A Computer Simulation of the Life of the Structures of a Fleet of Aircraft

A Life Cycle Risk and Reliability Model for Aircraft Structures

Arnold Anderjaska - Technical Data Analysis, Inc.
USAF Aircraft Structural Integrity Program (ASIP) - 2007
6 December 2007

Reasons for a Structural Area Inspection Frequency Evaluation (SAIFE) Program

- Use of Aircraft Beyond Design Life Increases need for Good Risk Analyses
- SAIFE Program has Unique Capabilities

Why the SAIFE Model?

- Repeated requirement to prevent progressive type failures from fatigue and corrosion
- *Reasons*:
  1. Design and Substantiation Criteria Changes
  2. Correction of Service Problems
  3. Establishment of Inspection Policies and Programs
- *Decisions Based on Two Critical Factors*:
  1. The probability of structural defects and catastrophic failure
  2. The burdens caused and alleviated by the proposed action

Why the SAIFE Model? (cont.)

- It is an impossible task to consider all the factors and variability's involved in predicting these two factors
- However, decisions have to be made and are made every day with only an implied prediction of these two factors without making a best estimate
- These decisions are based on the available analysis, tests, data and engineering judgment

Why the SAIFE Model? (cont.)

- Decision was made to develop a computer simulation that would quantify this engineering judgment and any resulting burdens
- Utilize all available information and resources to account for the significant factors in predicting these Two Factors
- Intended to Assist in the Evaluation of:
  - Possible actions on Old and Aging Aircraft
  - Detailed Criteria for the New Fatigue Rule
  - Proposed MSG-3 inspection programs
- To be realistic, all significant factors from design thru test, production, service and maintenance must be accounted for
- It must be recognized that this is a dynamic problem with feedback and response

SAIFE Simulation Model Accounts for the Following

- Design and Criteria Errors
- Test Schedule, Criteria, Errors and Results
- Production Schedule and Defects
- Service Usage, Schedule & Damage
- Corrosion and its Growth
- Fatigue Crack Initiation and Growth
- Inspection Changes & Modifications due to Service Experience
- The effect damage, corrosion and defects have on fatigue initiation and growth and residual strength
- Residual strength during damage growth is compared with the load exceedances to determine the probability of failure

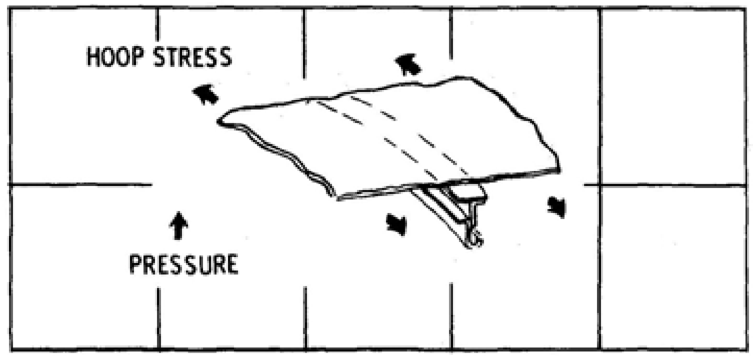
Key Points

- Simulation input was approximate but was based on a considerable effort to analyze extensive engineering, test and service data
- 10 years of MRR's
- Results compare favorably with service experience

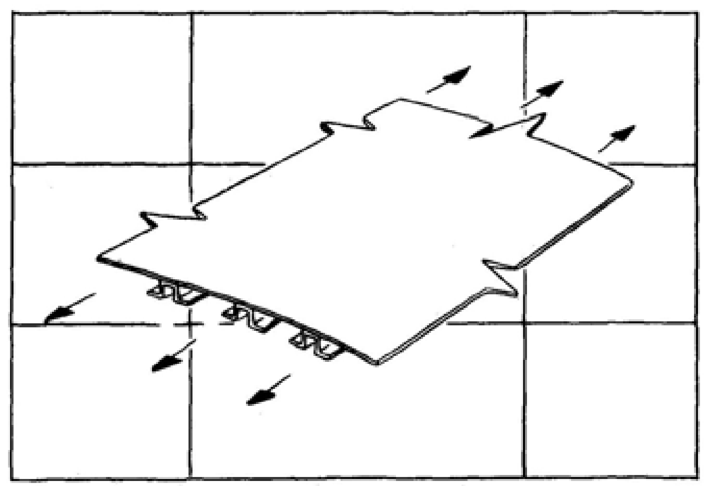
How the Model Works

- Input Definitions of:
  - Fleet (Hybrid – 747 Wing and DC-10 Fuselage)
  - Fatigue substantiation programs
  - Loading environment
  - Primary structure in terms of elements
  - Elements – fatigue life, crack growth rate, fail-safe strength, past corrosion and damage rates
  - Inspection program
  - Corrective action policies

Typical SAIFE Structural Elements



Fuselage Frame Element



Wing Stringer Element

SAIFE will Predict the Following for an Aircraft Fleet

- Number, Type and Size of Defect Crack as well as Occurrences & Detections
- Number of Complete Structural Failures
- Number of Modifications & Special Inspections
- SAIFE will Give History of Major Occurrences
- Repeated Trials will Provide Relative Probabilities of Complete Failure and some Information on Relative Burdens of Various Proposed Actions

Summarized Flow of Simulation

(Full Flow chart in Backup)

1st element predicts life from fatigue analysis, failure time in fatigue test, schedules inspection change/mod., if needed

→

1st A/C enters service - predicts defects & growth

→

Inspected – if detected, repairs, decides on inspection changes & mod. & schedules, estimates failure rate

↓

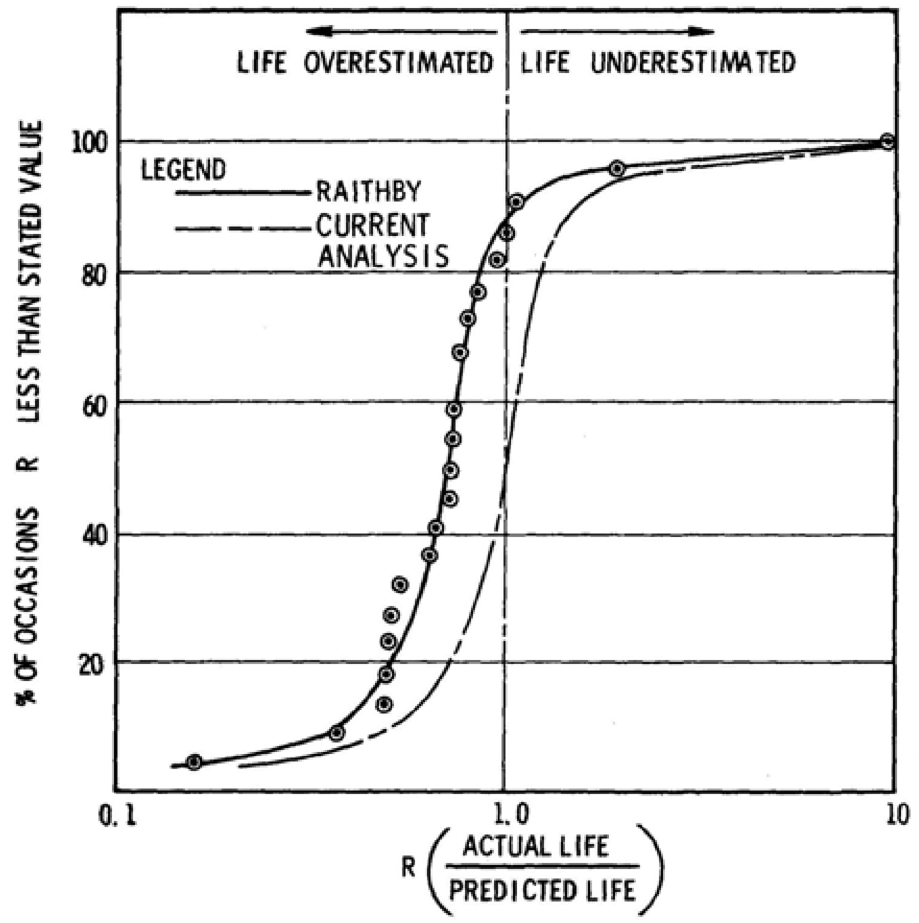
If not detected defect grows to failure or retirement

←

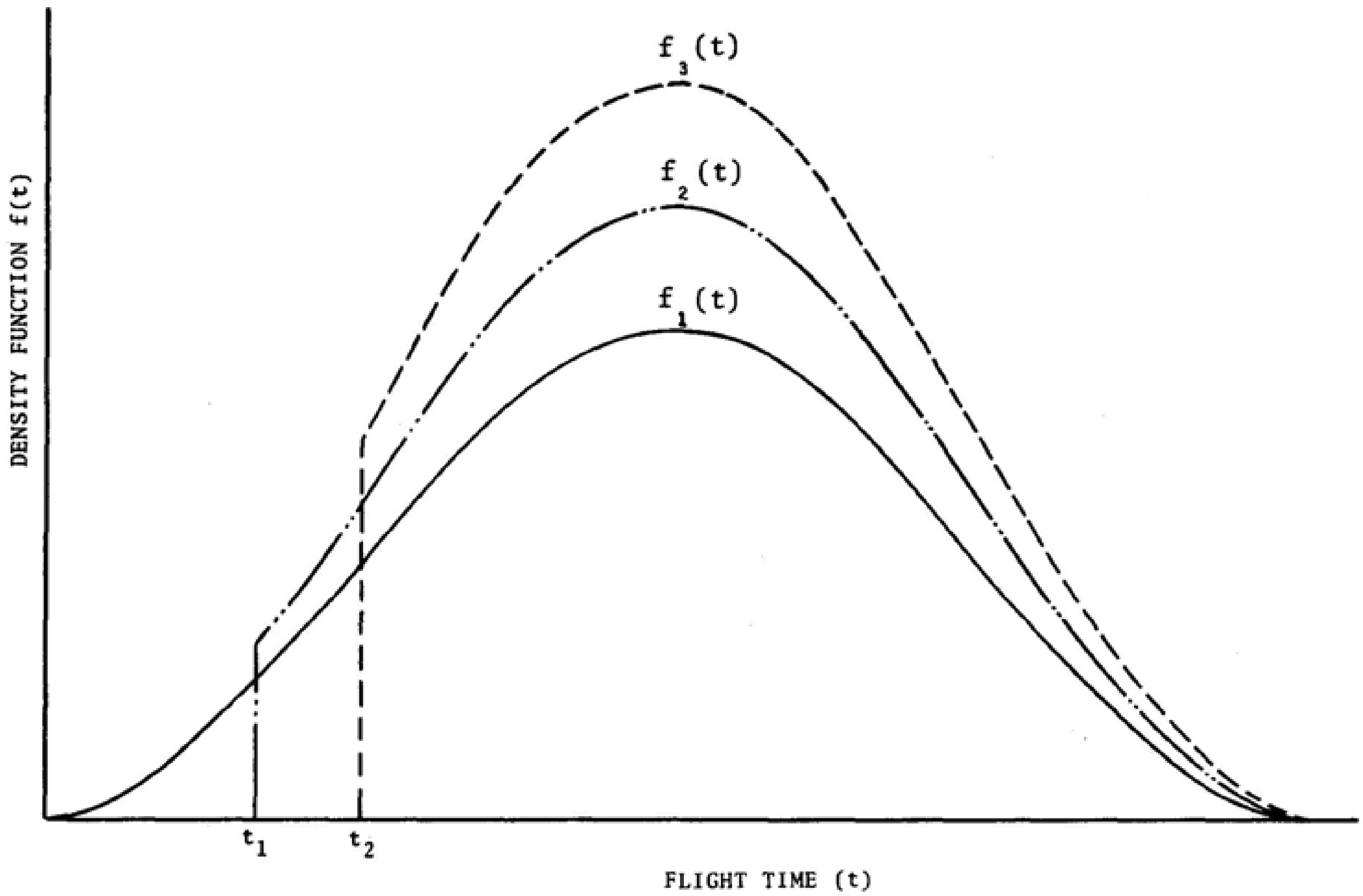
- Goes to next A/C
- If last A/C, goes to next Element
- If last element, end of simulation and print results

Major Elements of SAIFE Process

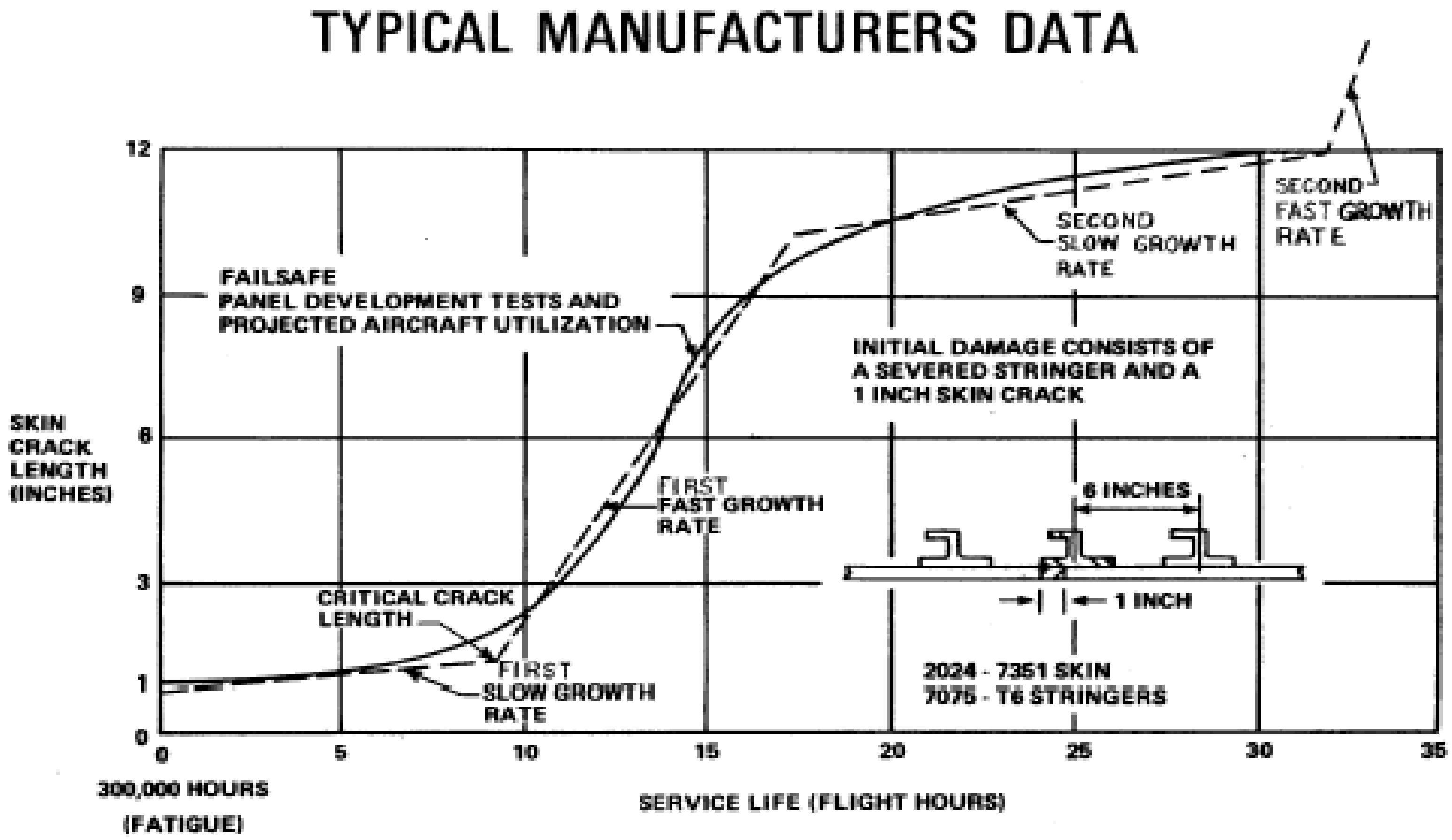
Account for Inaccuracies in Fatigue Analysis



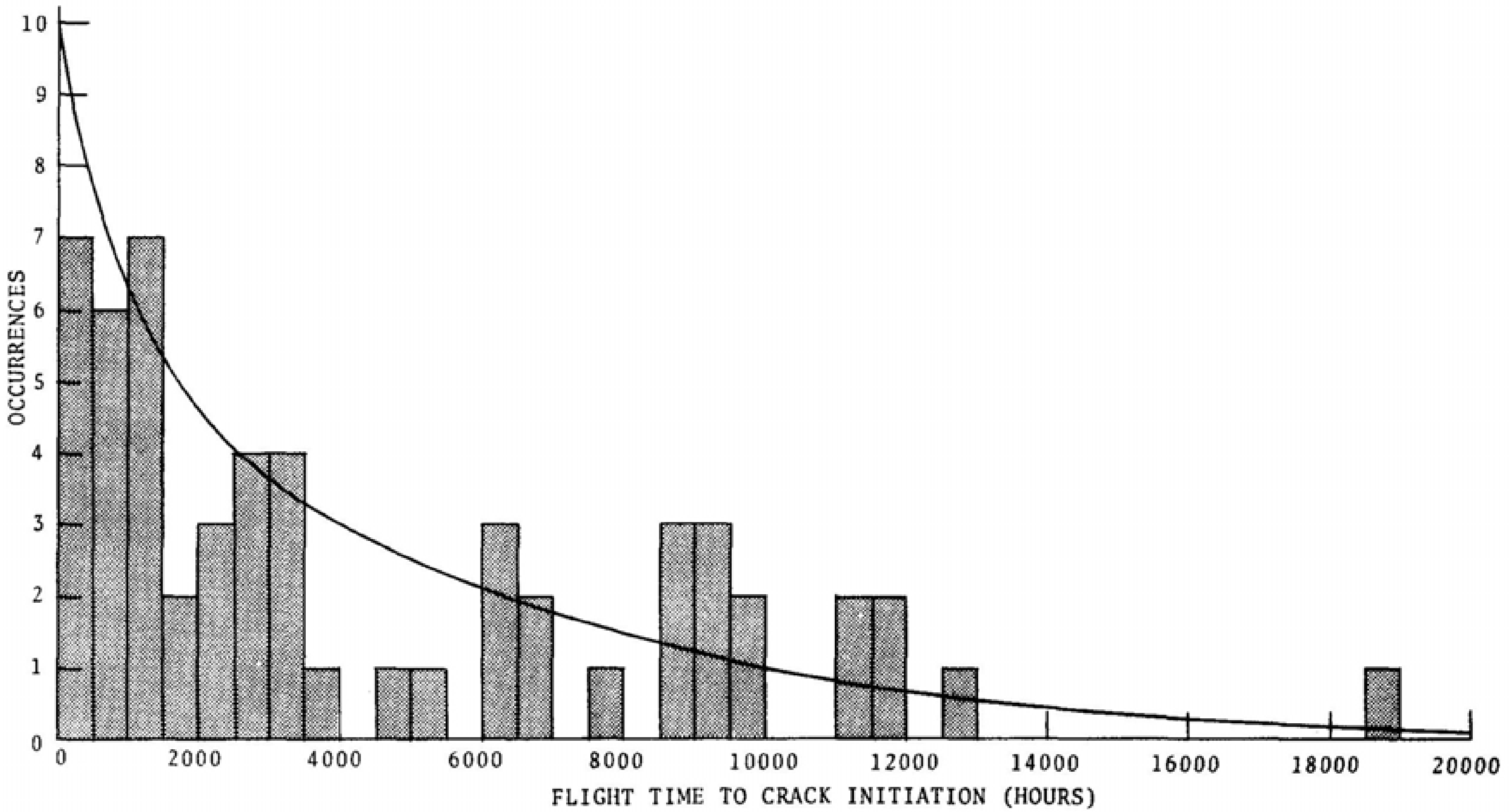
Predict 1st and 2nd Fatigue Cracks in Individual Elements



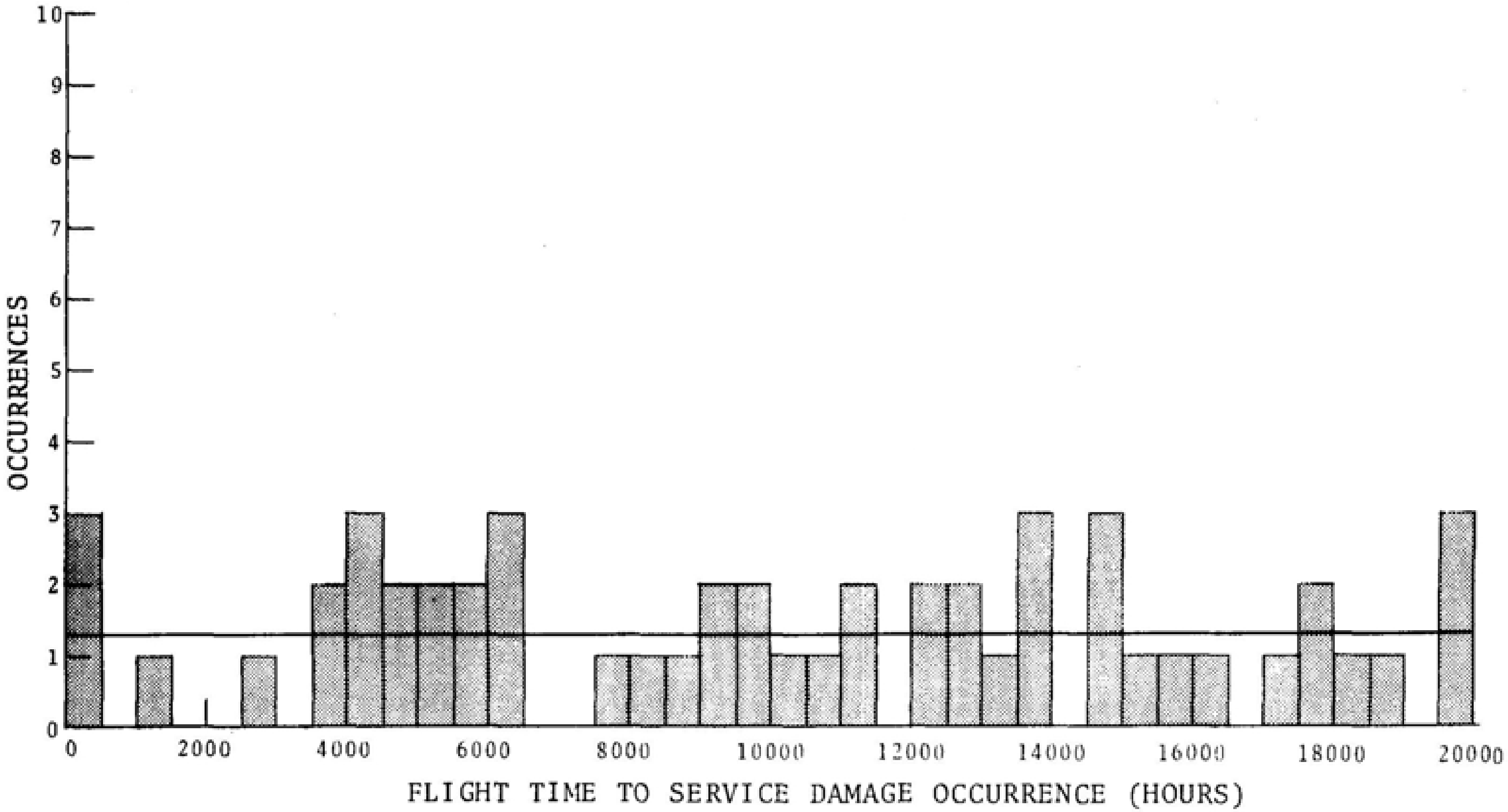
Predict Fatigue Crack Growth



Predict Fatigue Cracks from Production Defects

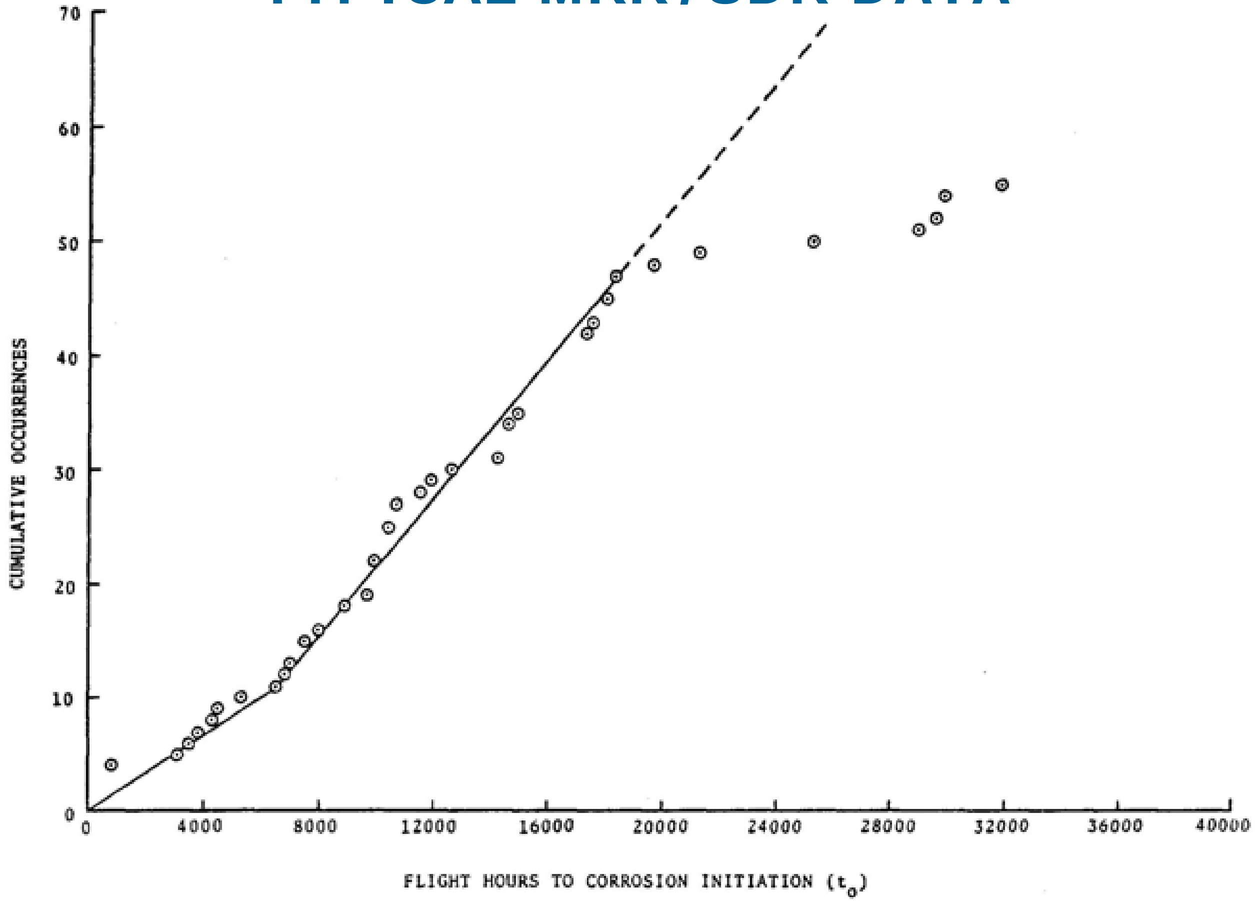


Predict Service Damage and Coincidental Fatigue Crack Initiation



Predict Corrosion Initiation

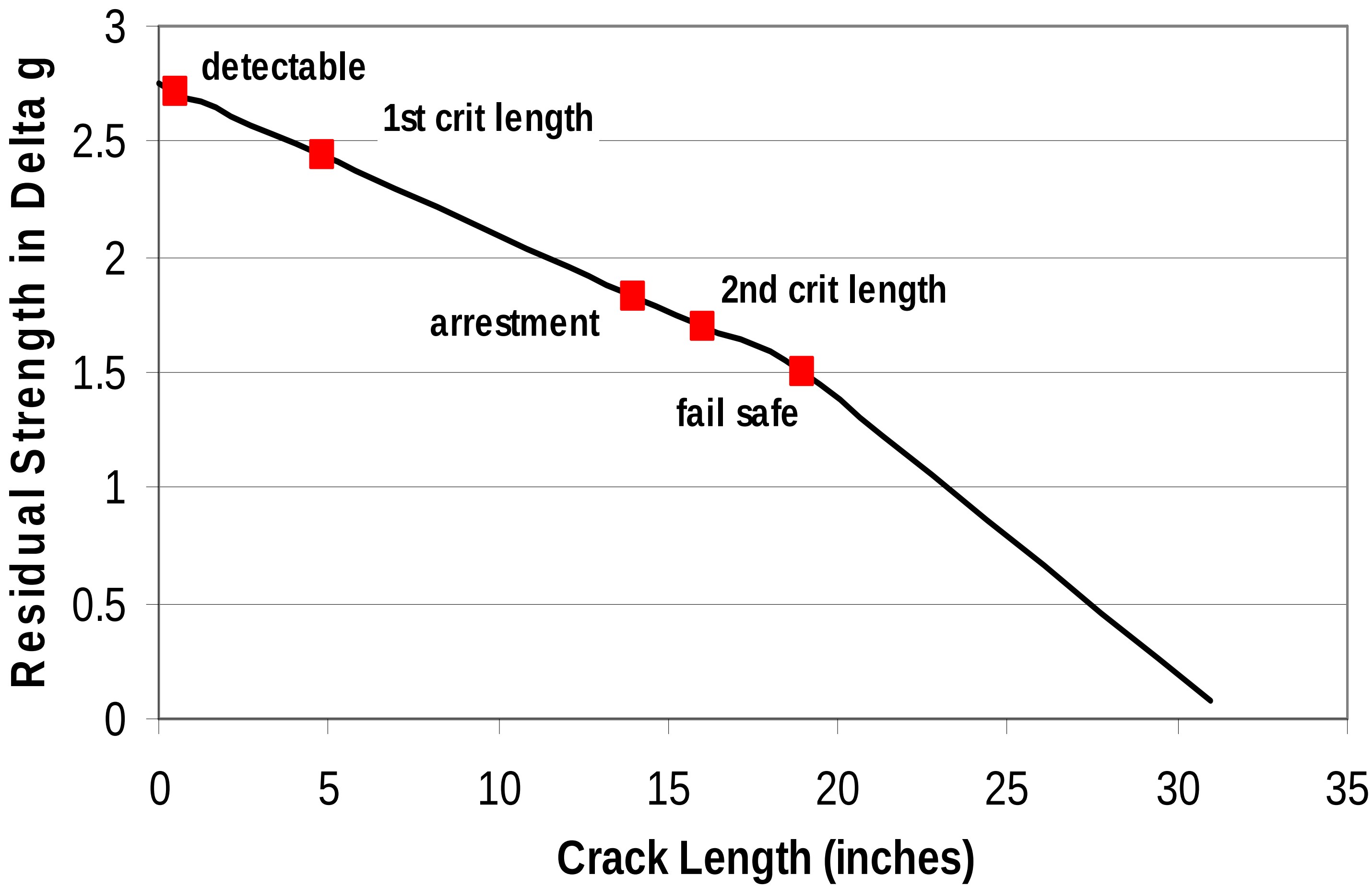
TYPICAL MRR/SDR DATA



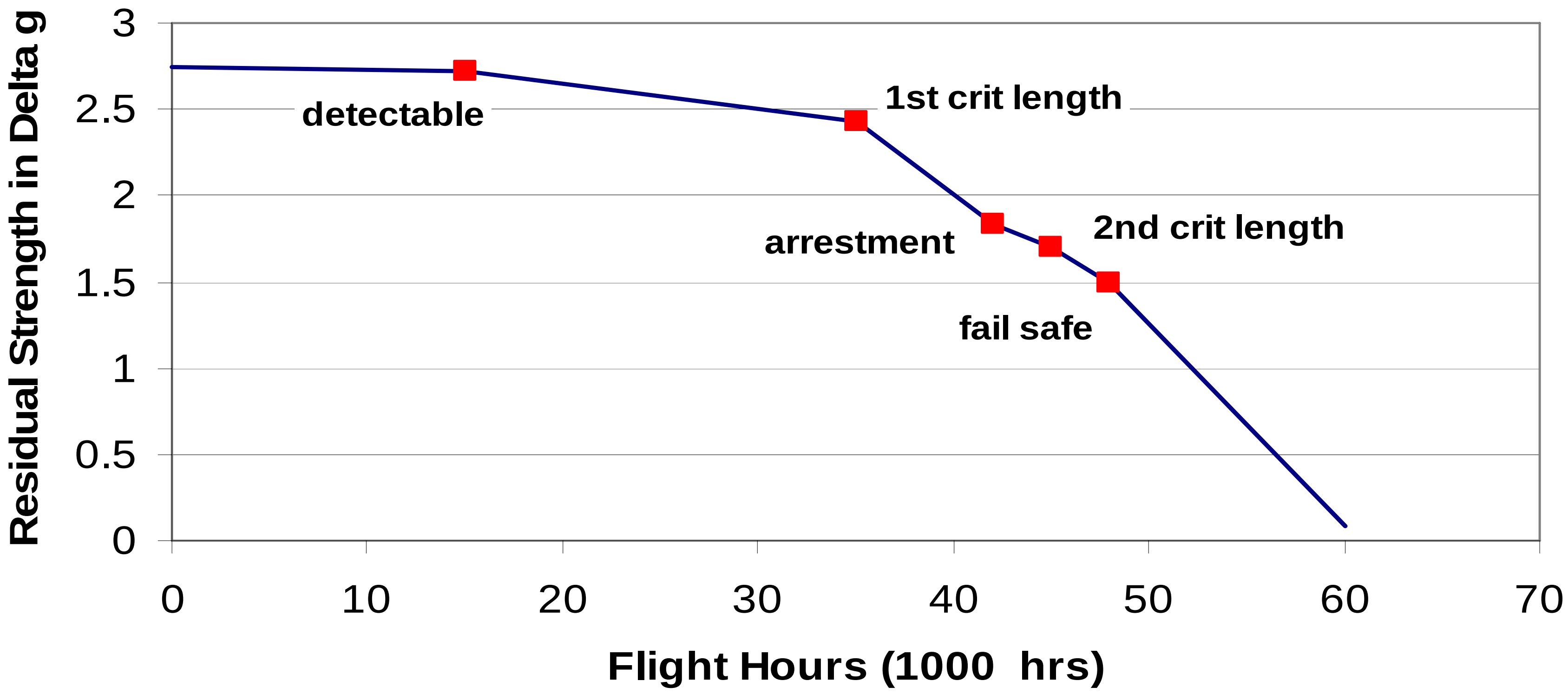
Corrosion Effects

- Decreases time to fatigue crack initiation
- Increases crack growth rates
- Presently does not affect residual static strength but could

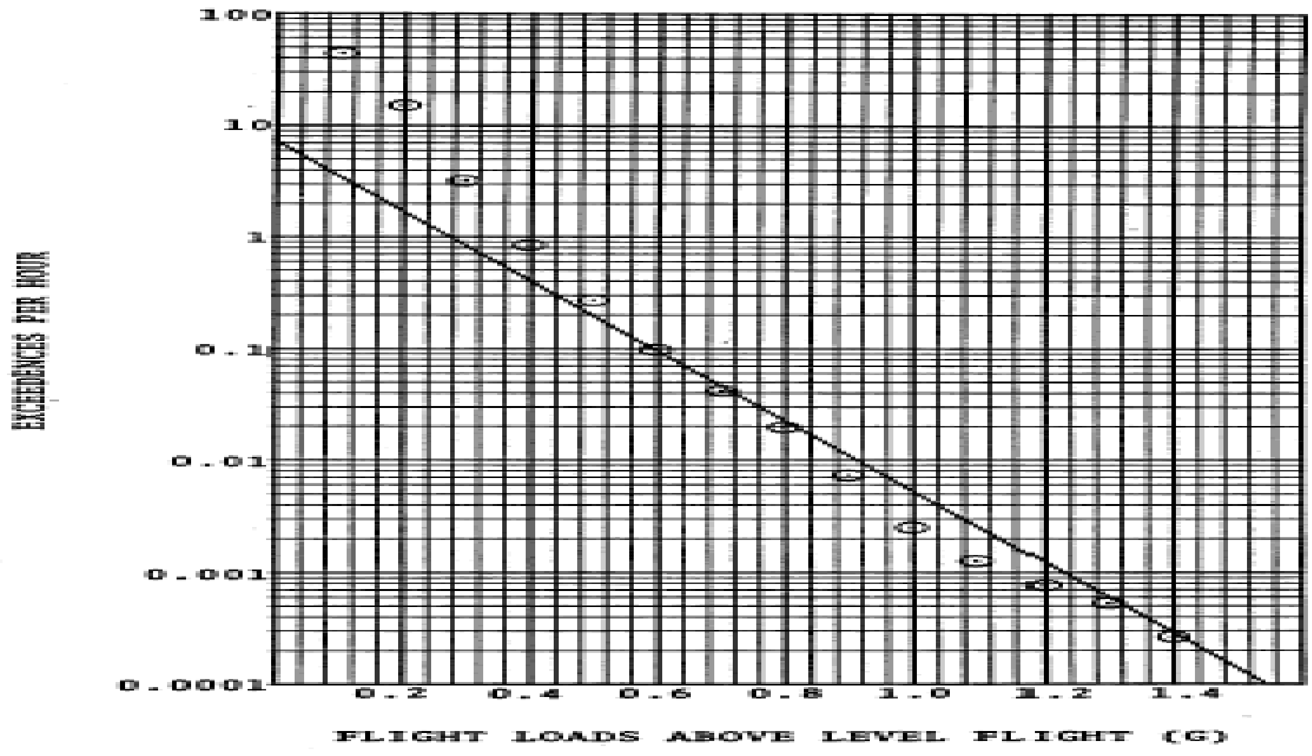
Estimate Residual Strength vs. Crack Length



Convert Residual Strength Curve to Flight Hours

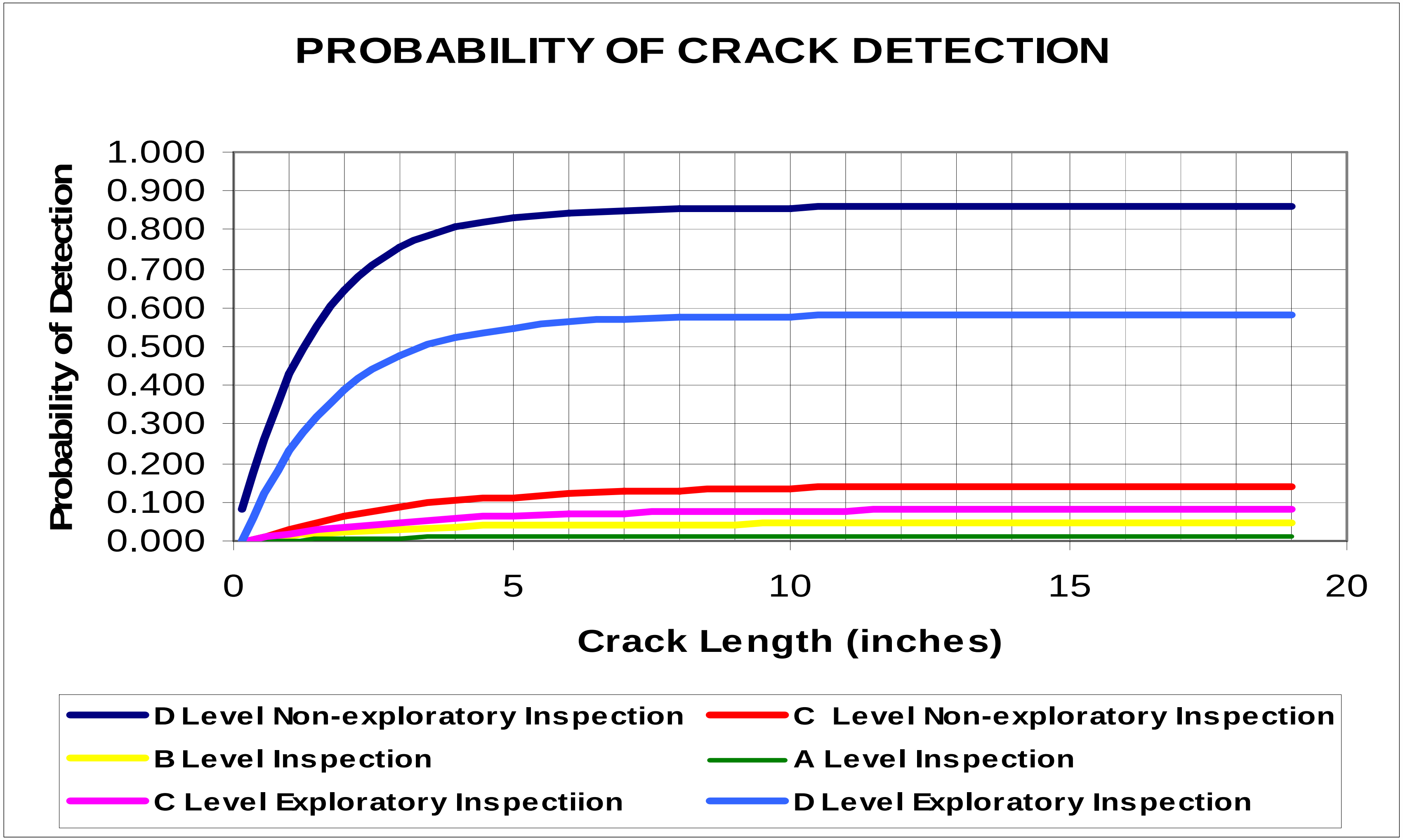


Estimate Probability of Crack Failure from Residual Strength & Load Exceedances

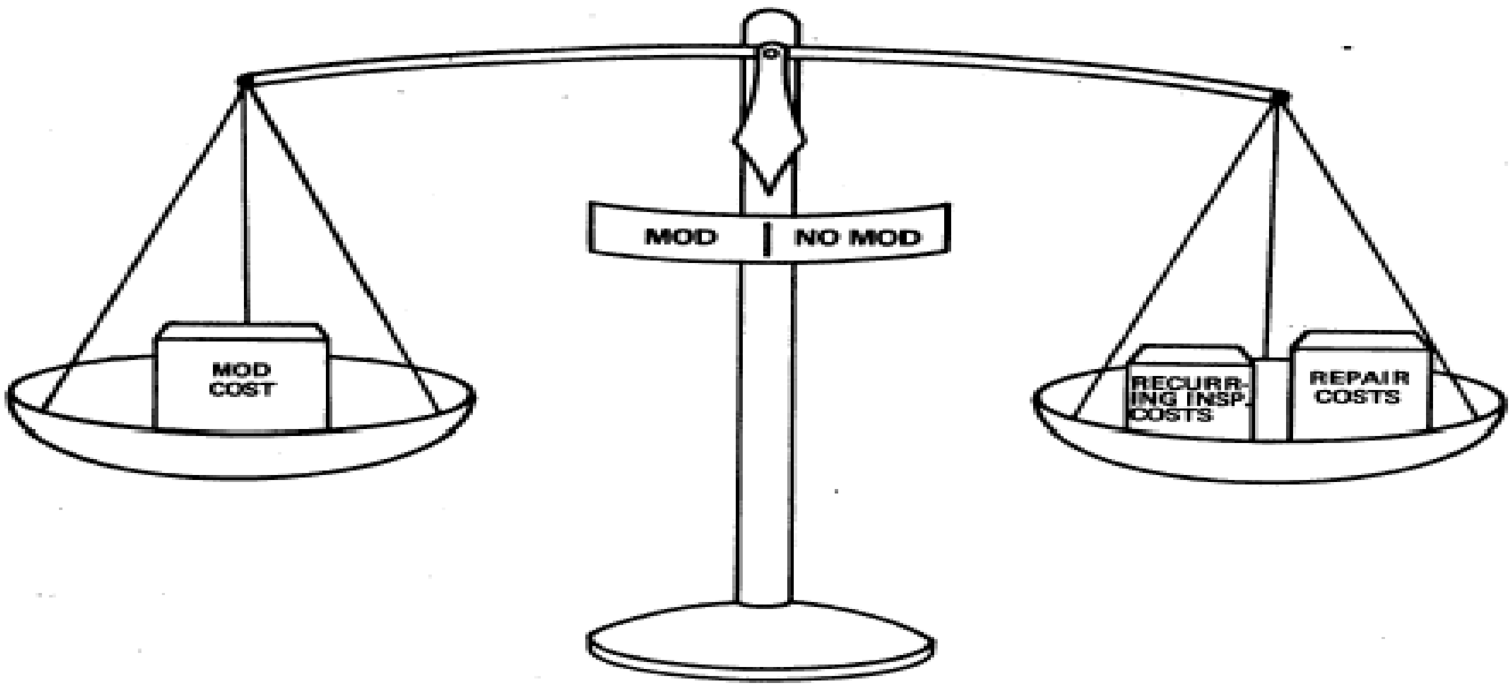


Flight Load Exceedances

Predict Whether Cracks Detected



Repair Detected Cracks and Decide if Inspections Increase and/or Modification Needed



Typical Element History Output

STRUCTURAL ELEMENT: FUS-MFR-SID-1740

PREDICTED AVERAGE FATIGUE LIFE: 157620 HOURS ACTUAL AVERAGE FATIGUE LIFE: 343268 HOURS

FATIGUE TEST LIFE:9999999 HOURS

NUMBER AND TIME TO INITIATION OF AIRCRAFT DEFECTS

	FIRST CRACK	CORROSION	SERVICE DAMAGE	PRODUCTION DEFECTS
OCCURRENCES	3	0	2	0
MIN(HRS)	2615	0	2615	-----
MAX(HRS)	36817	0	30910	-----
AVG(HRS)	23447	0	16762	-----

NUMBER AND LENGTH OF CRACKS DETECTED AT EACH LEVEL OF INSPECTION

	A-LEVEL	B-LEVEL	C-LEVEL	D-LEVEL	SPECIAL
OCCURRENCES	0	0	2	0	1
MIN(IN)	0.	0.	3.97	0.	2.49
MAX(IN)	0.	0.	7.62	0.	2.49
AVG(IN)	0.	0.	5.80	0.	2.49

NUMBER AND AREA OF CORROSION DEFECTS DETECTED AT EACH LEVEL OF INSPECTION

	A-LEVEL	B-LEVEL	C-LEVEL	D-LEVEL	SPECIAL
OCCURRENCES	0	0	0	0	0
MIN(SQ.IN)	0.	0.	0.	0.	0.
MAX(SQ.IN)	0.	0.	0.	0.	0.
AVG(SQ.IN)	0.	0.	0.	0.	0.

INSPECTION INTERVALS(HRS)					MOD NO	SAMPLING	TIME
INITIAL	25	315	1000	3200	0	15	
2	25	315	1125	4800	0	11	3800
3	25	315	1266	7200	0	8	8600
4	25	315	1424	10800	0	6	15800
5	25	315	1602	16200	0	5	26600
6	25	315	2002	20250	0	6	42800
7	25	315	2503	25313	0	7	67150
8	25	315	2503	8859	0	20	87223

CRACK LENGTHS AND CORRESPONDING CUMULATIVE PROBABILITY OF FAILURE

AIRCRAFT NO.	FLT. HOURS	CRK.LGT.	PROB. OF FAILURE
194	58262	3.97	+6.E-013
489	43273	7.62	+4.E-012
474	44773	2.49	+2.E-013

NUMBER OF SPECIAL INSPECTIONS CONDUCTED: 1

NUMBER OF STRUCTURAL MODIFICATIONS: 0

FINAL ACTUAL AVERAGE MODIFIED FATIGUE LIFE: 343268 HOURS

NUMBER OF AIRCRAFT MODIFIED IN SERVICE: 0

ESTIMATED ELEMENT FAILURE RATE:+1.72E-019/HR.

STRUCTURAL FAILURES

AIRCRAFT NO.	FLT. HOURS
------------	----------

RESIDUAL STRENGTH EQUALS FAIL-SAFE STRENGTH

AIRCRAFT NO.	FLT. HOURS
------------	----------

First Crack

C/D Level

Prob. of Failure

SAIFE Demonstration Results

Summary of Demonstration Run - Failure Rates

	Estimated Failure Rate using average		Estimated Failure Rate	
	Full	Sample	Full	Sample
Door Frame	2.54E-15	3.58E-15	6.70E-15	2.01E-13
Window Frame	5.02E-14	1.78E-14	1.16E-11	3.90E-14
Fuselage				
-Main Frame, Bottom	4.54E-18	6.47E-18	4.54E-18	1.08E-15
-Main Frame, Side	9.82E-18	9.49E-14	1.18E-16	1.84E-14
-Main Frame, Top	6.70E-18	2.17E-17	8.70E-18	2.85E-16
-Stringer, Bottom				
-Stringer, Side	1.61E-11	2.55E-13	3.63E-10	2.43E-10
-Stringer, Top	2.45E-16	1.61E-17	2.45E-16	8.60E-17
Wing				
-Access Frame	3.98E-12	2.90E-12	4.34E-12	3.82E-12
-Spar, Aft	8.55E-13	1.30E-12	1.09E-12	1.44E-12
-Spar, Center	4.64E-12	1.22E-11	1.11E-10	1.64E-11
-Spar, Forward	1.95E-14	0.00E-00	1.61E-14	0.00E-00
-Stringer, Aft	3.14E-12	2.80E-12	8.35E-12	3.99E-12
-Stringer, Center	4.64E-12	1.22E-11	1.11E-10	1.64E-11
-Stringer, Forward	4.63E-13	3.08E-12	2.04E-12	3.44E-12
Wing Center Section				
-Stringer, Aft	7.81E-13	3.08E-14	7.57E-13	0.00E-00
-Stringer, Center	2.90E-14	1.49E-15	1.11E-10	0.00E-00
-Stringer, Forward	5.07E-15	0.00E-00	2.04E-12	0.00E-00
-Spanwise Beam, Aft	1.18E-12	3.49E-14	5.86E-12	9.88E-13
-Spanwise Beam, Center	1.54E-13	1.94E-13	1.38E-13	0.00E-00
-Spanwise Beam, Forward	7.39e-14	4.69e-15	5.83E-14	0.00E-00
Pressure Loaded Total	4.80F-14	1.03E14	6.26E-13	4.23E-14
Flight Loaded Total	6.71E-11	3.02E-11	7.51E-10	2.84E-10
Total	5.00E-11	3.02E-11	5.83E-10	2.84E-10

Note: No actual failures occurred in demonstration run of 3.0E07 hrs.

Comparison of Cracks Detected at Each Inspection Level per Million Flight Hours

	FULL		SAMPLE		MRR-SDR	
	Cracks Detected	% of Total	Cracks Detected	% of Total	Cracks Detected	% of Total
Preflight	24.87	9.56	25.34	7.82	2.87	4.3
Service	20.89	8.03	20.18	6.42	7.93	11.8
Phase	28.49	10.95	29.86	9.22	10.94	16.3
Overhaul	147.24	56.59	200.45	61.87	24.21	36.1
Special	38.69	14.87	47.51	14.66	21.14	31.5
Total	260.18	100.00	323.98	100.00	67.09	100.0

Comparison of Size of Cracks Detected

	FULL Average Length (inches)	SAMPLE Average Length (inches)	MMR / SDR Average Length Where Reported (inches)
Preflight	1.573	1.943	----
Service	1.719	1.812	----
Phase	1.688	2.505	----
Overhaul	1.375	1.467	----
Special	1.771	2.014	----
Fuselage Total	1.741	1.815	1.99
Wing Total	1.118	1.470	2.16
Total	1.515	1.718	2.089 (1.567)*

* All reports, assuming 5/8" length when not reported

Examples of SAIFE Parametric Study

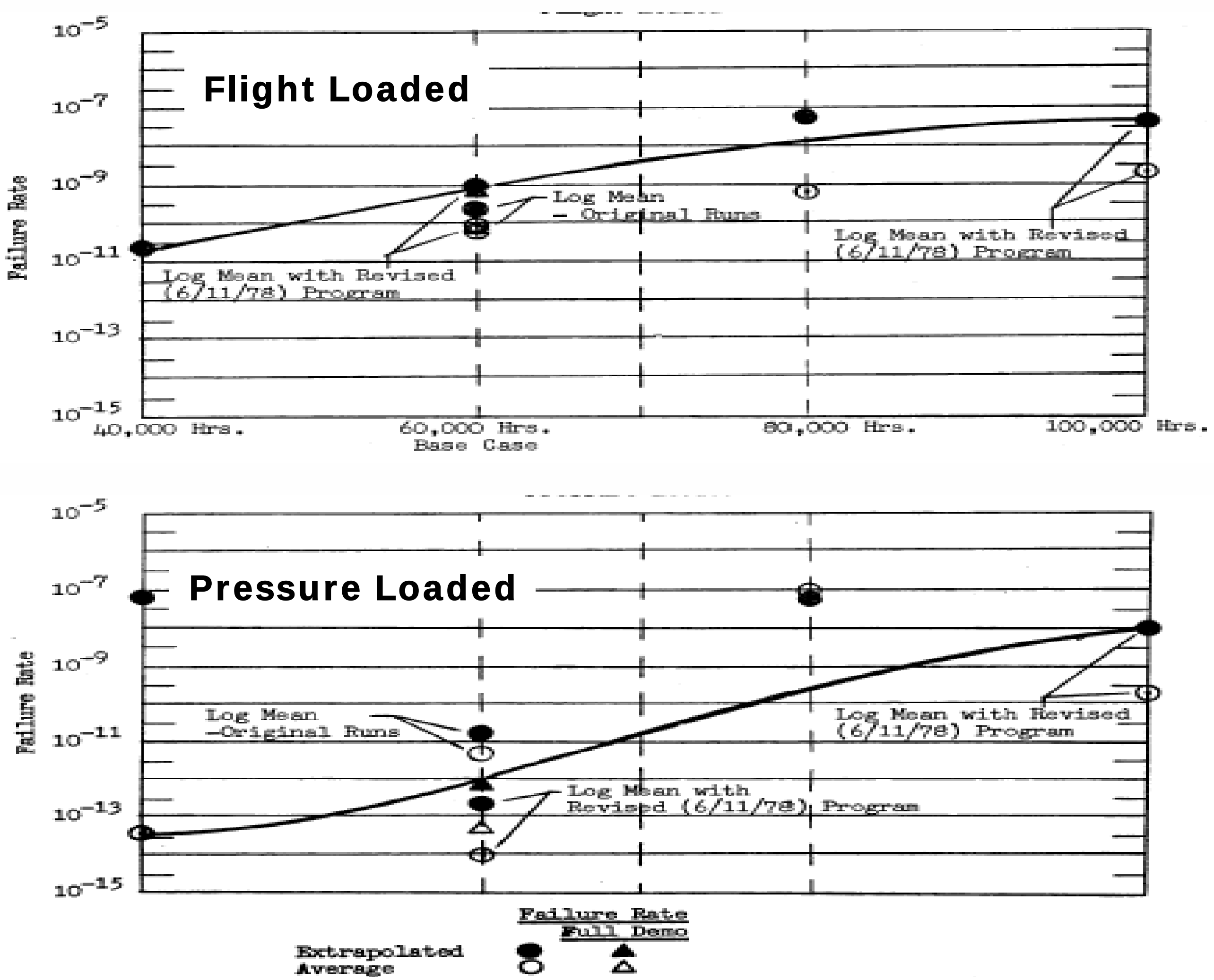
Fleet Usage Life

- Usage life varied from planned life (60,000 hrs)
- Distribution of sample results – log normal, mean plotted
- Base case – log mean of 3 runs
- Failure rate tends to lower asymptote F (overload rate).
- Review of detailed results indicates time available for crack growth is a major factor

IMPLICATIONS:

- Wide-body safety level satisfactory for planned life (60,000 hrs)
- Safety level with normal practices inadequate for extended usage beyond planned life

Fleet Usage Life (cont.)



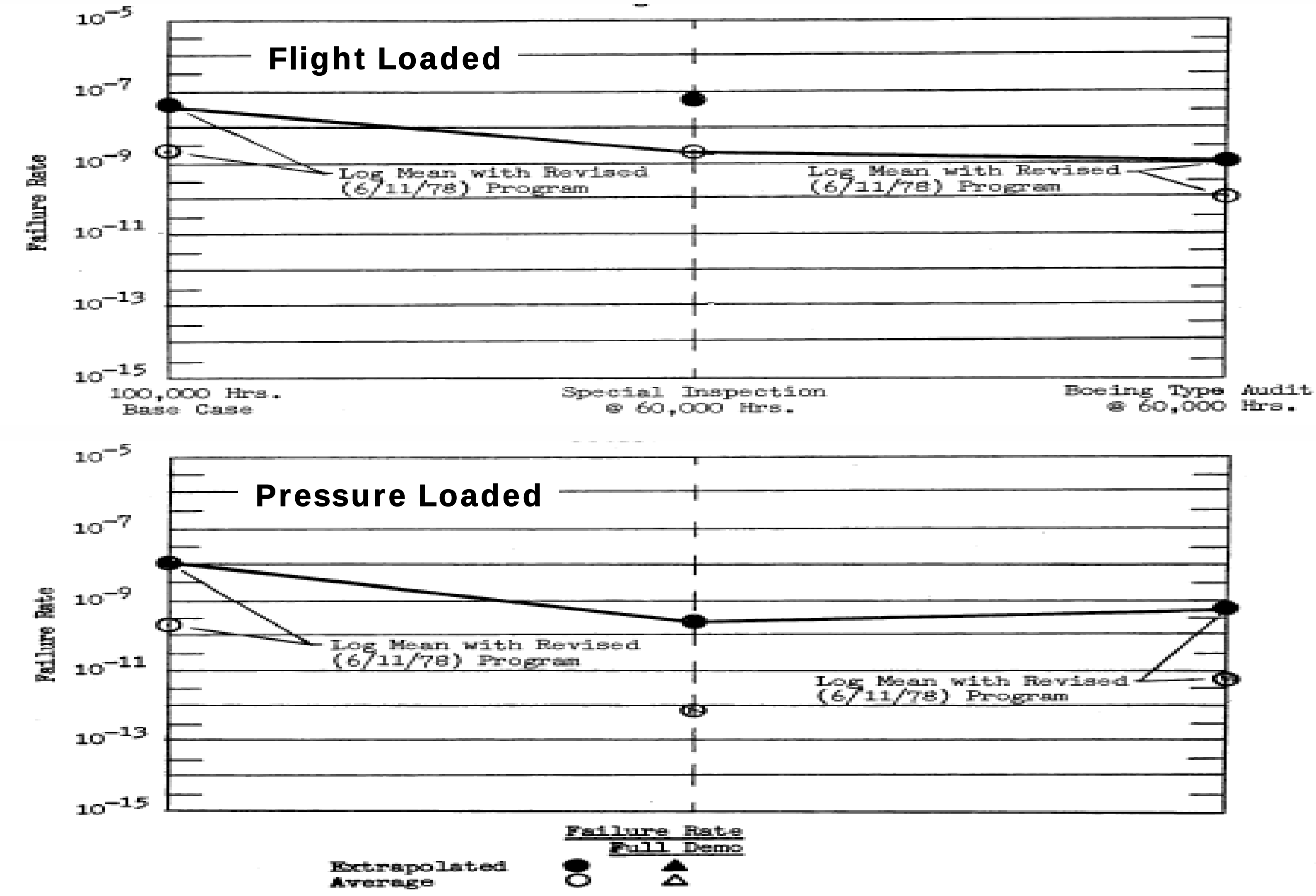
Action on Old Age Aircraft

- Usage life extended to 100,000 hours on all runs
- Special complete internal and external inspections at 60,000 flight hours (1 run)
- Audit at 60,000 flight hours – Limit D check to 15,000 hours in all areas and use internal NDT in areas of low fatigue life with poor detectability (3 runs)
- Base case – normal inspections (3 runs)
- Review of results indicates that runs with corrective action underestimates their effectiveness

IMPLICATIONS:

- Safety level with normal program is inadequate for 100,000 hours
- Corrective action evaluated provides a safety improvement that is adequate with audit approach being more effective
- More runs could be useful

Action on Old Age Aircraft (cont.)



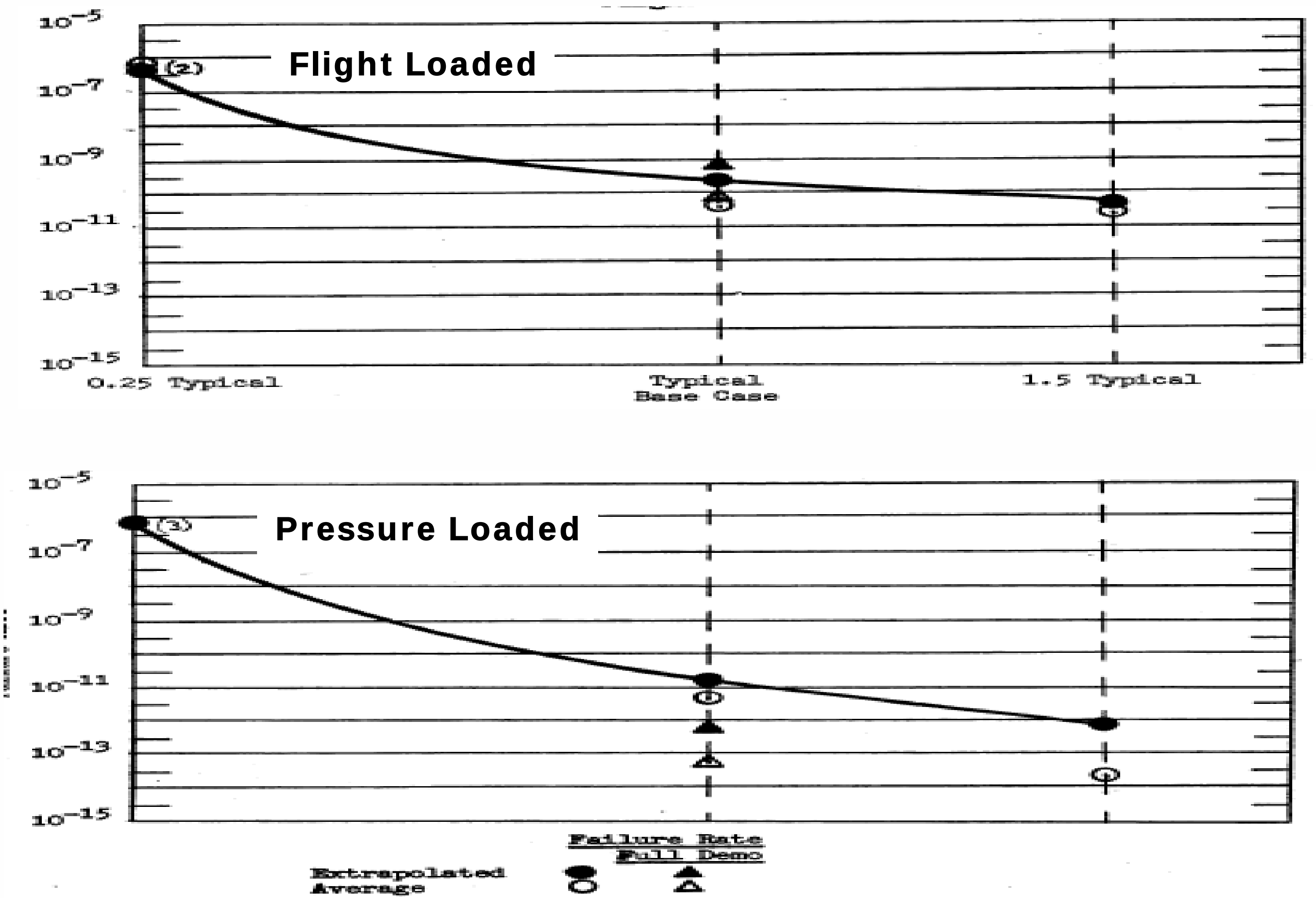
Critical Crack Length

- Critical crack length defined as first length at which crack propagation rate sharply increases
- Typical wide-body critical crack length (5 to 14 inches) varied as a F (material and stress level)
- Crack with shorter critical crack length reduces strength faster
- Detail review indicates runs typical

IMPLICATIONS:

- Reduction in typical critical crack length would drastically reduce safety level
- Increase in typical critical crack length would result in only small increase in safety level

Critical Crack Length (cont.)



Conclusions of Original SAIFE Parametric Study

- Present Designs, Inspection Programs and Practices Provide Adequate Safety for Original Planned Life and Usage
- Effective Special Action (i.e., More Stringent Inspection and/or Modification) Needed if Life or Usage Well Beyond that Originally Planned

Recommendations of Original SAIFE Parametric Study

- Strengthen Existing Continued Structural Monitoring by issuing Guidance Material on Assessment and Results in Supplemental Inspection Document (SID)
- Reassess and Issue or Revise SID whenever:
  - Aircraft will be used well beyond the original planned life
  - New operators experience or capability is marginal
  - Aircraft used in mission more severe than originally planned
  - Service experience indicates that large portions of structure is marginal

Current Conclusions

- SAIFE can be used for individual elements, types of elements or a complete airplane
- SAIFE can supplement current typical Risk Analyses (which cover only one local critical area and account for only a limited number of variables) by providing valuable insights and overall global view
- SAIFE should be improved and further use explored

Backup Slides

FIG 3, SHEET 1 OF 4

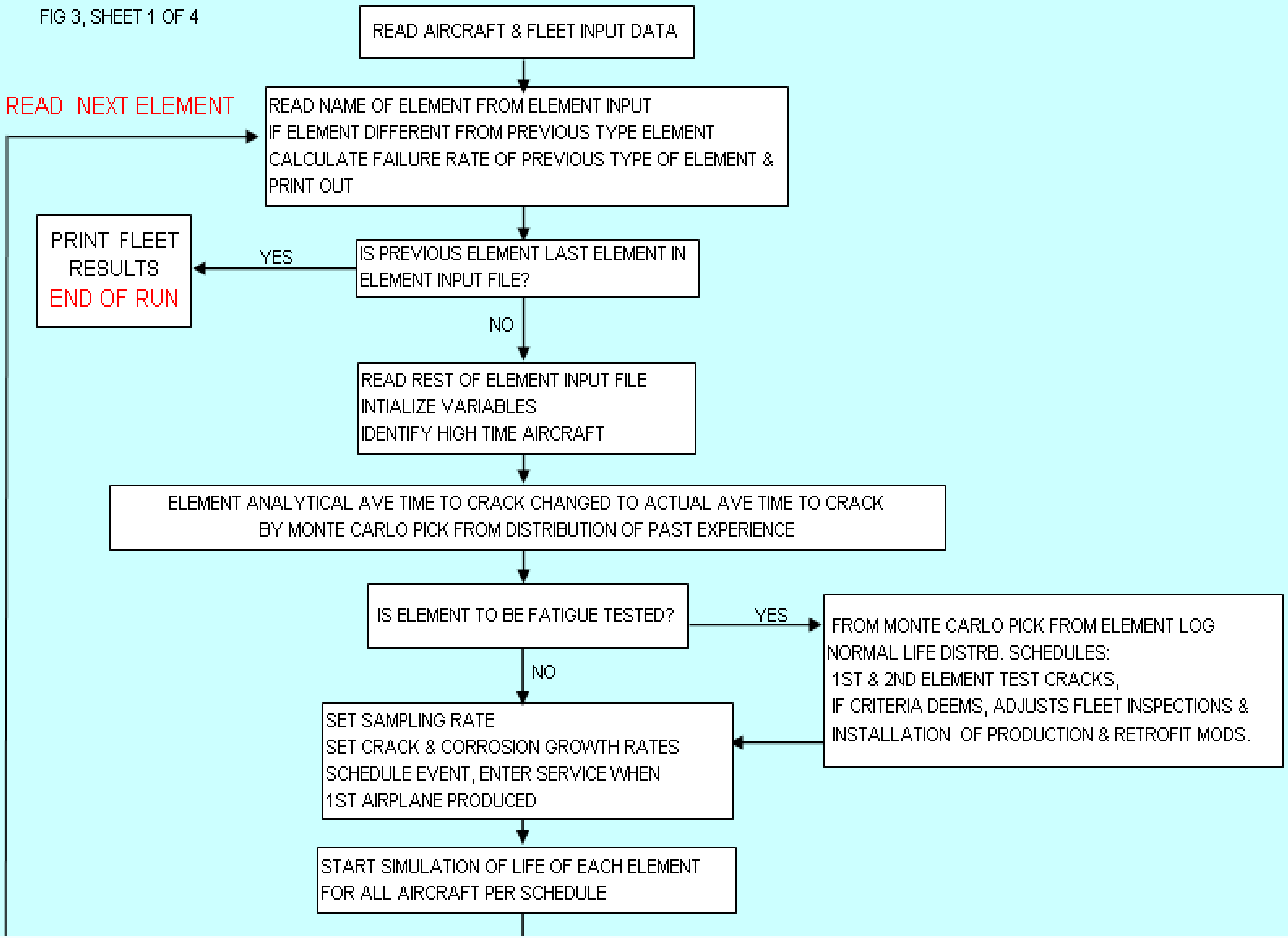


FIG 3, SHEET 2 OF 4

IF EVENT ENTER SERVICE NEXT:
IF PREVIOUS AIRPLANE IS LAST AIRPLANE IN FLEET, RETURN TO READ NAME OF NEXT ELEMENT
CREATE AIRPLANE IN ACTIVE FLEET
PREDICT FACTOR FOR THIS AIRPLANE FOR ADJUSTING CRACK INITIATION, CRACK GROWTH RATES, LOAD EXC'DS TO ACCOUNT FOR SEVERITY OF LOAD ENVIRONMENT
BASED ON MONTE CARLO PICKS & FACTOR SETS AND/OR SCHEDULES:
1ST & 2ND CRACK & CORROSION INITIATION, CRACK & CORROSION GROWTH RATES, PRODUCTION DEFECTS & SERVICE DAMAGE
SCHEDULES EVENT ENTER.SERVICE FOR NEXT AIRPLANE

IS NEXT AIRPLANE ENTER SERVICE THE NEXT EVENT?

YES

NO

IF EVENT INSTALL MODIFICATION FROM TEST OR SERVICE NEXT:
SETS AND/OR SCHEDULES MODIFICATION :
1ST & 2ND CRACK & CORROSION INITIATION, CRACK & CORROSION GROWTH RATES , PRODUCTION DEFECTS,& SERVICE DAMAGE AS IN ORIGINAL DESIGN & TEST
IF CRACK PRESENT BEFORE MOD , CALCULATES LENGTH OF CRACK(S) & PREDICTS RISK TO DATE (PROBABILITY OF LOAD EXCEEDING RESIDUAL STRENGTH)

IF EVENT CORROSION INITIATION NEXT:
ADJUST AND/OR SCHEDULE 1ST & 2ND CRACK INITIATION & GROWTH RATES
IF CRACK EXISTS, CALCULATES LENGTH OF CRACK(S) & PREDICT RISK TO DATE

FIG 3, SHEET 3 OF 4

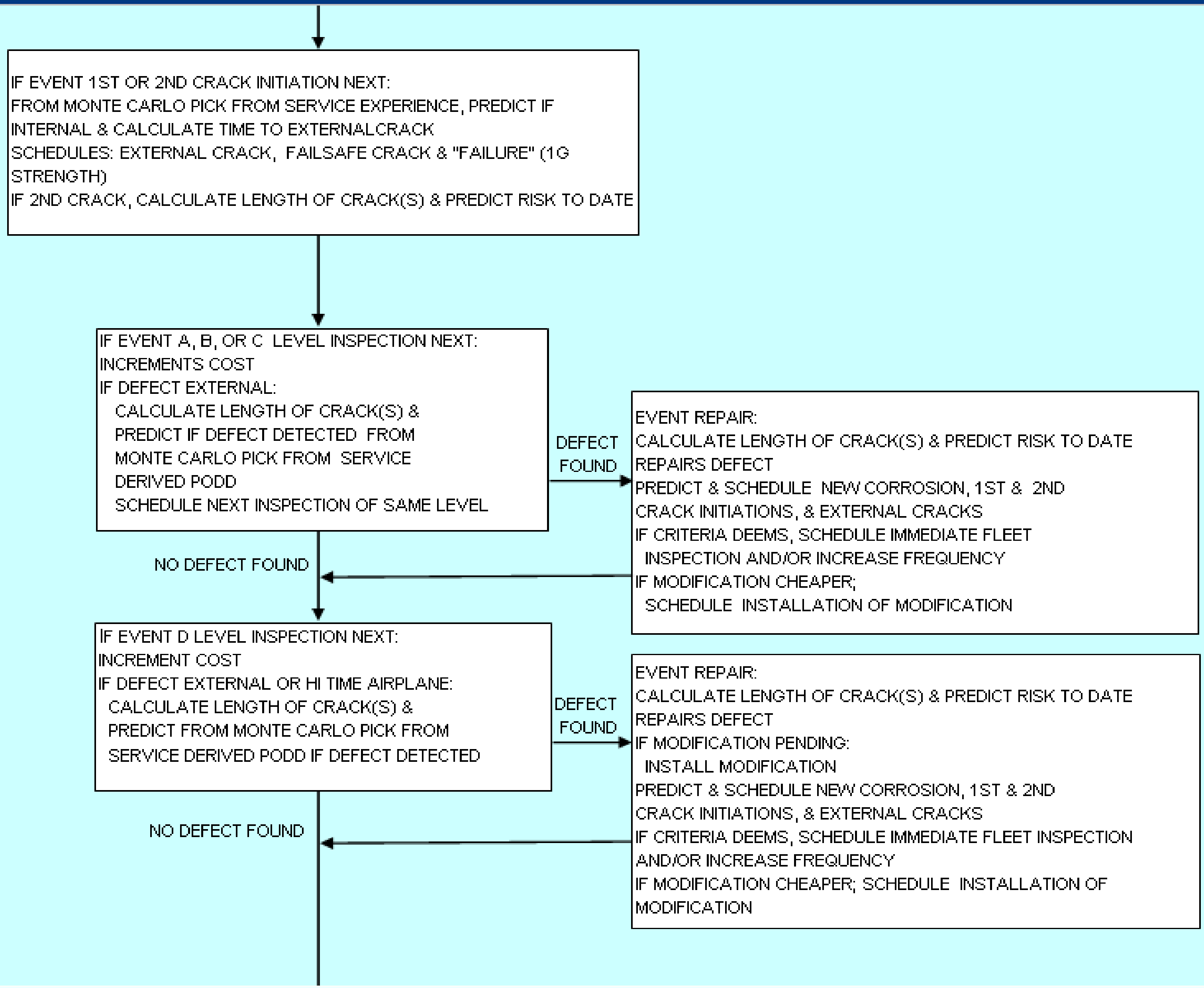


FIG 3, SHEET 4 OF 4

IF EVENT IN SERVICE DAMAGE NEXT:
SCHEDULE 1ST CRACK NOW
RESCHEDULE 2ND CRACK AND 2ND STRENGTH REDUCTION &
EXTERNAL 1ST & 2ND EXTERNAL CRACKS

IF EVENT REACH FAIL SAFE LENGTH NEXT:
RECORD & CALCULATE LENGTH OF CRACK(S) & PREDICT RISK
TO DATE

IF EVENT CERTAIN FAILURE (1G STRENGTH) NEXT:
RECORD &, CALCULATE LENGTH OF CRACK(S) & PREDICT RISK
TO DATE

IF EVENT IMMEDIATE FLEET INSPECTION NEXT:
CALCULATE CORROSION AREA & LENGTH OF CRACK(S) &
PREDICT FROM MONTE CARLO PICK FROM SERVICE DERIVED PODD
IF DEFECT DETECTED ASSUME INSPECTION TO BE INTERNAL IF
INSTIGATING DEFECT WAS INTERNAL
IF DEFECT FOUND TAKE SAME CORRECTIVE ACTION AS IN A, B & C
INSPECTIONS

IF EVENT IS TO RETIRE THIS AIRPLANE FROM SERVICE
RECORD & REMOVE AIRPLANE FROM ACTIVE FLEET
IF ANY CRACKS, CALCULATE LENGTH OF CRACK(S) &
PREDICT RISK TO DATE.

IF ALL SCHEDULED ACTIVITIES (EVENTS, PROCESSES ETC) COMPLETED
RETURN TO READ NAME OF NEXT ELEMENT