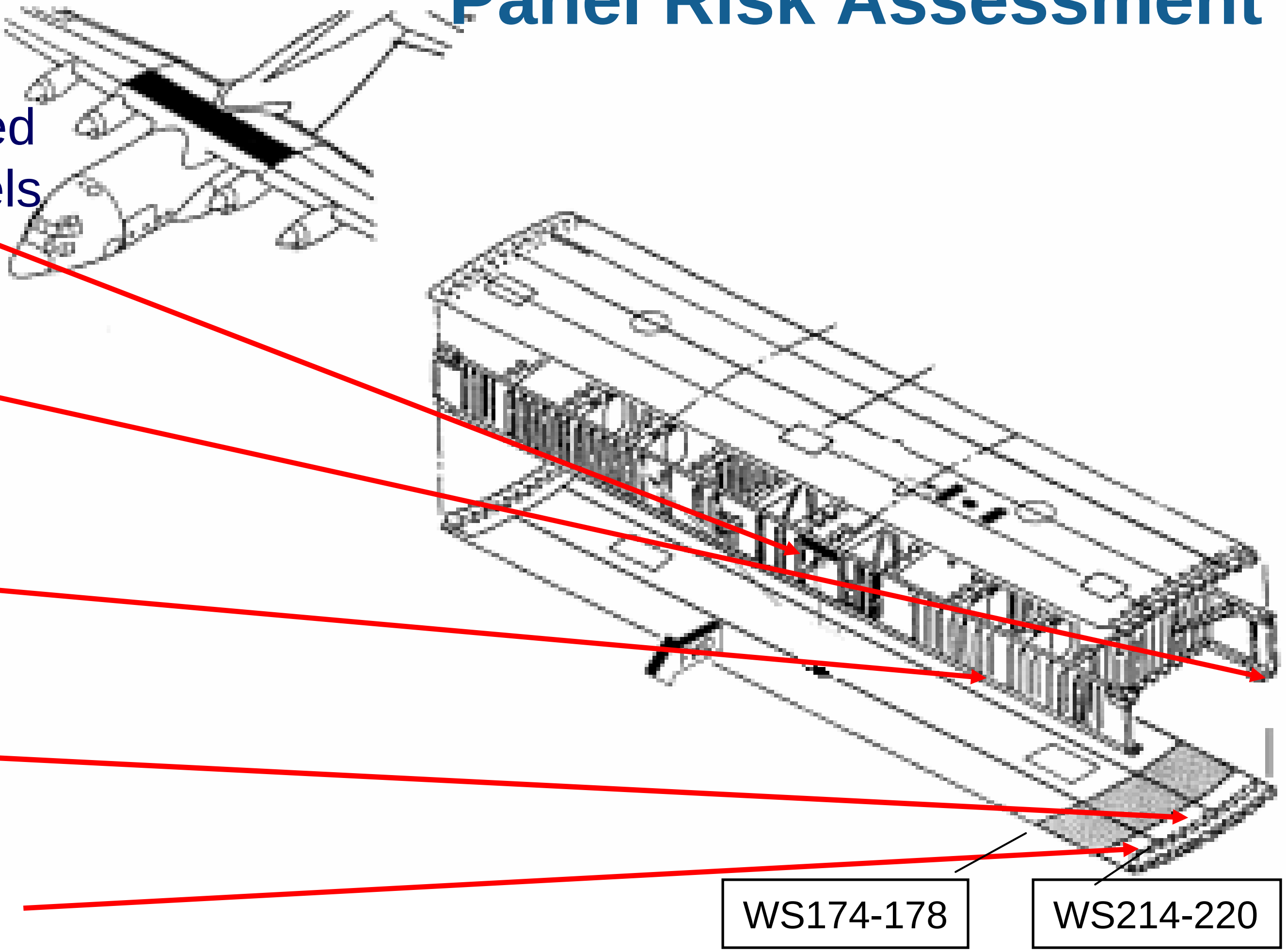
HOLSIP-Based Risk Analysis Tool (NRC in-house)



- ProDTA is under development, with a goal to become a tool for CF fleets

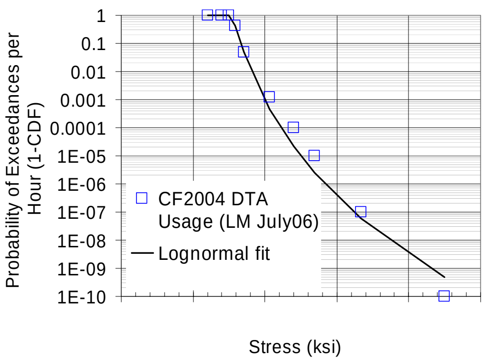
Case Study: CC130 CFCW-1 Lower Surface Panel Risk Assessment

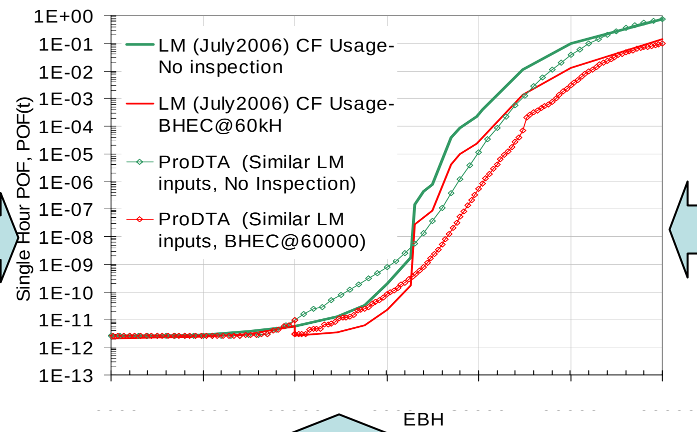
- **CW-1:**10 of 30 A/C inspected had cracked Lower Aft Wing Panels
- CW-12: 11 cracked/severed Corner Fittings
- CW-14: 12 cracked/severed Lower Forward Spar Caps
- CW-9: 13 cracked Rainbow Fittings
- CW-11: 14 cracked Lower Forward Wing Panels



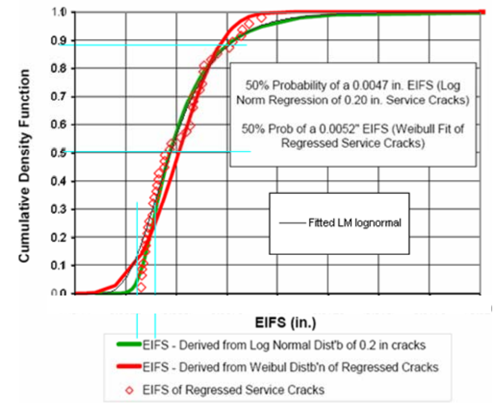
Case Study: CC130 CFCW-1 PoF Cal. using ProDTA

Stress Exceedance (Lognormal)

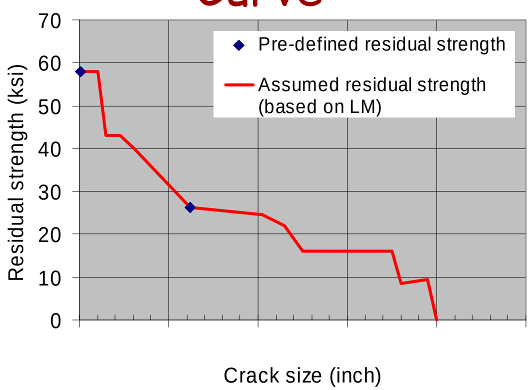




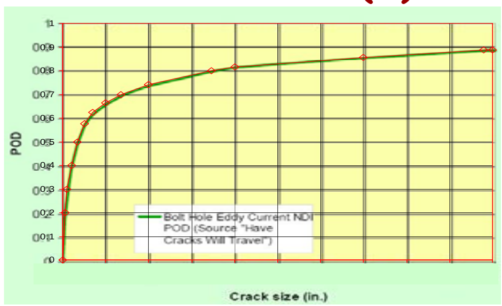
Initial Crack Size Distr. (EIFS, IDS)



Residual Strength Curve



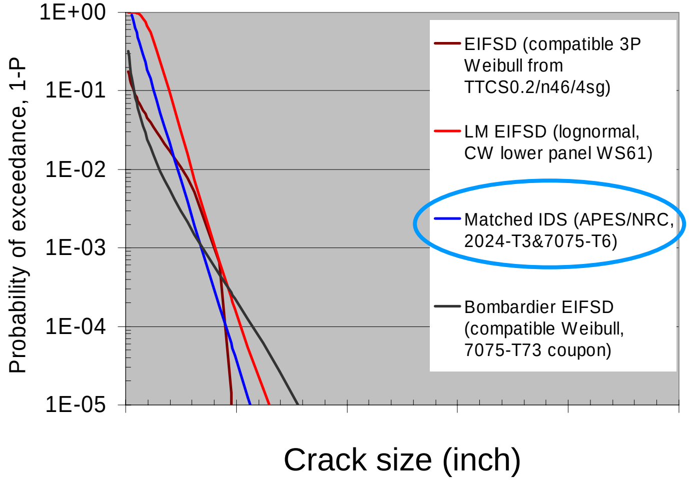
Bolt Hole Eddy Current POD(a)



Crack growth curve (EBH, CF)

- ProDTA verified OEM's results.

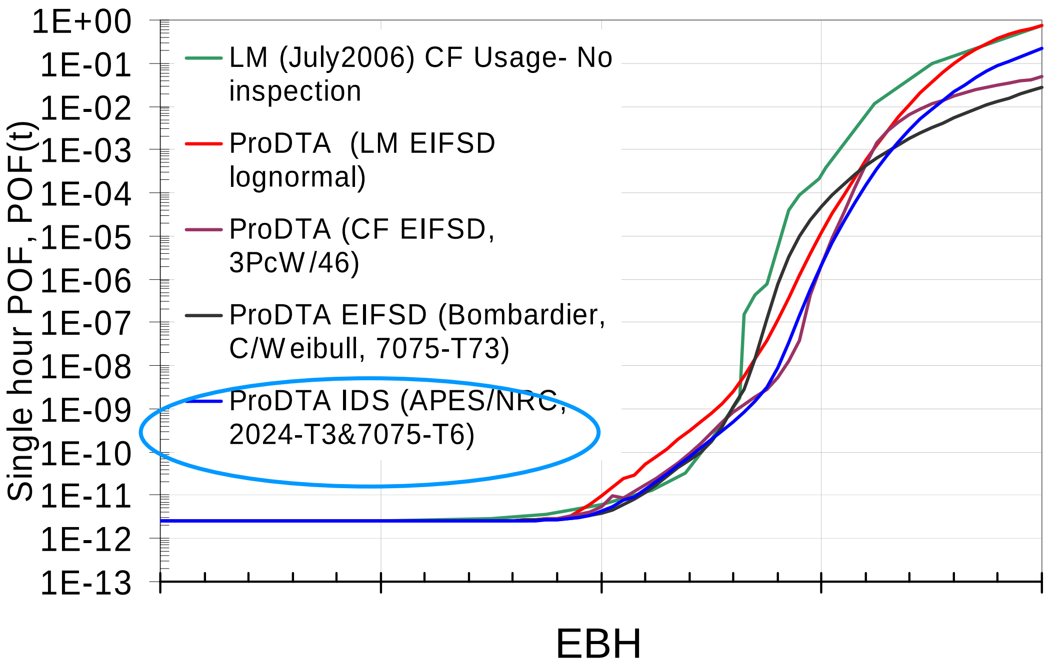
Significance of ICSD (EIFSD vs. IDS) on RA results



Probability of exceedance (1-CDF) for ICSD

Different ICSDs

- Bombardier, coupon based EIFSD
- NRC/APES, material&coupon based IDS



Single flight hour POF, using different initial crack size distribution (ICSD) curves

- If the usage is known, IDS could result in reasonable PoF results.
- It is possible to do risk analysis BEFORE in-service cracks are found.

Next Case Study: CC130 Risk Analysis with MSD/WFD

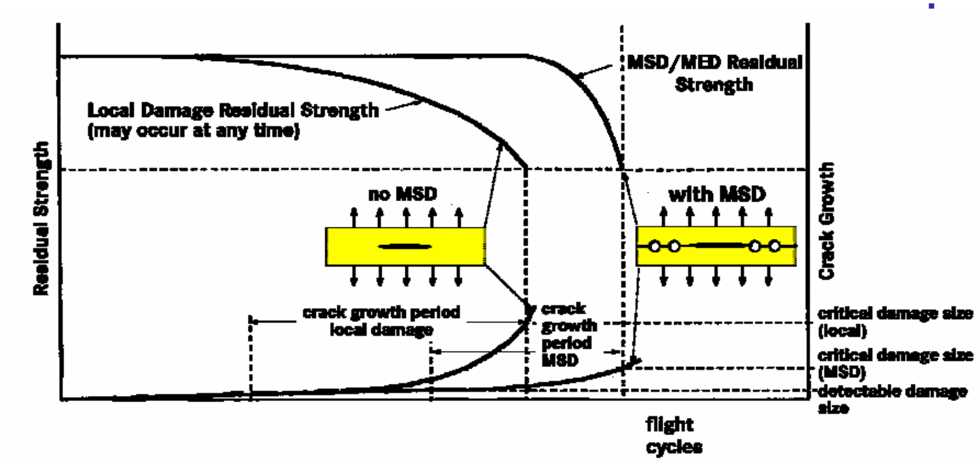
Probabilistic

Monte Carlo Simulation

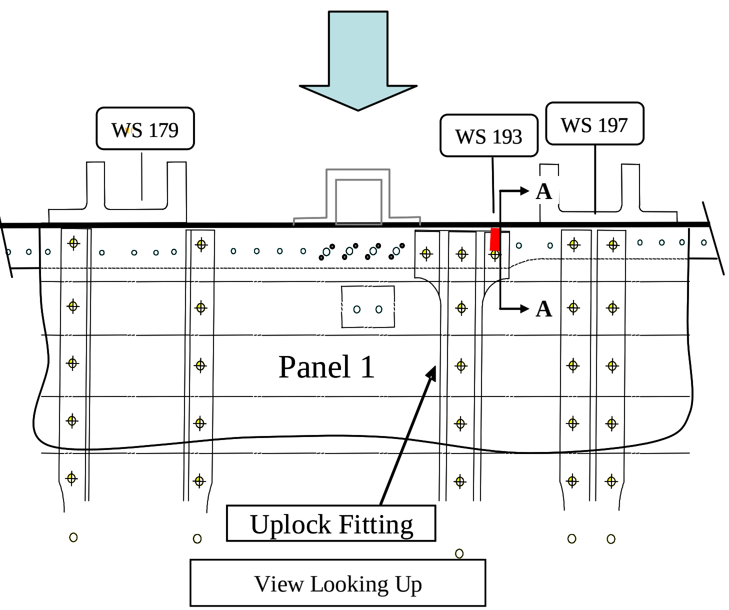
Deterministic

- Stress Exceedance Curve
- Initial Damage Scenario (Multiple holes with randomized primary and secondary flaw sizes)
- PoD in multiple holes inspection
- ICSD/EIFS/IDS Distribution

- LEFM Crack Growth (new beta factors for multiple crack interaction)
- Residual Strength with crack plus load redistribution (Net Section Ligament or CTOA or T-Integral)

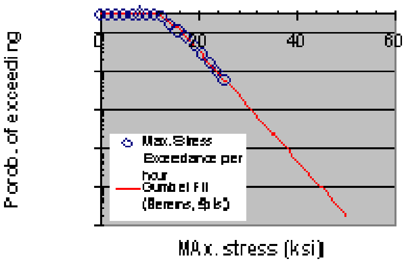


Case Study: Risk Analysis Trial on CP140 (P3)

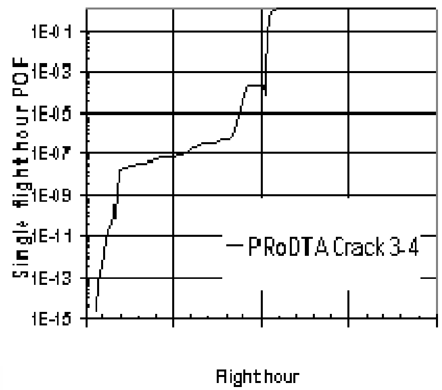


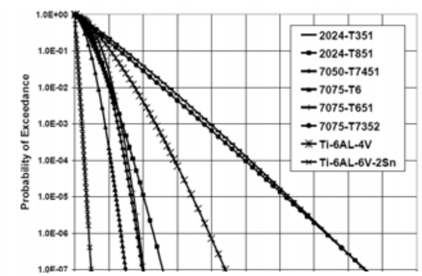
- **Problem definition**: CP140 locations, geometry, configuration
- **RA input data**
  - ✓ Initial crack size distribution (ICSD – EIFSD and IDS)
  - ✓ Crack growth data (a - t curve) - preliminary
  - ✓ Max. stress distribution (stress exceedance curve)
  - ✓ Residual strength data (σ_{RS}- a curve)
  - ✓ POD data (POD - a curve) – reference curve
- ✓ **Goal**: demo. NRC ProDTA capability, check data availability for CP140 risk analysis

Case Study: CP140 (P3) PoF Cal. using ProDTA

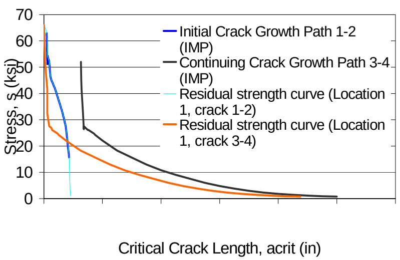


Max. Stress (Exceedance)

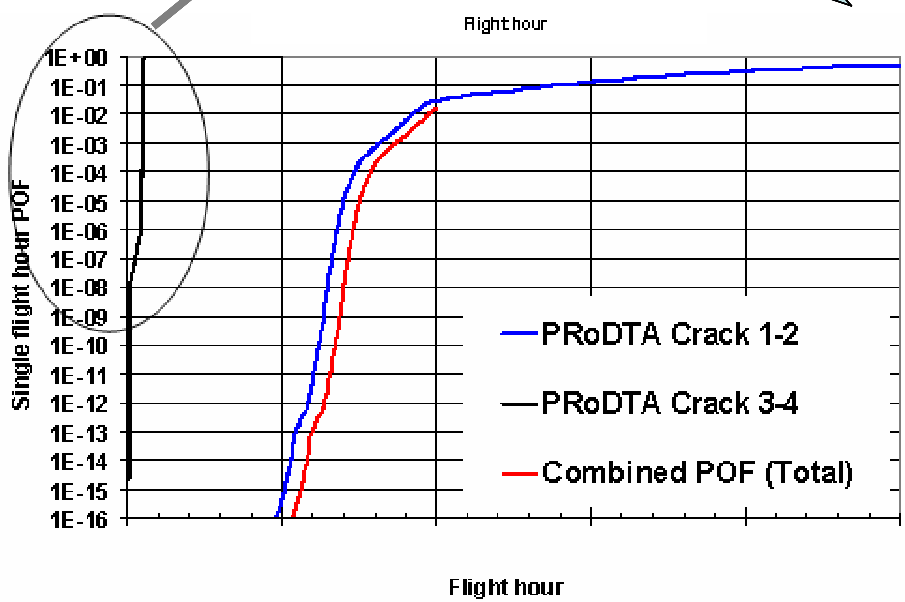


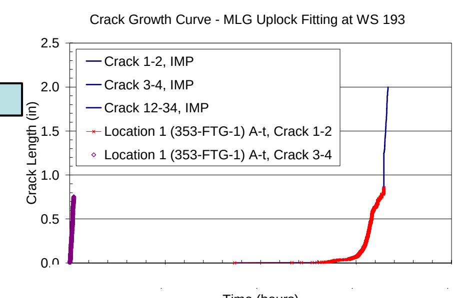


No ICSD yet, try USAF EIFSD!



Residual Strength





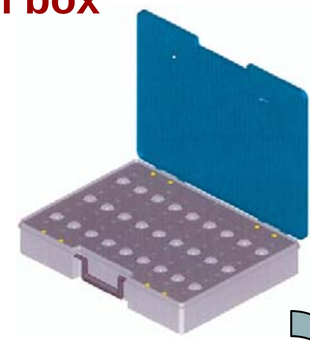
Crack growth curve

- Demonstrated the feasibility of risk analysis for CP140 using ProDTA.

Development of Cost Effective POD/NDI for CF

Generic Bolt Hole Eddy Current POD Study

Coupon box

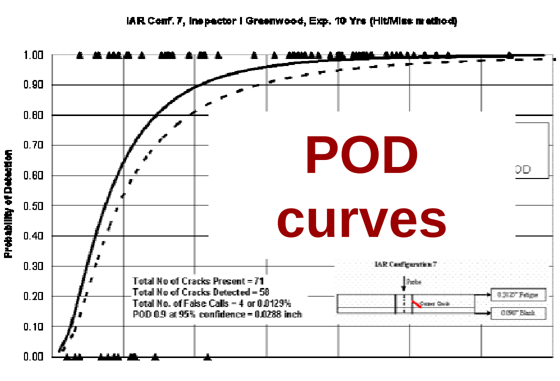


Goal: to replace 0.050” rogue flaw size with the crack size at 90% POD at 95% confidence (90/95) for DTA and Risk Analysis

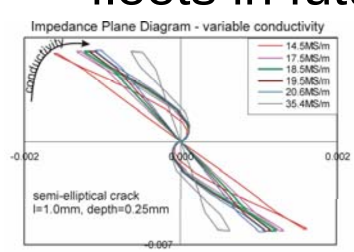
Inspector Test Result Data Sheet					
Date			Equipment		
Inspector ID:			Probe		
Organization			Frequency:	Threshold	
Box ID			Magnitude Scale	Noise Level	
	Test Identification			Comments	
Box and Set Number	Crack Indication (Y/N)	Signal Magnitude	Phase Angle		
A01					
A02					
A03					
A04					
A05					
A06					
A23					
A24					
A25					
A26					

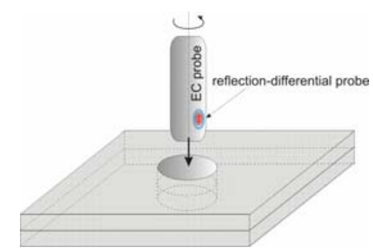
Report card

Application: CC130, CP140 (USN designation P3) and likely all CF fleets in future



POD curves





Side goal: Eddy Current Modeling to deter. POD

Concluding Remarks

- To meet the CF challenges, a new life management paradigm, HOLSIP, is being developed that takes into account cyclic loading and time related effects, to accurately determine the risk associated with manufactured quality and service-induced damage.
- The risk assessment module ProDTA, based on HOLSIP, is very flexible, and expandable to handle different inputs. ProDTA is being further developed along with cost-effective NDI/POD development.
- HOLSIP is not just another crack growth model. It is a new way to evaluate structural integrity of existing and new designs. It has the potential to form the core of future SHM (DPHM) systems.

Future Work

- NRC will continue to work with DND to further the development of the HOSLIP framework in order to meet their future requirements for aircraft certification and sustainment.
- In association with DND, procedures will be developed to carry out generic risk assessments, which will allow them to perform quantitative risk assessments on other CF fleets.
- Processes will be developed to ensure the proper capture of the data required to carry out a risk assessment on an individual aircraft. This will include carrying out teardowns, in-service inspections and crack data recording, sensor interpretation (e.g. corrosion, crack sensors) as well as cost-effective NDI/POD modeling and data fusion.
- Maintenance optimization (variable inspection interval, NDI options, and repair techniques options) will be incorporate into risk assessment.

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Acknowledgements

- The authors would like to thank all the agencies who provided support throughout this work:
  - the National Research Council Canada,
  - Canadian Department of National Defence through Defence Research and Development Canada and DGAEPM, and
  - United States Air Force Corrosion Program Office through NCI, Lockheed Martin, and S&K Technologies, Inc.

- In addition, the authors would like to thank Dr. David Hoeppner and Mr. Craig Brooks for their guidance and assistance that they have provided over the years in the development of the HOLSIP paradigm.

Questions?