B-1 Maintenance Schedule Impact Based on Risk Assessment Results

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Agenda

- Why risk assessment strategy?
- Key improvements to Boeing's Risk-Based Design and Maintenance System (RBDMS) code
- Comprehensive risk assessment process
  - Process I: Produce risk results and determine the impact of maintenance schedules for Force Structural Maintenance Plan
  - Process II: Identify optimal maintenance schedule
- Demonstration example
- Summary

Why Risk Assessment Strategy?

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- Mil-Std-1530C task 5.5.6.3 (risk analysis updates) specifies three major reasons to update the risk analyses are to:
  - Evaluate detected and anticipated aircraft structural damage. The results shall be used in conjunction with IAT data described in 5.5.1 to establish the individual aircraft maintenance times.
  - Evaluate economic and/or availability impacts associated with maintenance options such as inspection and repair/replacement as needed versus modification.
  - Determine the structural integrity risk associated with operating the aircraft beyond the design service life.

The Goal Is to Impact Force Structural Maintenance Plan Using Risk Assessment Strategy Given A 1.E-7 Requirement

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Key improvements to Boeing’s Risk-Based Design and Maintenance System (RBDMS) code

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- Input data
  - Distribution types expanded for initial and repair crack size distributions
  - Lognormal Probability Of Detection (POD) curve and probability of inspection input
- Methodology and code improvement
  - Develop strategy to improve the robustness of the proposed probabilistic method
  - Interval probability of failure developed
  - Crack missed distribution created
  - Graphical User Interface (GUI) for RBDMS developed
  - Produce risk data for 21 years of operations
  - Identify optimal inspection intervals based on 1.E-7 risk

RBDMS and PROF Used The Same Risk Assessment Strategy

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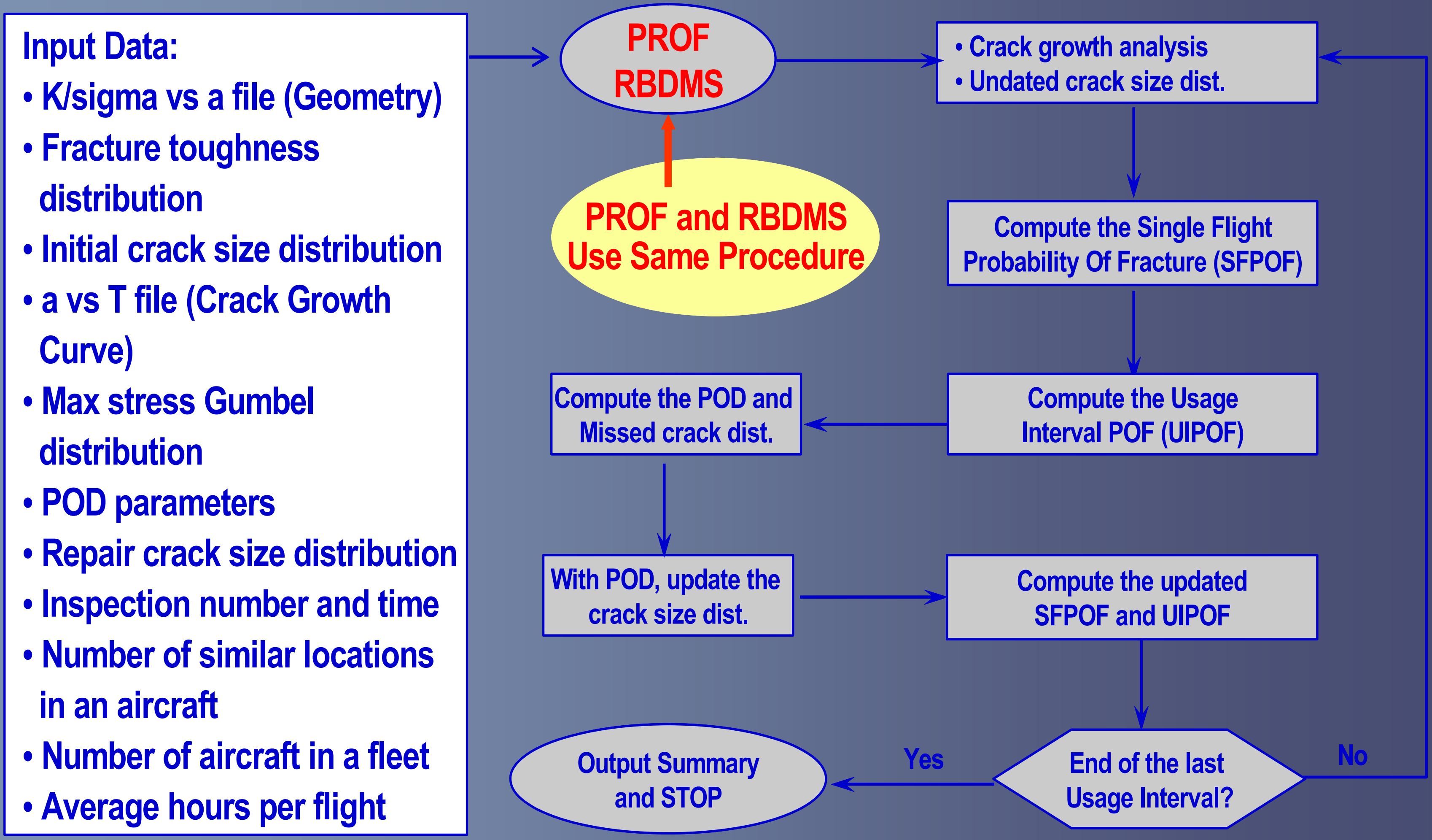

Input Data:
- K/sigma vs a file (Geometry)
- Fracture toughness distribution
- Initial crack size distribution
- a vs T file (Crack Growth Curve)
- Max stress Gumbel distribution
- POD parameters
- Repair crack size distribution
- Inspection number and time
- Number of similar locations in an aircraft
- Number of aircraft in a fleet
- Average hours per flight

PROF
RBDMS

PROF and RBDMS Use Same Procedure

- Crack growth analysis
- Undated crack size dist.

Compute the Single Flight Probability Of Fracture (SFPOF)

Compute the Usage Interval POF (UIPOF)

Compute the POD and Missed crack dist.

With POD, update the crack size dist.

Compute the updated SFPOF and UIPOF

End of the last Usage Interval?

Output Summary and STOP

Proposed Comprehensive Risk Assessment Process I

- Identify all critical locations that require inspection within the near term of seven years (from current FSMP plan).
- Identify input data for all locations and start to define random variables based on the available data.
- Run RBDMS GUI to define the input data of its first analysis to evaluate the risk at the current accumulated hours of usage and the risks for the current accumulated hours ± 1 to 10 years of usage hours.
- From the 21 yearly risk data, users must perform a simple check to make sure that the risk increases monotonically because without inspections the crack should increase monotonically.
  - Provide FSMP data to determine the risk associated with postponing the inspection for one to five years (to aid in aligning inspections to PDM).
  - If the risk is much smaller than the requirement of 1.0E-7. It is important to change the current accumulated hours and yearly usage hours.

Proposed Comprehensive Risk Assessment Process II

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- From the process I, the first inspection given a 1.0E-7 risk requirement can be estimated through risk data.
- Then, for the second inspection interval, an approximate 0.75 times the first inspection interval hours will be used as an initial step to start this second analysis. Based on the results, continue to modify the second inspection hours until all risks before POD inspection are less than 1.0E-7 level.
  - A simple check procedure for the results
    - POD should be increased most of the time.   However, when a large POD was found, it is possible that the second POD will be less than the first one.
    - Inspection intervals should be reduced most of the time unless a large portion of crack size has been detected in the first interval.
    - Risk should be increased faster in the second inspection interval because more hours are added and the crack size is always growing.

Demonstration Example
Wing Location Two Problem Definition

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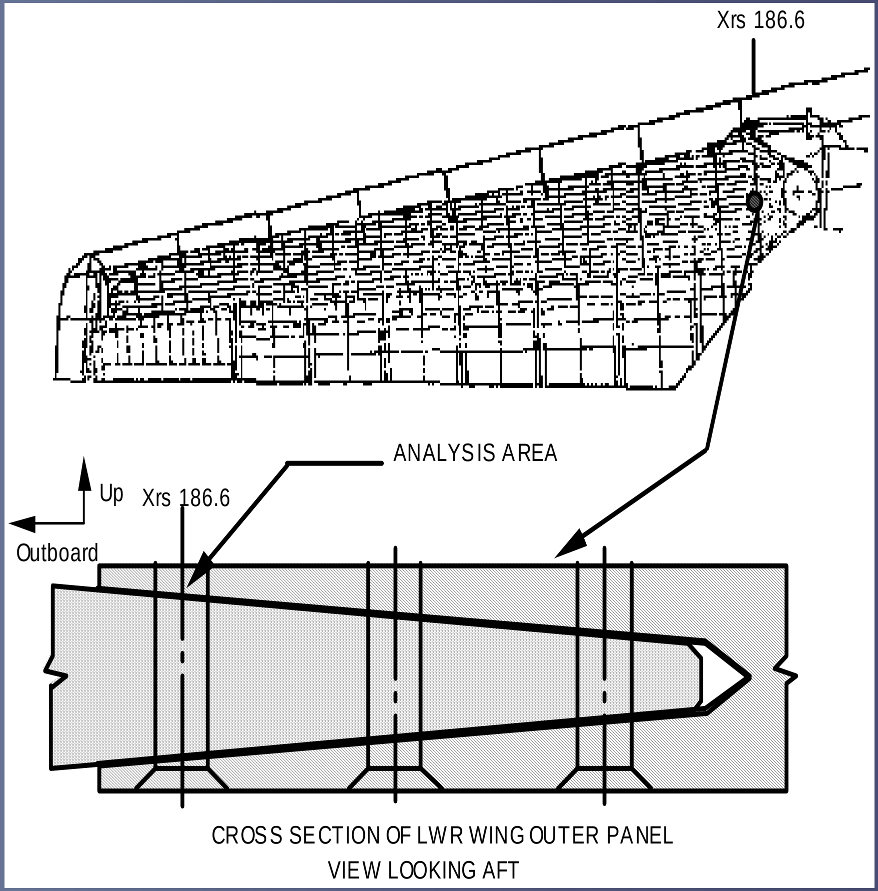
- The wing splice is the singular load path for the primary wing bending load. It is a fish mouth joint comprised of two titanium plates with an aluminum plate in between. The joint is held together with three rows of high interference fit TaperLok fasteners.
- Damage tolerance analysis currently shows this joint is in need of inspections. Because of the inspection requirement and the criticality of the load path, it was determined that the wing splice was a candidate for using probabilistic analysis techniques.
- Deterministic approach select two inspection intervals, 5000 and 5000.



CROSS SECTION OF LWR WING OUTER PANEL
VIEW LOOKING AFT

Wing Location Two
Input Data Uncertainties Modeling

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- Several generic initial crack size distributions were evaluated:
  - Two distributions were identified in the PROF III code as alternative distributions. One was a combination lognormal/uniform distribution that was extremely conservative and not very realistic (99.9% Lognormal with mean = 0.0009455 and std dev = 0.000595744, 0.1% Uniform with upper bound = 0.05 and lower bound = 0.) . Another one was a Weibull distribution (shape: 0.575 and scale: 0.0002187) that was much more typical of an accepted initial distribution.
  - Two alternative distributions were developed based on long-standing standards of a median crack size of 0.0025 in. and a one in a million crack size of 0.05 in. One of these distributions was a lognormal (with mean = 2.955E-3 and std dev = 1.862E-3) and the other was a Weibul (with shape = 0.998855, scale = 0.00360825). Both were more conservative than the PROF provided Weibull distribution and the Weibull was more conservative than the lognormal.
  - It was decided that the Weibull with shape = 0.998855 and scale = 0.00360825 based on the standards of 0.0025 in. median crack size and 0.05 in. for a one in a million crack size should be used as a conservative yet realistic initial crack dist. when limited data exist.

Wing Location Two
Input Data Uncertainties Modeling

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- Repair crack size distribution
  - Since we will use Eddy Current inspection technique for finding the crack, it is reasonably to assume 0.05” as the repaired initial crack size
  - Given the same 0.05”, the uniform distribution with lower and upper bounds of 0.0 and 0.05 should be a reasonable distribution to model the repair crack size distribution.
  - In addition, repair crack size distributions used in the PROF III code were considered. Exponential distribution was used by the PROF III code to model the repair crack size distribution.
    - Weibull (shape = 1.0, scale = 0.00723842), CDF(0.05) = 0.999
    - Weibull (shape = 1.0, scale = 0.00542868), CDF(0.05) = 0.9999
    - Weibull (shape = 1.0, scale = 0.00434294). CDF(0.05) = 0.99999

Wing Location Two
Input Data Uncertainties Modeling

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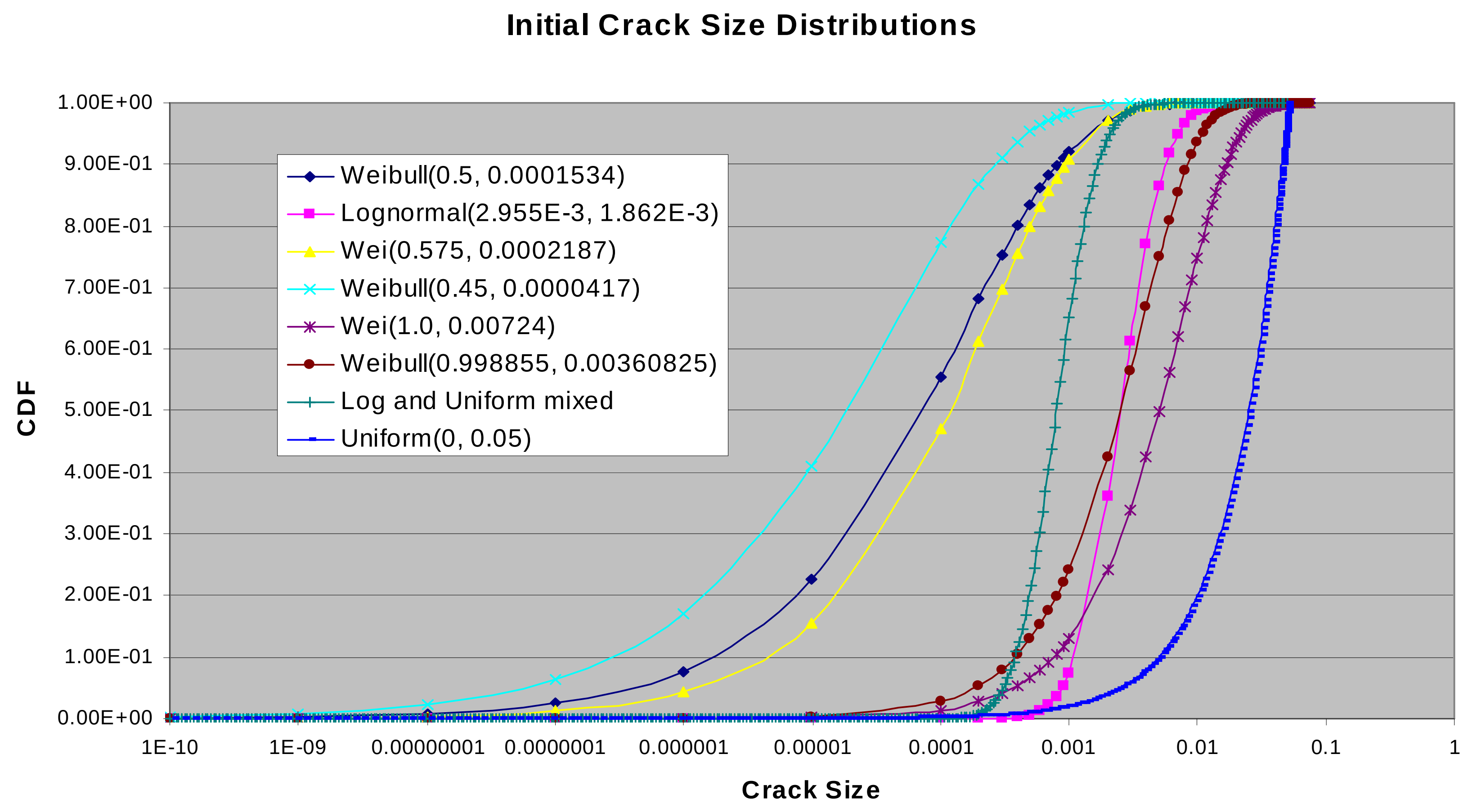
- Demonstration of input and repair crack size distributions



Wing Location Two
Input Data Uncertainties Modeling

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- Fracture toughness distribution
  - To determine the parameters of a strength variable, it usually can be done by using the strength variable’s A-based (above the value has 99% population with 95% confidence) and B-based (above the value has 90% population with 95% confidence) values.
  - Without actual data, a normal distribution with the coefficients of variation (μ/σ) values range from about 3% to 10% for aluminum and titanium alloys and most steels to model this Kc distribution.

FCL Names	Mean	Standard Deviation	Coefficient of Variation
AIF18	68.00	3.20	4.71%
HS-6U	205.60	7.80	3.79%
W2	33.00	2.20	6.67%
W16	34.00	2.20	6.47%
W27	38.00	2.20	5.79%
W33	27.00	2.20	8.15%
WCT6b	70.00	3.20	4.57%
WCT12	205.60	7.80	3.79%
WCT61	205.60	7.80	3.79%
		Average	5.30%
		Standard deviation	1.55%

Wing Location Two
Input Data Uncertainties Modeling

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- The distribution of this maximum stress peak in a flight is modeled in terms of a Gumbel distribution (Extreme Value Distribution, EVD).
- For practical purposes, it can be assumed that the stress peak that will cause fracture is the largest peak to be encountered in the flight. A procedure was proposed to model the maximum stress distribution by using the load exceedance data.

Sigma MAX	No. of Cycles	Peak CDF (1-(Column B/22587.52)	Observed CDF max/flight Column C^(22587.52/100)	Gumbel Transform LN(-LN(Column D)	1-Column D	8 point calculated EXP(-EXP(-(sigma-B)/A))	Prob of exceeding 1- (8 point calculated)
6.85	22587.52	0.0000	0.0000		1.0000	0.0000	1.0000
9.01	13326.55	0.4100	0.0000	5.3052	1.0000	0.0000	1.0000
10.04	7862.61	0.6519	0.0000	4.5710	1.0000	0.0000	1.0000
10.70	4638.91	0.7946	0.0000	3.9498	1.0000	0.0000	1.0000
11.27	2736.94	0.8788	0.0000	3.3733	1.0000	0.0000	1.0000
11.81	1614.78	0.9285	0.0000	2.8186	1.0000	0.0000	1.0000
12.32	952.71	0.9578	0.0001	2.2756	0.9999	0.0000	1.0000
12.82	562.10	0.9751	0.0034	1.7391	0.9966	0.0000	1.0000
13.32	331.64	0.9853	0.0354	1.2063	0.9646	0.0015	0.9985
13.81	195.66	0.9913	0.1401	0.6756	0.8599	0.0526	0.9474
14.24	115.44	0.9949	0.3143	0.1461	0.6857	0.2301	0.7699
14.58	68.11	0.9970	0.5055	-0.3825	0.4945	0.4283	0.5717
14.93	40.18	0.9982	0.6689	-0.9109	0.3311	0.6179	0.3821
15.32	23.71	0.9990	0.7888	-1.4387	0.2112	0.7740	0.2260
15.77	13.99	0.9994	0.8694	-1.9665	0.1306	0.8836	0.1164
16.19	8.25	0.9996	0.9208	-2.4948	0.0792	0.9392	0.0608
16.44	4.87	0.9998	0.9525	-3.0220	0.0475	0.9590	0.0410
16.69	2.87	0.9999	0.9717	-3.5508	0.0283	0.9724	0.0276
16.94	1.69	0.9999	0.9832	-4.0804	0.0168	0.9815	0.0185
17.19	1.00	1.0000	0.9900	-4.6051	0.0100	0.9876	0.0124

Example: W-2 8-point Fit Results

Wing Location Two Input Data Uncertainties Modeling

- A least square fit was used to determine the Gumble EVD. For conservatism, 8-points fit (with Scale (Asig) = 0.618 and Location (Bsig) = 14.478) was selected as a better model.

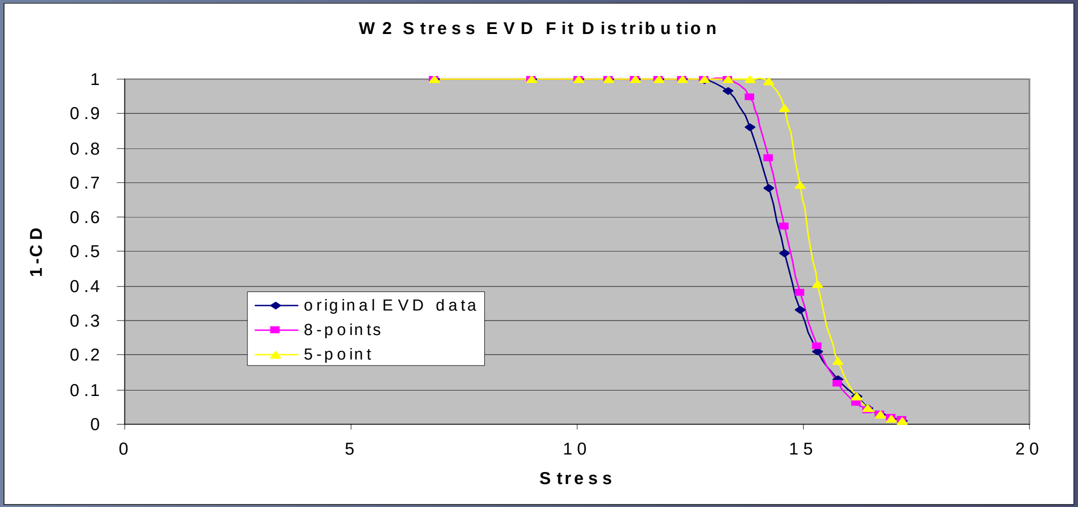

Table B.2 Comparison of 5 and 8-points fit results

	5 points			8 points		
FCL Names	Mean	Standard Deviation	COV	Mean	Standard Deviation	COV
AIF18	18.00	0.43	0.024	17.30	0.73	0.042
HS-6U	14.21	1.04	0.073	14.22	0.96	0.067
W2	15.28	0.61	0.040	14.83	0.79	0.053
W16	14.31	0.81	0.056	14.16	0.87	0.061
W27	18.00	0.43	0.024	17.30	0.73	0.042
W33	10.90	0.38	0.035	10.65	0.49	0.046
WCT6b	15.41	0.47	0.030	14.62	0.73	0.050
WCT12	43.97	1.28	0.029	42.59	1.88	0.044
WCT61	27.96	1.05	0.038	27.05	1.44	0.053

Wing Location Two
Input Data Uncertainties Modeling

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- A new lognormal POD model was developed to replace the approximate POD curve (approximate to lognormal) as shown below:

$$POD(a) = \left[1 + \exp\left(-\frac{\pi}{3} \left(\frac{\ln(a - a_{\min}) - \mu}{\sigma} \right) \right) \right]$$

- Probabilities of detection (POD) curves were produced based on 90% detection (95% confidence level) of 0.075 inches using the eddy current inspection method.
  - POD(0.075) = Φ ((dlog(0.075-amin)-dlog(amed)) / asteep) = 0.9
  - (dlog(0.075-amin)-dlog(amed)) / asteep = Φ^{-1} (0.9) = 1.28
- In addition, a probability of inspection was added to account for potential human errors or other uncontrollable uncertainties, so final POD*(a),
  - POD*(a) = POD(a) * POI
- For Wing 2, the following POD input data were used:
  - Median (50% Crack Size, inch) = 0.06
  - POD Slope (Steepness) = 0.184
  - Minimum Crack Size (inch) = 1.E-20
  - Probability Of Inspection (0<POI<1) = 1.

Wing Location Two
Input Data Uncertainties Modeling

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- Other key input data:
  - Crack growth Curve – from the deterministic analysis results
  - Geometry file data file – from the deterministic analysis results
  - For interval probability of failure, the following data are important:
    - No. of aircraft in a fleet
    - Average flight hours
    - No. of similar locations in an aircraft
- One special input requirement is the crack size value of the last input value of the crack growth curve and geometry file. This value will be considered as the critical crack size that will be used by the crack size failure mode.
  - The same crack growth curve and geometry file applied by both PROF and RBDMS codes.

Wing Location Two
Results Summary and Discussions

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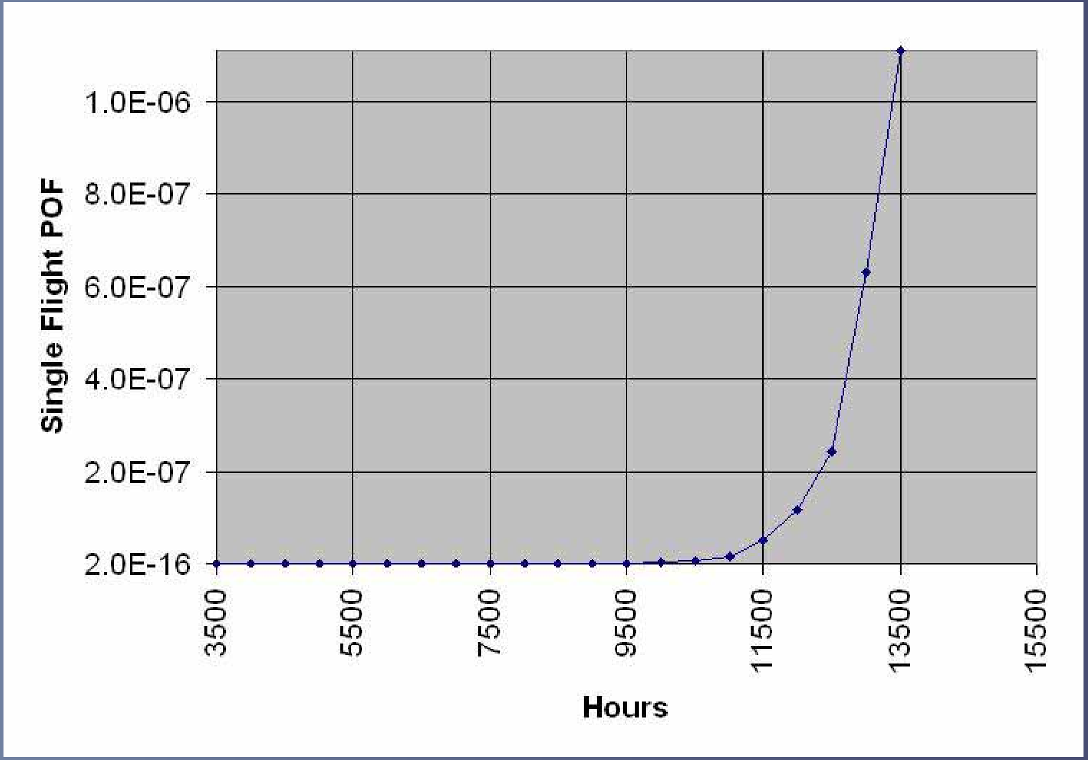
- RBDMS Results – to search for hours where probability of failure ~ 1.E-7
  - Found that at 11500 hours, the risk is closest to 1.E-7

SFPOF Output Data Summary

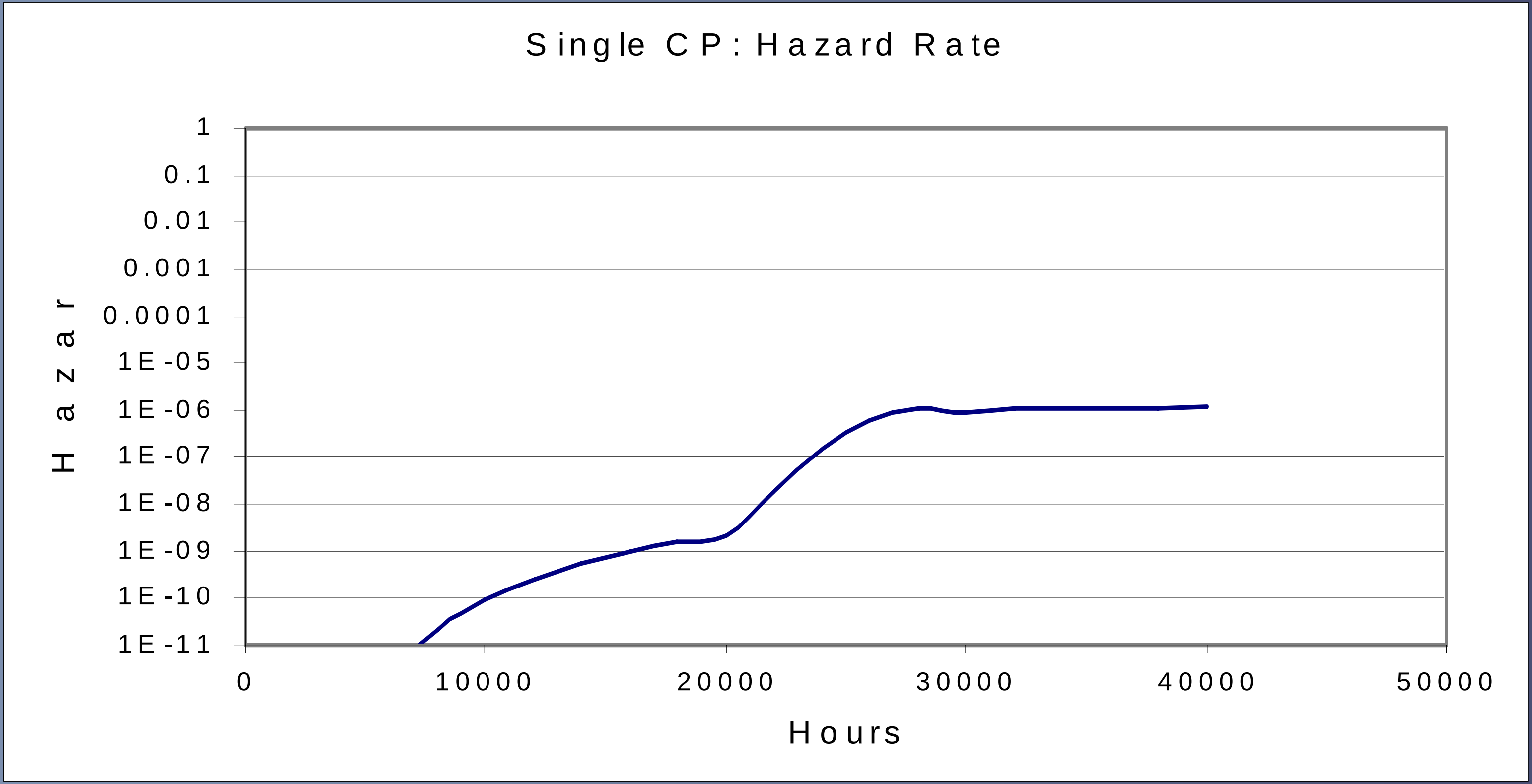
21

Hours	Single Flight POF
3500.0	0.2000E-15
4000.0	0.2000E-15
4500.0	0.2000E-15
5000.0	0.2000E-15
5500.0	0.6756E-15
6000.0	0.4050E-14
6500.0	0.3823E-13
7000.0	0.2581E-12
7500.0	0.1407E-11
8000.0	0.7102E-11
8500.0	0.3033E-10
9000.0	0.1492E-09
9500.0	0.5320E-09
10000.0	0.1846E-08
10500.0	0.6105E-08
11000.0	0.1572E-07
11500.0	0.5201E-07
12000.0	0.1166E-06
12500.0	0.2434E-06
13000.0	0.6295E-06
13500.0	0.1110E-05



Wing Location Two
Results Summary and Discussions

- PROF III Results – to search for hours where probability of failure ~ 1.E-7
  - Found that ~ 23000 hours the risk is approximately 1.E-7



Wing Location Two
Results Summary and Discussions

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- RBDMS Results – to search for first and second inspection intervals
  - 11500 and 7000

SFPOF Output Data Summary

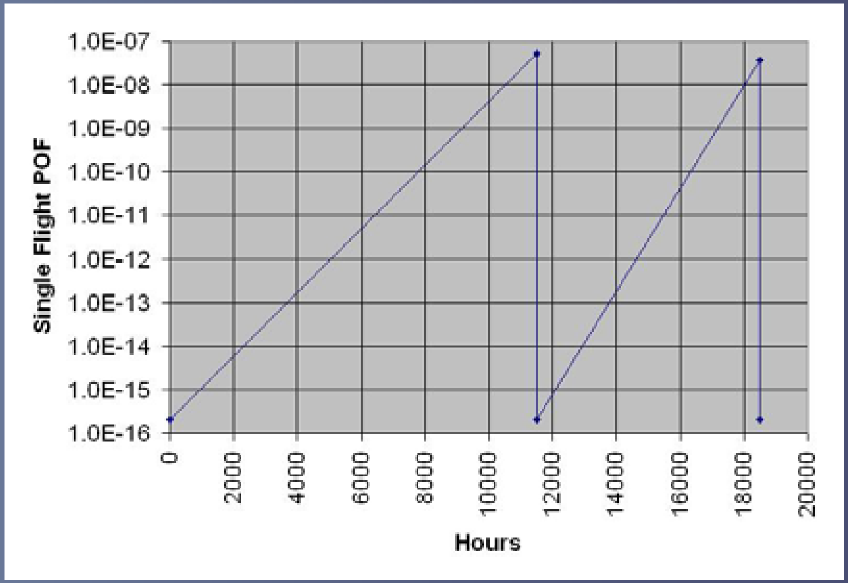
4

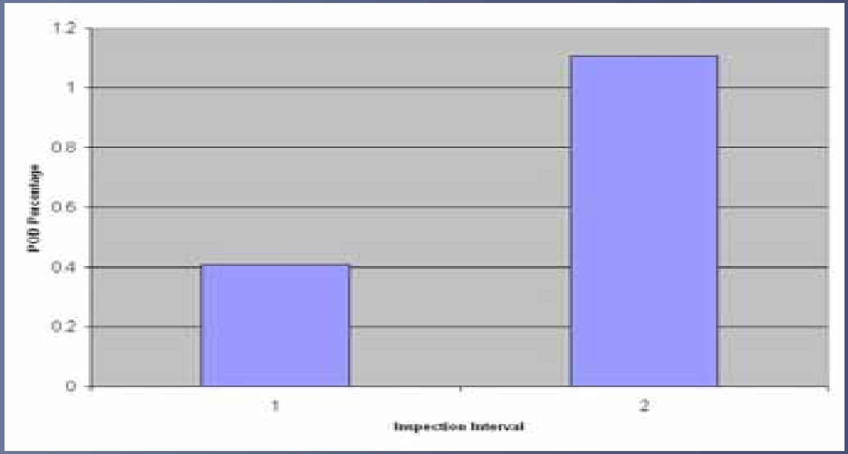
Hours	Single Flight POF
11500.0	0.5201E-07
11500.0	0.2000E-15
18500.0	0.3613E-07
18500.0	0.2000E-15

POD Output Data Summary

2

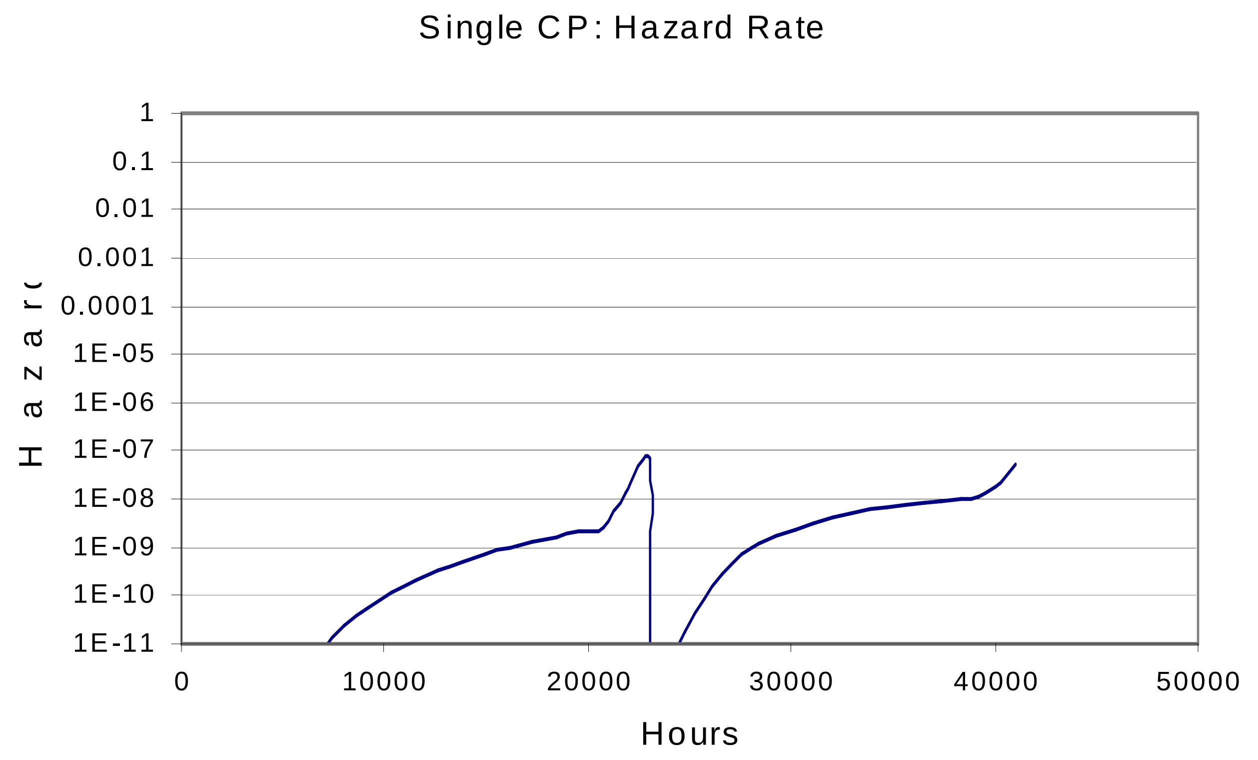
Hours	Prob. of Detection
11500.0	0.4063E-02
18500.0	0.1107E-01





Wing Location Two
Results Summary and Discussions

- **PROF III Results – to search for first and second inspection intervals**
  - **23000, 18000**



Wing Location Two
Results Summary and Discussions

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- Results from the PROF code and other initial crack size distributions

FCL Name	1st Inspection	SFPOF	POD (%)	2nd Inspection	SFPOF	POD (%)
PROF Wei(0.575, 0.0002187)	23000	6.64E-8	1.84	18000	5.24E-8	3.87
RBDMS Wei(0.575, 0.0002187)	11500	5.20E-8	0.41	7000	3.61E-8	1.11
RBDMS Log/Uniform mixed	8500	7.73E-8	0.136	7800	6.24E-8	0.877
RBDMS Wei(0.998855, 0.00361)	8500	8.9E-8	22.23	6000	8.53E-8	34.25
RBDMS Log((2.955E-3, 1.862E-3))	9500	5.198E-8	11.81	6000	5.623E-8	28.89

- Notice that initial crack size distribution using long standing assumptions are more conservative especially for the Weibull distribution (0.998855, 0.00361)

Summary

- Based on the proposed comprehensive risk assessment process, a Risk-Based Design Maintenance System (RBDMS) code was developed with added features proposed within the PROF III code.
  - A simple user-friendly graphical user interface for the RBDMS code was developed with a user's manual.
- The developed RBDMS was used to successfully calculate the risk and determine the inspection intervals for the identified Wing 2 fatigue critical location.
  - As shown, given the risk requirement of 1.E-7, the inspection intervals calculated from the RBDMS code (11500, 7000) is much larger than the inspection intervals (5000, 5000) from the deterministic approach
  - The results were also solved by the PROF III code for comparison. After comparison, it was determined that the RBDMS code produced more conservative (higher) risk assessment than the PROF III code.

Existing FSMP Deterministic Approach

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- Point location analysis
  - Pull in data for 21 tracking points from IAT for each A/C
  - Adjust to bring in line with most recent DADTA
  - Ratio tracking point data to all other analysis points
  - Determine total hours to next inspection
  - Revise hours based on any previous inspections
  - Determine remaining hours and approximate date for next inspection
  - Give special consideration to analysis locations that are fail-safe
- Zone location analysis
  - Bring in data from point location analysis
  - Define which similarly located analysis points belong together in larger inspection zones
  - Accumulate PDM schedule for each A/C
  - Run excel macros to determine shortest inspection interval for each zone per A/C and denote time compared to PDM schedule
  - Pick out which zones require near term inspections (within 7 years)

Proposed FSMP Risk Approach

- Near term inspections based on deterministic approach
  - Perform risk analysis on each near term point
    - Determine risk if inspection is put off until next PDM
    - Determine risk for each year until next 5 year PDM cycle
      - This requires risk analysis up to 10 years prior and 10 years after the scheduled deterministic inspection time
  - Run excel macro to distribute the risk data around the projected inspection date
  - Publish risk data in FSMP in addition to (or in place of) the deterministic inspection schedule
- Other inspections
  - Risk analysis can be performed on zones that are not near term
  - Will most likely show extremely low risk

FSMP Demonstration Example W2 Zone – Risk Data Distributed

- Risk is determined for each aircraft on an individual basis
  - Severity factor is calculated based on historical data from IAT
  - Usage is based on FSMP projected usage
  - Curve fit equation used to determine risk
  - PDM prior to when deterministic analysis requires inspection
  - Each year up to the next scheduled PDM
- Results presented in tabular format in FSMP
  - Deterministic inspection results remain
  - Risk values higher than 1.E-7 are highlighted
  - Years that fall within the 7-year planning period are highlighted

FSMP Example W2 – Calculated Risk

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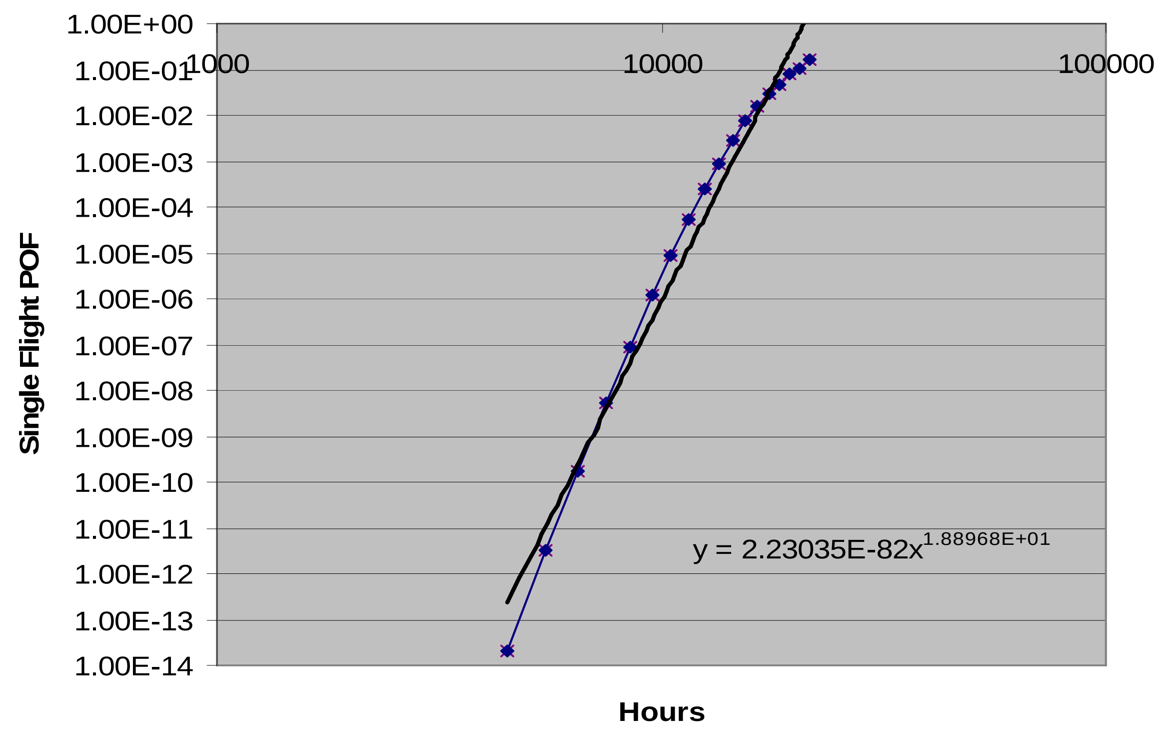
- W-2 zone with Weibull Distribution (0.998855, 0.00361)
  - A curve was fit to the data to establish an equation representing the risk data over time. It was found that a power equation was the best fit.

SFPOF Output Data Summary
21

Hours	Single Flight POF
1500.0	0.2000E-15
2500.0	0.2000E-15
3500.0	0.2000E-15
4500.0	0.2082E-13
5500.0	0.3380E-11
6500.0	0.1709E-09
7500.0	0.5183E-08
8500.0	0.8905E-07
9500.0	0.1175E-05
10500.0	0.8825E-05
11500.0	0.5444E-04
12500.0	0.2452E-03
13500.0	0.8520E-03
14500.0	0.2841E-02
15500.0	0.7717E-02
16500.0	0.1566E-01
17500.0	0.2902E-01
18500.0	0.4722E-01
19500.0	0.7949E-01
20500.0	0.1037E+00
21500.0	0.1649E+00



FSMP Example W2 – Risk Data Presentation

Aircraft	Projected	PDM*		Plus 1 year		Plus 2 year		Plus 3 year		Plus 4 year		Next PDM	
Number	Year	year	risk	year	risk	year	risk	year	risk	year	risk	year	risk
A/C 04	2021	2017	2.1E-09	2018	4.5E-09	2019	9E-09	2020	1.8E-08	2021	3.4E-08	2022	6.5E-08
A/C 07	2024	2022	1E-08	2023	1.9E-08	2024	3.4E-08	2025	6.1E-08	2026	1.1E-07	2027	1.8E-07
A/C 08	2019	2018	2.1E-08	2019	3.9E-08	2020	6.9E-08	2021	1.2E-07	2022	2.1E-07	2023	3.6E-07
A/C 10	2015	2013	3.6E-09	2014	1.1E-08	2015	3.4E-08	2016	9.6E-08	2017	2.6E-07	2018	6.5E-07
A/C 12	2012	2008	1.2E-10	2009	5.7E-10	2010	2.4E-09	2011	9.4E-09	2012	3.3E-08	2013	1.1E-07
A/C 15	2011	2007	4.8E-10	2008	1.6E-09	2009	4.7E-09	2010	1.4E-08	2011	3.7E-08	2012	9.4E-08
A/C 16	2016	2012	3.3E-10	2013	1.2E-09	2014	3.9E-09	2015	1.2E-08	2016	3.4E-08	2017	9.3E-08

* PDF prior to projected year (deterministic approach) for inspection

🟨 ⇒ Yellow box means year that fall within the 7-year planning period

🟪 ⇒ Purple box means that risk value higher than 1.E-7

FSMP Strategy Summary

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- Benefits
  - Provide OK/ALC engineers with a probabilistic risk based analysis to help determine the best inspection time
  - B-1 ASIP in compliance with Mil-Std-1530C
  - With potential delay of inspections due to calculated smaller risk, the following benefits were demonstrated
    - less inspection frequency
    - increase aircraft availability by postponing inspections
- Disadvantages
  - Potentially even more fluctuation in proposed inspection dates then with the current deterministic analysis
- Potential improvements
  - Curve fitting strategy may be enhanced to examine the input data range
  - Year by year risk calculation instead of curve fit. Time consuming but we may find a way to reduce the computation effort.
  - Risk update after each flight and after inspection and repair