

LEVEL

(12)

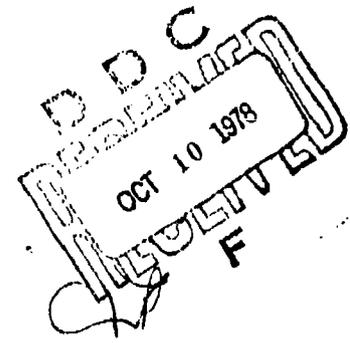
NOV 11 11 05 46 89

DDC FILE COPY AD A059730

**STRUCTURAL AREA INSPECTION
FREQUENCY EVALUATION (SAFE)**

Volume I. Executive Summary

Carter J. Dinkelloo
Martin S. Moran



APRIL 1978
FINAL REPORT

Document is available to the U.S. public through
the National Technical Information Service,
Springfield, Virginia 22161.

Prepared for

**U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590**

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

1. Report No. FAA-RD/78-29-1		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle STRUCTURAL AREA INSPECTION FREQUENCY EVALUATION Volume I. Executive Summary.				5. Report Date April 1978	
7. Author(s) Carter J./Dinkeloo Martin S./Moran				6. Performing Organization Code	
9. Performing Organization Name and Address Technology Incorporated P.O. Box 3036, Overlook Branch Dayton, Ohio 45431				8. Performing Organization Report No.	
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590				10. Work Unit No. (TRAIS)	
15. Supplementary Notes				11. Contract or Grant No. DOT-FA74WA-3493	
16. Abstract To assist in the evaluation of proposed structural inspection programs for commercial jet transport aircraft, a logic was developed to simulate structural defects, failures, and inspections. This logic was incorporated in a computer program entitled Structural Area Inspection Frequency Evaluation (SAIFE). With the objective of quantifying the evaluation process currently used to establish and modify inspection intervals, SAIFE accounts for the following factors: (1) aircraft design analysis; (2) fatigue testing; (3) production, service, and corrosion defects; (4) probability of crack or corrosion detection; and (5) aircraft modification economics. As a five-volume document, this report covers the initial contract effort plus a subsequent parametric analysis as follows: Volume I presents the SAIFE logic and documents the methodology for the decision-making processes in the simulation logic. Volume II (entitled Description of Simulation Logic) details the SAIFE simulation logic, presents the background data for the analytical functions and decision-making processes, and includes data for a typical simulation problem. Volume III (entitled Demonstration Input, Inspection Survey, and MRR Data) presents data tabulations derived from historical trends and design input data for a SAIFE demonstration problem. As the user's manual for the SAIFE computer program, Volume IV (entitled Software Documentation and User's Manual) contains detailed computer logic flow diagrams and a complete listing of the program which is written in SIMSCRIPT II.5. Volume V (entitled Results of Model Demonstration) presents the results of the program application to a hypothetical aircraft and compares these results with the service experience of operational aircraft.				13. Type of Report and Period Covered Final Report	
17. Key Words Aircraft experience simulation; aircraft inspection intervals; aircraft hazard rate and reliability; production, service, and corrosion defects; crack or corrosion detection probability; crack growth.			18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151.		
19. Security Classif. (of this report) UNCLASSIFIED		20. Security Classif. (of this page) UNCLASSIFIED		21. No. of Pages 38	22. Price

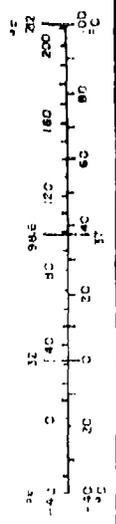
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	meters	m
yd	yards	0.9	kilometers	km
mi	miles	1.6		
AREA				
m ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

When You Know	Multiply by	To Find	Symbol
LENGTH			
millimeters	0.04	inches	in
centimeters	0.4	inches	in
meters	3.3	feet	ft
kilometers	1.1	yards	yd
	0.5	miles	mi
AREA			
square centimeters	0.16	square inches	in ²
square meters	1.2	square yards	yd ²
square kilometers	0.4	square miles	mi ²
hectares (10,000 m ²)	2.5	acres	
MASS (weight)			
grams	0.035	ounces	oz
kilograms	2.2	pounds	lb
tonnes (1000 kg)	1.1	short tons	
VOLUME			
milliliters	0.03	fluid ounces	fl oz
liters	1.1	pints	pt
liters	1.06	quarts	qt
liters	0.26	gallons	gal
cubic meters	35	cubic feet	ft ³
cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)			
Celsius temperature	9/5 then add 32	Fahrenheit temperature	°F



© 1987 by The McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. ISBN 0-07-060000-0

PREFACE

Technology Incorporated prepared this first volume of a five-volume report to document the simulation logic for the Structural Area Inspection Frequency Evaluation (SAIFE) in accordance with Article II, paragraph B of Contract DOT-FA74WA-3493. (Volume I along with Volume II completes the requirements of Phases I and II of the contract.) The effort is sponsored by the Aircraft Safety and Noise Abatement Division, Systems Research and Development Service of the Federal Aviation Administration.

The principal Technology Incorporated personnel engaged on this program were Mr. Carter J. Dinkeloo, project engineer, who served as principal investigator; Mr. Martin S. Moran, research engineer, who developed the model for the SAIFE computer program; and Mr. Ronald I. Rockafellow, program manager.

The contract monitors for the FAA were Messrs. Herbert Spicer and Charles Troha of the Aircraft Safety and Noise Abatement Division. The technical monitor was Mr. Arnold E. Anderjaska of the Flight Standards Division.

ACQUISITION for	Waste Section <input checked="" type="checkbox"/>
LAB	Bull Section <input type="checkbox"/>
LOG	<input type="checkbox"/>
PREPARED BY	
DATE	
EX	
DISCONTINUITY AVAILABILITY CODES	
	SPECIAL
A	

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
I INTRODUCTION	1
II SIMULATION OBJECTIVES	3
1. SAIFE Applications	3
2. SAIFE Output	4
III APPROACH TO THE SIMULATION PROBLEM	8
1. Background	8
2. Computer Simulation Language	9
3. Monte Carlo Method	9
4. Probability Model	10
IV SIMULATION LOGIC	14
1. Input Data/Generate Fatigue Lives (Block 1)	15
2. Develop Modification Because of Fatigue Test Failure (Block 2)	17
3. Reduce Fatigue Life Because of Production, Service, or Corrosion Defects (Block 3)	20
4. Reduce Strength Because of Crack or Corrosion Growth/Predict Time to Failure (Block 4)	22
5. Periodic Inspection of Elements/Aircraft Deleted from Fleet (Block 5)	24
6. Repair Element to Original Strength (Block 6)	25
7. Special Instructions, Increase Inspection Frequency (Block 7)	25
8. Develop Modifications Because of Service Experience (Block 8)	26
V PARAMETRIC STUDY	28
1. Background	28
2. Estimation Techniques	28
3. Output	32
VI SUMMARY AND CONCLUSIONS	36
REFERENCES	37
BIBLIOGRAPHY	38

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Approach to SAIFF Simulation Problem	2
2	Prediction of Time to Element Failure	13
3	Flow Diagram Showing Major Aspects of SAIFF Logic	14
4	Typical Aircraft Elements Used in the SAIFF Simulation	15
5	Comparison of Predicted and Actual Fatigue Life	16
6	Cumulative Distribution of Fatigue Lives Using a Two-Parameter Weibull Distribution	18
7	Typical Component Fatigue Test	19
8	Histogram of Crack Occurrences on Production- Damaged Elements	21
9	Histogram of Crack Occurrences on Service- Damaged Elements	21
10	Typical Cumulative Distribution of Corrosion Occurrence	23
11	Probability of Crack Detection During a Periodic Inspection	24
12	Probability of Corrosion Detection During a Periodic Inspection	25
13	Service Modification Decision Logic	26

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	SAIFF Output for an Individual Element	5
2	SAIFF Output for an Element Type	7
3	Expanded SAIFF Output for an Individual Element	34
4	Expanded SAIFF Output for an Element Type . . .	35

I. INTRODUCTION

It is the mutual goal of the FAA, airframe manufacturers, and air carriers to constantly improve the structural integrity and inspection efficiency of civil aircraft. The good safety record of U.S. air carriers indicates that the current process of establishing and modifying structural inspection programs has been successful. However, with the increasing size and complexity of second- and third-generation transport aircraft, there is a need to quantify more precisely the present subjective evaluation process which relies heavily on reliability analyses of the new design and on operational experience of similar aircraft.

Because of the extreme complexity of the evaluation process, a computer simulation of all critical aircraft service life aspects was judged the most rational means for quantifying the process more exactly. As a five-volume document, this report presents the resultant Structural Area Inspection Frequency Evaluation (SAIFE) simulation logic. SAIFE accounts for the following factors: (1) aircraft design analysis; (2) component and full-scale fatigue testing; (3) production, service, and corrosion defects; (4) probability of crack or corrosion detection; and (5) aircraft modification economics. It treats these factors in a logical sequence that realistically represents the procedure currently used to establish and modify inspection intervals. SAIFE is designed to provide a repeatable method for evaluating proposed inspection programs. However, it is not intended to supplant the Maintenance Review Board or the air carrier use of the Standard Operations Specification - Aircraft Maintenance.

In addition to presenting the SAIFE logic, this report documents the research conducted to establish the quantitative functions required for decision logic in the simulation. Some of the documentation for these functions, such as fatigue life scatter, are taken from work conducted in other studies. Other functions, such as the probability of defect detection, are the result of work conducted as part of this contract. Whatever the source, all analytical information is referenced throughout the report.

Subsequent to the initial demonstration, the model and demonstration input was refined in a joint effort by Technology Incorporated and the FAA. The revised input and model is defined in appendices to Volumes III and IV respectively. The demonstration was rerun with the revised model and input by the FAA and the results are given in an appendix to Volume V.

Figure 1 illustrates the data sources and analytical functions that are integrated into the SAIFE logic. As Volume I, this volume presents the basic method and procedure used to determine the analytical functions and to develop the logic required for constructing the simulation and parametric study logic.

Volume II presents the detailed simulation logic incorporated in SAIPE and all the background data required for the analytical functions and decision-making processes. It also includes the data required for a typical simulation program.

Volume III presents data tabulations derived from studies to determine historical trends. Conducted as part of this contract, these studies included processing Mechanical Reliability Reports over a 10-year period and conducting a survey of the experience of air carrier maintenance inspectors. This volume also contains the design input data required for a SAIPE demonstration problem and parametric study.

Volume IV is the user's manual for the SAIPE computer program. It includes software logic flow diagrams for each routine and event in the program developed during the initial contract effort plus subsequent parametric studies and also includes a source listing of the program which is written in the computer language SIMSCRIPT 11.5 ①.

Volume V summarizes and evaluates the results of a demonstration computer run conducted on a typical, but hypothetical, wide-body aircraft. This volume discusses revisions to the program logic as well as the demonstration and parametric study output.

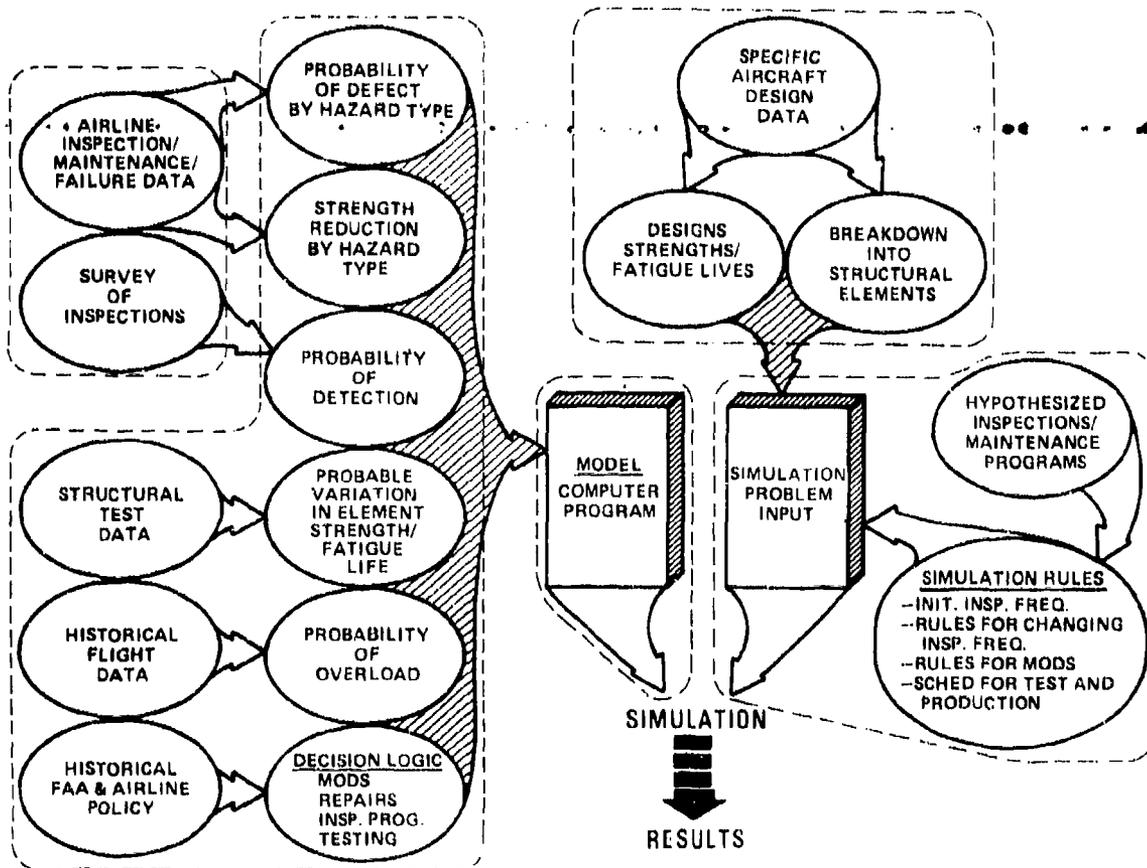


Figure 1. Approach to SAIPE Simulation Problem

II. SIMULATION OBJECTIVES

I. SAIFE Applications

The primary objective of the SAIFE project was to develop a program for evaluating inspection intervals. Since this development was a first attempt to simulate the evaluation process, it was also intended to develop a program with sufficient flexibility to permit its application to related studies, such as the effect of material selection on aircraft safety and the relative cost of repairing or modifying an airframe structure.

The primary objective, evaluating inspection intervals, can be accomplished by two different approaches. First, since SAIFE automatically increases or decreases inspection intervals, a proposed set of intervals, along with the desired increase or decrease percentages, can be specified. The simulation output will be a series of altered intervals that will successively increase or decrease depending on the number and criticality of the defects generated during the simulation. Steadily increasing or decreasing intervals probably indicate that the initial intervals should be re-examined and revised prior to being implemented. Constantly fluctuating intervals may indicate a proper choice of initial intervals, although a change-by-change analysis of the results is undoubtedly in order.

The second approach involves specifying a zero increase or decrease percentage and making parallel simulation runs with two or more sets of inspection intervals. Specifying a zero percentage change will prevent automatic interval changes and consequently permit a comparison of the number of defects occurring as a result of each set of intervals. A variation of this approach would be to maintain one set of inspection intervals, but to change the lowest interval that applies to an area to be inspected. For instance, certain accessible portions of the wing interior might be moved from the C interval to the B interval. The effects of this change could be evaluated after making parallel simulation runs and comparing the number of resulting defects.

The input and output formats of the simulation permit evaluating inspection intervals and other variables on problems of varying size. Volume V of this report presents an evaluation of a demonstration which encompassed an entire wide-body aircraft. An evaluation of this extent is most likely to be made during the certification process for a new aircraft model, such as the B-747.

Evaluations of smaller scope may be made when only a discrete portion of an aircraft has been modified, the DC-9 fuselage stretch for example. In such an evaluation, the simulation may include only the fuselage with the unmodified portions of the aircraft disregarded.

Simulation runs may also be conducted on individual components only. In such runs one or two problem areas on the wing, for instance, may be evaluated, and have their inspection intervals reduced while leaving those for the rest of the wing the same as before.

Because of the flexibility of the simulation program, primarily in the area of input parameters, several different stages in an aircraft's life cycle may be evaluated. During the initial design stage the effect of material selection can be evaluated by conducting comparative simulation runs with various fatigue lives, crack growth rates, and corrosion resistance ratings. This type of design evaluation can also be conducted when individual components are being modified or redesigned.

Cost evaluations can be conducted with SAIFE when a repair or modification decision is required since the simulation logic compares the one-time cost of modification with the repeated cost of repair and possibly increased inspection costs.

2. SAIFE Output

For each element simulated, SAIFE generates the number of defects - cracks, corrosion, service damage, and production damage - that occur during the service life of the aircraft. Except for production damage, the minimum, maximum, and average flight hours at which the defects occur are also presented. Since production damage does not depend on flight time, only the number of occurrences is presented.

The simulation output also includes the number of cracks and corroded areas detected. These numbers permit making a comparison between the defects which occurred and those which were detected. If the two do not agree, either multiple defects were present in an element and all were repaired when one was detected or defects were not detected before the aircraft was retired. The minimum, maximum, and average sizes of the defects, along with the number of defects detected, are presented for each inspection level.

The output for individual elements, as exemplified in Tables 1 and 3, presents the initial set of inspection intervals which is input information and each subsequent change to the C and D intervals made by the SAIFE logic.

The output for individual elements also contains flight hour and aircraft identification information whenever the residual strength equaled the fail-safe strength, often referred to as fail-safe damage. Flight hour and aircraft identification information is also presented for each element that had a structural failure.

TABLE 1. SAIFE OUTPUT FOR AN INDIVIDUAL ELEMENT

AIRCRAFT TYPE: HYBRID AIRCRAFT SERVICE LIFE: 60000 HOURS
 NUMBER OF AIRCRAFT IN FLEET: 500 STRUCTURAL ELEMENT: FUS-SIR-TOP-1300

PREDICTED AVERAGE FATIGUE LIFE: 20200 HOURS ACTUAL AVERAGE FATIGUE LIFE: 207193 HOURS

NUMBER AND TIME TO INITIATION OF AIRCRAFT DEFECTS

FIRST CRACK	CORROSION	SERVICE DAMAGE	PRODUCTION DEFECTS
8	1	0	0
25911	48658	0	
57616	48658	0	
64828	48658	0	

NUMBER AND LENGTH OF CRACKS DETECTED AT EACH LEVEL OF INSPECTION

	A-LEVEL	B-LEVEL	C-LEVEL	D-LEVEL	SPECIAL
OCCURRENCES	0	0	0	0	1
MIN(IN)	0.	0.	0.	0.	1.85
MAX(IN)	0.	0.	0.	0.	1.85
AVG(IN)	0.	0.	0.	0.	1.85

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

	A-LEVEL	B-LEVEL	C-LEVEL	D-LEVEL	SPECIAL
OCCURRENCES	0	0	1	0	0
MIN(SQ.IN)	0.	0.	11.97	0.	0.
MAX(SQ.IN)	0.	0.	11.97	0.	0.
AVG(SQ.IN)	0.	0.	11.97	0.	0.

INSPECTION INTERVALS(MRS)

INITIAL	25	200	1000
2	25	200	1200
3	25	200	1500
4	25	200	18750
5	25	200	23418
			6203

NUMBER OF SPECIAL INSPECTIONS CONDUCTED: 1
 NUMBER OF STRUCTURAL MODIFICATIONS: 0
 FINAL ACTUAL AVERAGE MODIFIED FATIGUE LIFE: 207193 HOURS
 NUMBER OF AIRCRAFT MODIFIED IN SERVICE: 0

STRUCTURAL FAILURES RESIDUAL STRENGTH EQUALS FAIL-SAFE STRENGTH
 AIRCRAFT NO. FLT. HOURS AIRCRAFT NO. FLT. HOURS
 ----- ----- ----- -----
 486 54897 486 52560

The simulation output for individual elements is summarized by element to provide pertinent information in less voluminous form. Tables 2 and 4, examples of this output form, summarize the defects that occurred and those that were detected for an element type.

The output also contains information on inspection intervals, but instead of listing each change in the interval, it presents only the initial, shortest, and largest intervals that occurred on any one of the individual elements.

The output for fail-safe damage and structural failure is a list of all instances when these events occurred on any element of a particular element type. Again flight hour and aircraft identification information are included, and the element station number has been added to identify the specific element.

The SAIFE output provides information that will assist qualified FAA personnel in making decisions on a proposed inspection plan by showing the results of that plan in terms of the number, extent, flight hours, and criticality of the defects that probably will occur if the plan is implemented.

TABLE 2. SAFE OUTPUT FOR AN ELEMENT TYPE

AIRCRAFT TYPE: HYBRID		AIRCRAFT SERVICE LIFE: 60000 HOURS		
NUMBER OF AIRCRAFT IN FLEET: 500		AIRCRAFT SERVICE LIFE: 60000 HOURS		
SUMMARY OF STRUCTURAL ELEMENT: FUS-STR-TOP				
NUMBER AND TIME TO INITIATION OF AIRCRAFT DEFECTS				
FIRST CRACK	CORROSION	SERVICE DAMAGE		
899	69	19		
1942	5058	3922		
5995	57923	57792		
43456	34842	34896		
PRODUCTION DEFECTS		10		
NUMBER AND LENGTH OF CRACKS DETECTED AT EACH LEVEL OF INSPECTION				
A-LEVEL	R-LEVEL	C-LEVEL	D-LEVEL	SPECIAL
0	0	219	91	76
0.	0.	.30	.19	.21
0.	0.	32.63	13.43	4.74
0.	0.	3.20	1.36	1.43
NUMBER AND AREA OF CORROSION DEFECTS DETECTED AT EACH LEVEL OF INSPECTION				
A-LEVEL	B-LEVEL	C-LEVEL	D-LEVEL	SPECIAL
0	0	50	5	5
0.	0.	.80	1.16	4.63
0.	0.	25.45	73.03	36.94
0.	0.	5.09	21.69	19.64
INSPECTION INTERVALS(HRS)				
INITIAL	25	1000	12000	
SHORTEST	25	204	1256	
LONGEST	25	3482	23434	
NUMBER OF SPECIAL INSPECTIONS CONDUCTED: 93				
NUMBER OF STRUCTURAL MODIFICATIONS: 2				
NUMBER OF AIRCRAFT MODIFIED IN SERVICE: 0				
STRUCTURAL FAILURES		STA. NO.	RESIDUAL STRENGTH EQUALS FAIL-SAFE STRENGTH	
AIRCRAFT NO.	FLT. HOURS		AIRCRAFT NO.	FLT. HOURS
2A	51581	1080	490	42917
486	54497	1300	196	51619
			416	46859
			2	56605
			109	55251
			28	43395
			186	56552
			439	55754

III. APPROACH TO THE SIMULATION PROBLEM

1. Background

Structural inspection and maintenance programs account for a significant portion of the operating cost of a commercial transport aircraft. Initially the inspection program for a particular aircraft type is developed by the Maintenance Review Board (MRB) during the certification process. Subsequently, as fleet experience is gained, the inspection program is modified after a Standard Operating Specification - Aircraft Maintenance has been submitted by the air carrier and approved by the Federal Aviation Administration. The resulting inspection program is based on subjective analyses that account for historical experience on previous aircraft types, experience on the present aircraft, and design data on the present aircraft. The success of this procedure is evidenced by the excellent safety record of U.S. air carriers.

However, with the pressure on air carriers to continue to operate on a profitable basis and the continued responsibility of the FAA to improve air transport safety, the inspection intervals for primary aircraft structures must be determined on a more objective basis. In response to this need, the FAA initiated the SAIFE (Structural Area Inspection Frequency Evaluation) project. The objective of this project was to assemble all the logic currently used to establish inspection frequencies into a single simulation program that would be capable of investigating the interactions between the primary aircraft service life factors: ultimate strength, fatigue life, flight loads, production and service damage, corrosion, probability of defect detection, and modification economics. The simulation would then permit determining the effect of changing an economic parameter, such as inspection interval, on the overall safety of the aircraft fleet. The judgment of what could be an acceptable level of aircraft safety, of course, still rests with the FAA.

Since this approach differs significantly from those currently used to evaluate inspection intervals, it was felt that a high degree of flexibility was required. The primary provisions for this flexibility are the means for defining the life characteristics of each element from input data instead of from predetermined program constants and the means for evaluating an entire aircraft, a large segment of an aircraft, or an individual element.

Because of the complexity of the logic involved in determining the inspection program for a commercial aircraft fleet, it is not possible to develop one or even a set of deterministic equations. Therefore, SAIFE uses a series of probabilistic distributions and deterministic equations to simulate a logic sequence that considers all the subjective elements currently considered in arriving at an inspection program. Based on the logic developed by Anderaska in Reference 1, the simulation is intended to

handle large aircraft fleets by determining the outcome of probabilistic events for individual aircraft from a random number algorithm. This procedure is commonly referred to as a Monte Carlo technique.

2. Computer Simulation Language

The complexity and magnitude of the proposed project requires using the most efficient techniques available. The computer simulation language SIMSCRIPT 11.5 ① is ideally suited to this project since it is designed to handle simulations where hundreds of events are happening concurrently and in a chronological sequence such as in the SAIFE application.

SIMSCRIPT is also a desirable computer language from the user's viewpoint since its free-form English format makes it easy to interpret the source program and it reduces the coding and debugging effort. In addition, SIMSCRIPT provides system functions to generate the random numbers required in SAIFE.

The SAIFE computer program has been written to operate on both the IBM 360/65 and CDC 6600 computers equipped with a SIMSCRIPT 11.5 compiler.

3. Monte Carlo Method

When a system to be simulated is so complex that its operation cannot initially be analytically expressed, whether deterministically or probabilistically, gaming techniques are used to simulate the system systematically. Frequently the simulation is divided into parts, each described by a frequency distribution or an algebraic formula. Entirely numerical, the calculation process consists of supplying numbers to the system and of obtaining resultant numbers from it. Often the numbers supplied are random numbers obtained from a published table, dice, computer, or any device uniformly producing random numbers such as a roulette wheel; hence the name Monte Carlo for such a device and the corresponding method. These numbers are fed into the system as cumulative probabilities such as a fatigue life distribution. A Monte Carlo treatment of a problem permits testing statistically the sensitivity of the result and isolating the influence of a single parameter. To aid in the modeling of statistical phenomena, the computer simulation language SIMSCRIPT 11.5 provides eleven system functions for generating independent, pseudo-random samples from commonly encountered statistical distributions.

The samples are considered to be pseudo-random because they are determined from an algorithm that is repeatable. Therefore, the algorithm is technically not a pure random number.

In the simulation each of these functions has as its arguments (1) the parameters that describe the distribution and (2) a random number stream index. Each time one of the functions is

called, a random number is generated from the indicated stream, and an appropriate transformation is made to convert the number to the correct sampling distribution. If the statistical distribution of interest is not available, it can easily be generated from the uniform distribution. In principle, all that is required is to equate the two cumulative distributions:

$$\int_0^x f(x) dx = \int_0^{RN} 1 \cdot d(RN) \quad (1)$$

and

$$F(x) = RN \quad (2)$$

where RN = a random number drawn from a uniform distribution

F(x) = desired cumulative distribution of the random variable x

Thus, if the inverse function of F(x) can be determined, the desired distribution of random numbers is readily available:

$$x = F^{-1} F(x) = F^{-1}(RN) \quad (3)$$

However, for functions whose inverse cannot be analytically determined, approximation techniques can be used to generate the desired distribution of random numbers.

4. Probability Model

The SAIFE simulation logic is based on dividing the primary aircraft structure into basic elements, such as wing spar and fuselage frame, and then determining the time to crack and/or corrosion initiation for each element. The logic then projects the time to failure of the element considering the effects of such random environmental phenomena as flight loads, and production and service damage. As discussed in Section III.3, the straightforward application of the Monte Carlo method generates these times when the probability density function of the times to failure is known. However, since this function is seldom known, the Monte Carlo method may be modified if the hazard rate, $\lambda(t)$, for the random environmental phenomena can be determined.

The following discussion treats the situation where a structure has a fatigue crack initiation at time $t = 0$ and the objective is to know the probability of failure before time t . If the structure has not failed up to time t , then the probability of failure in the time interval between t and $t + dt$ may be expressed in probability theory as

$$F(t + dt | t \geq t) = \frac{F(t + dt) - F(t)}{1 - F(t)} \quad (4)$$

where $F(t + dt | t \geq t)$ = probability of failure before time $t + dt$, assuming nonfailure before time t

$F(t + dt)$ = probability of failure before time $t + dt$

$F(t)$ = probability of failure before time t

$1 - F(t)$ = probability of nonfailure before time t

Dividing and multiplying the right side of Equation (4) by dt yields

$$F(t + dt | t \geq t) = \frac{dt}{1 - F(t)} \frac{F(t + dt) - F(t)}{dt} \quad (5)$$

or

$$F(t + dt | t \geq t) = \frac{1}{1 - F(t)} \frac{dF}{dt} dt \quad (6)$$

Now let

$$\frac{1}{1 - F(t)} \frac{dF}{dt} = \lambda(t) \quad (7)$$

where $\lambda(t)$, called the hazard rate, may be interpreted as (1) the probability per unit of time that an item will fail in the next small interval of time if it has not failed before the start of the interval or (2) the number of items failing per unit of time divided by the number intact at the beginning of the interval. From probability theory,

$$f(t) = \frac{dF(t)}{dt} \quad (8)$$

where $f(t)$ is the probability density function. Substitution of Equation (8) into Equation (7) yields

$$\lambda(t) = \frac{f(t)}{1 - F(t)} \quad (9)$$

where $R(t)$ is the probability of nonfailure before time t . Rewriting Equation (7) gives

$$\frac{dF}{dt} + \lambda F = \lambda \quad (10)$$

Equation (1) is an exact differential equation and may be solved by integration. Rewriting Equation (10) yields

$$\frac{dF}{dt} = -\lambda(F-1) \quad (11)$$

or

$$F-1 = Ce^{-\int \lambda(t) dt} \quad (12)$$

Therefore,

$$F(t) = 1 + C e^{-\int \lambda dt} \quad (13)$$

Applying the boundary condition $F(0) = 0$ to Equation (13) yields $C = -1$. Equation (13) then becomes

$$F(t) = 1 - e^{-\int \lambda(t) dt} \quad (14)$$

where $F(t)$ is the cumulative distribution function of times to failure. Now the Monte Carlo method can be used to generate a stream of random times to failure. Drawing a random number from a uniform distribution with range 0 to 1 and equating it to $F(t)$ in Equation (14) yields

$$RN = 1 - e^{-\int_0^t \lambda(t) dt} \quad (15)$$

Then the indicated integration is performed, and t is solved for in terms of the random number RN . This technique can be used to generate the times for any phenomenon whose hazard rate $\lambda(t)$ can be determined. The hazard rate can be either a constant or a function of time. Figure 2 represents the basic relationships indicated in Equation (15) as applied to a fuselage stringer element.

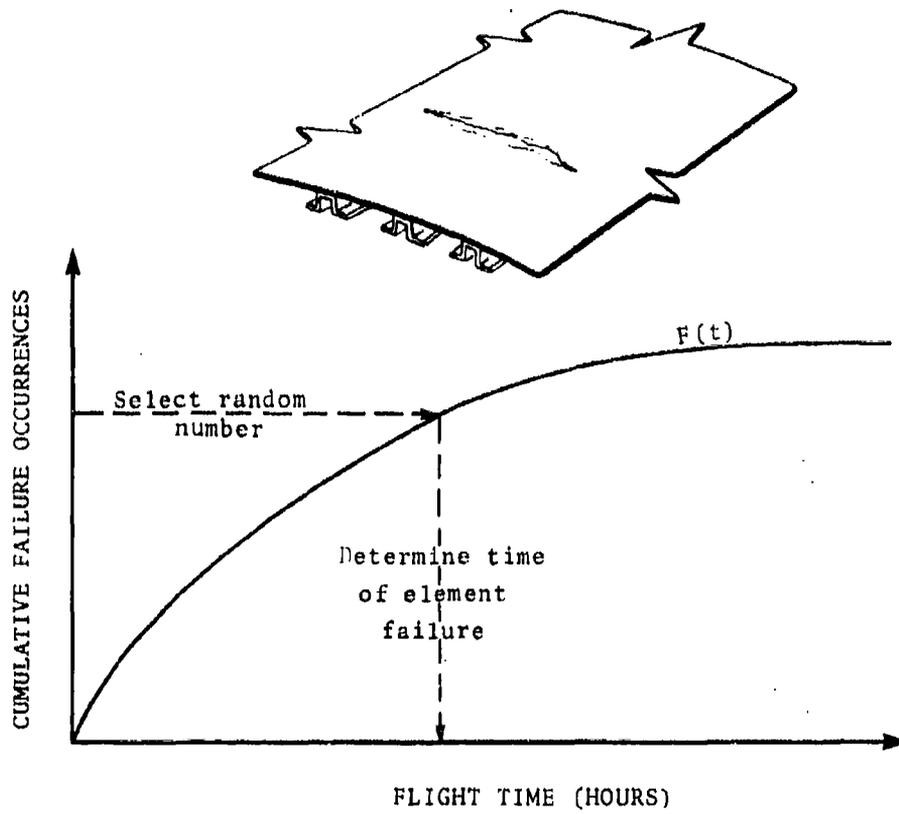


Figure 2. Prediction of Time to Element Failure

IV. SIMULATION LOGIC

The eight blocks in Figure 3 represent the major aspects of the SAIFE simulation logic. As detailed in the following sections, whose numbering correlates with the block numerals, each block contains one or two basic ideas in the simulation logic.

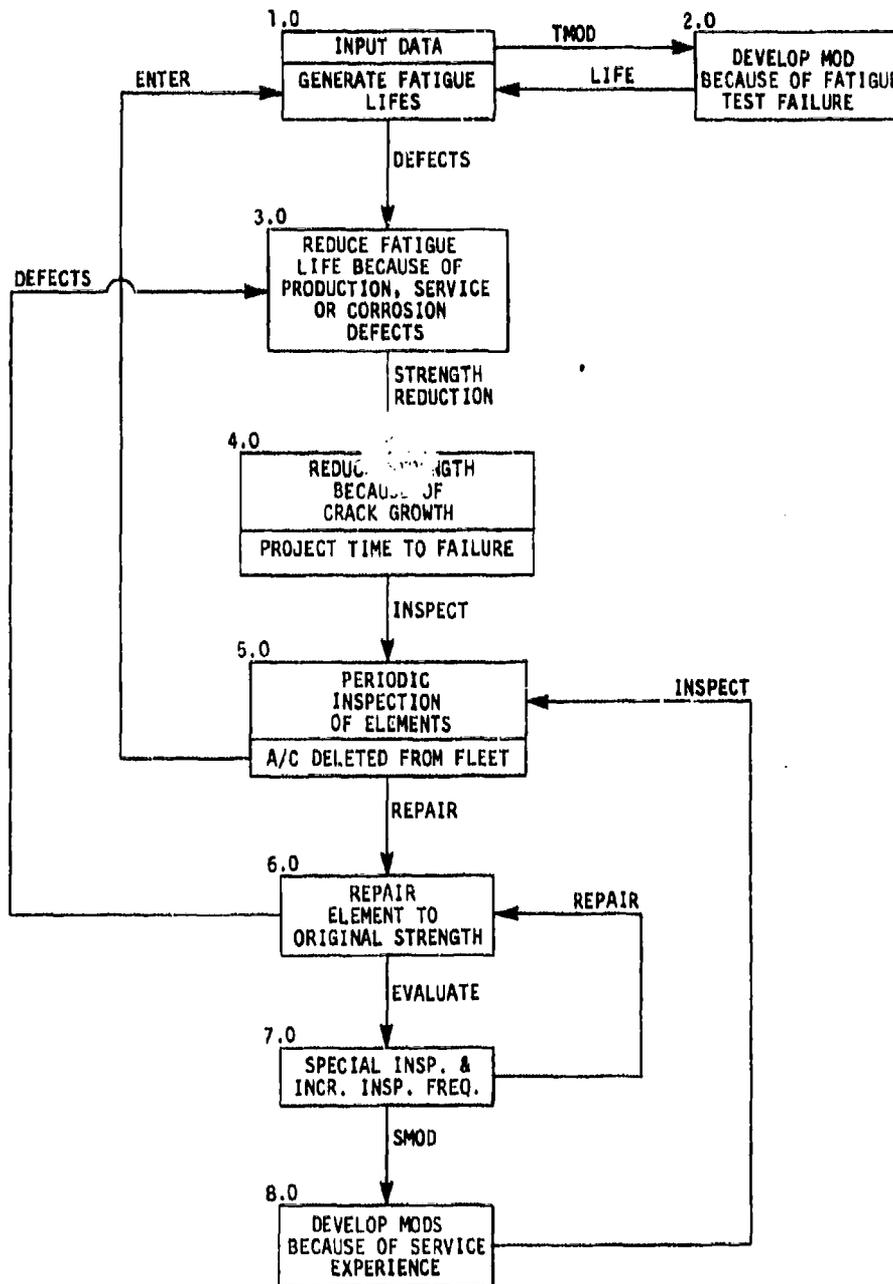
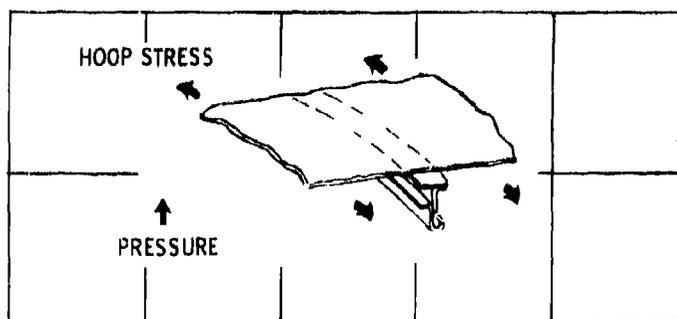


Figure 3. Flow Diagram Showing Major Aspects of SAIFE Logic

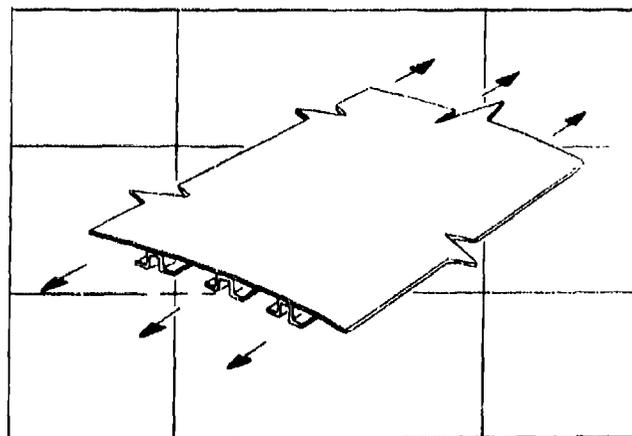
1. Input Data/Generate Fatigue Lives (Block 1)

The input data can be divided into three categories: fleet information, aircraft design data, and historical data. The fleet information identifies the type of aircraft, for example, B-747; the number of aircraft in the fleet; and the expected service life of the aircraft.

The aircraft design data includes a complete detailed breakdown of the aircraft structure into its basic elements. Two element types, a wing stringer and a fuselage frame, are illustrated in Figure 4. With such a structural breakdown, the fatigue life, ultimate strength, crack growth rate, corrosion resistance, and corrosion growth rate of each element must be determined. Since all these parameters have a direct effect on the inspection interval to be evaluated, the more accurately they are defined, the more valid the final evaluation will be. The input data for a demonstration problem is documented in Volume III of this report.



Fuselage Frame Element



Wing Stringer Element

Figure 4. Typical Aircraft Elements Used in the SAFE Simulation

In many instances, historical information is the only source of data that is useful for defining operational factors. Of particular interest are the corrosion occurrence rate, the service damage occurrence rate, and the production defect occurrence rate. The source of such information is the Mechanical Reliability Report (MRR), called the Service Difficulty Report (SDR) after 1972. All U.S. air carriers are required by regulation to submit an MRR/SDR whenever they find and repair a defect. Volume III presents the MRR/SDR data covering the 10-year period from 1963 through 1973 which was analyzed during the current program for the SAIFE project. Information on catastrophic and non-catastrophic accidents was obtained from the National Transportation Safety Board (NTSB) Aircraft Accident Reports.

Since in practice a statistical approach is not used in fatigue life prediction analysis, the actual fatigue life of a structure of a given design will usually differ from that analytically predicted. The probability of the actual fatigue life being greater or less than that predicted was studied by K.D. Raithby (Reference 2). The relationship determined by Raithby is illustrated in Figure 5. The mean and standard deviations of this distributional relationship are input parameters which enable the user of SAIFE to account for improvements in fatigue analysis techniques. An example of the relationship resulting from improved analysis techniques is also shown in Figure 5.

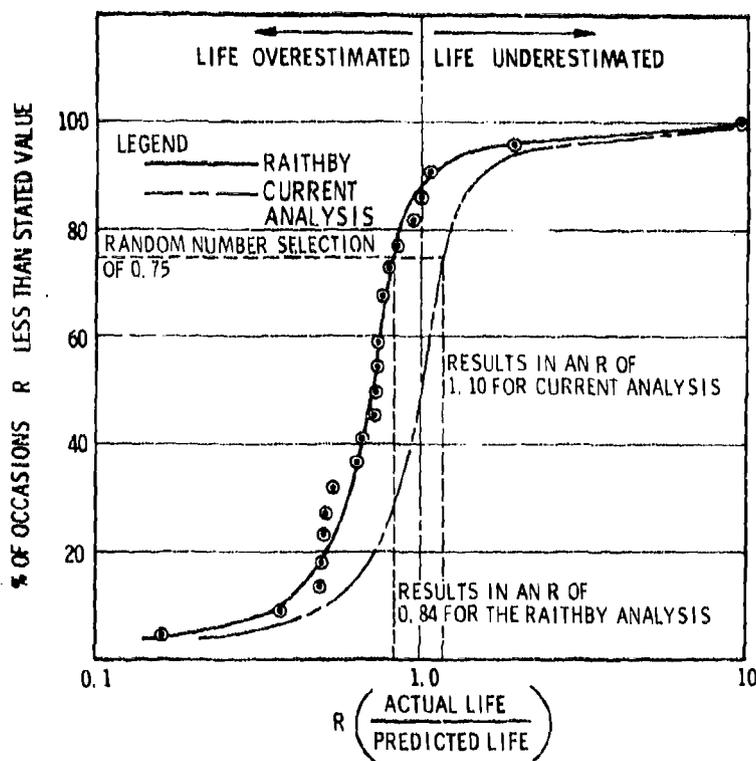


Figure 5. Comparison of Predicted and Actual Fatigue Life

For each element the Monte Carlo method is used to select a predicted life multiplier, R. The actual average fatigue life is then determined from the equation

$$\text{Actual Life} = \text{Predicted Life} \times R \quad (16)$$

The example illustrated in Figure 5 shows that a random number selection of 0.75 results in a predicted life multiplier of 0.84 for the "Raithby" curve and 1.1 for the "Current Analysis" curve.

It is a well-established fact that the fatigue lives of a group of nominally identical elements are not deterministic; consequently, they must be defined by a probabilistic distribution. Further, it has been established that the probabilistic distribution of fatigue lives for elements on operational aircraft is primarily a function of two variables: basic material fatigue scatter and operational environment variation. Investigations conducted by Freudenthal (Reference 3) and Abelkis (Reference 4) conclude that both of these effects can be accounted for by a single distribution. Although the exact mathematical formulation of the distribution is different in each of the studies, the end results are similar. The SAIPE logic uses the two-parameter Weibull distribution developed by Freudenthal. Although not as accurate at the extreme values as the distribution developed by Abelkis, the two-parameter Weibull distribution is more flexible and can be more easily modified to account for any changes in material technology.

After the average fatigue life of an element has been determined, the fatigue life for each element in each aircraft can be determined by deriving a probabilistic distribution according to Freudenthal's technique and then applying the Monte Carlo method to this distribution to select the desired fatigue life. Figure 6 illustrates this procedure.

A unique fatigue life is determined for each element in each aircraft as the aircraft is introduced into service. As illustrated in Figure 6, if a random number of 0.750 is selected, the fatigue life of the individual element is 1.05 times the previously determined average.

2. Develop Modification Because of Fatigue Test Failure (Block 2)

One of the criteria used in the design of commercial jet transports, particularly the wide-body aircraft, is an average fatigue life for the airframe that would be twice the service life. This criterion was used on the DC-10 (Reference 5) and on the B-747 (Reference 6). Because of the demonstrated uncertainty of fatigue life prediction, fatigue tests (such as illustrated in Figure 7) are routinely conducted on airframe sections and components and occasionally on full-scale aircraft. The results of these tests are used to determine whether the airframe should be modified.

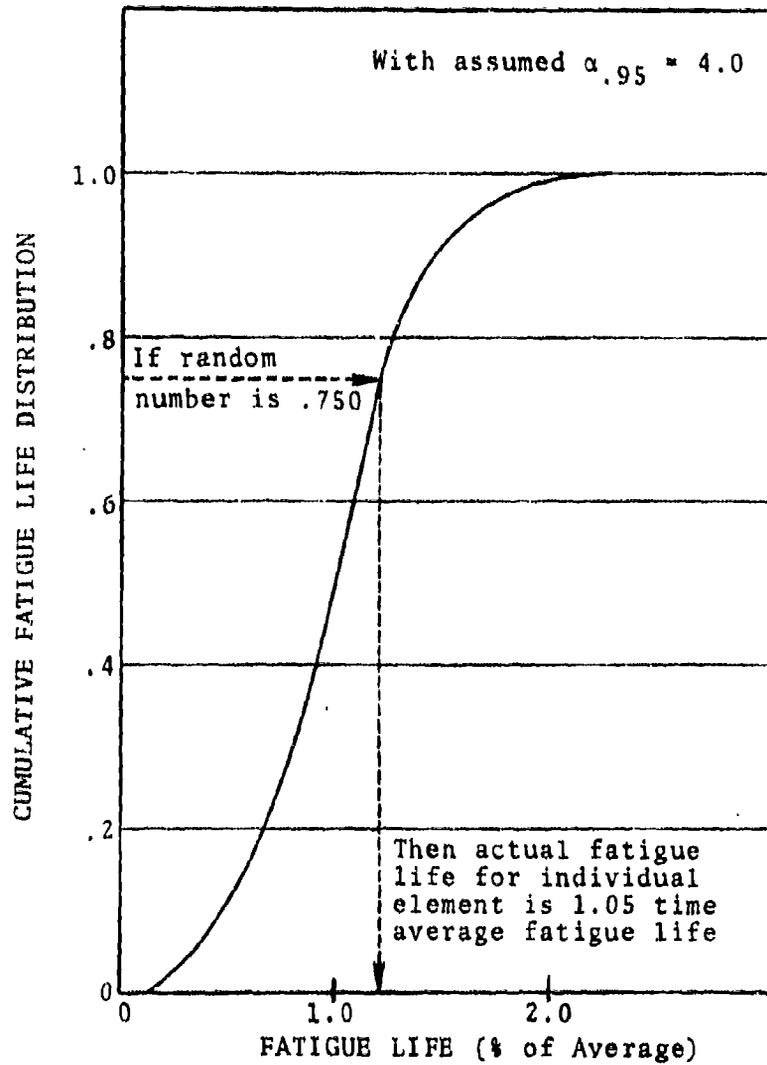
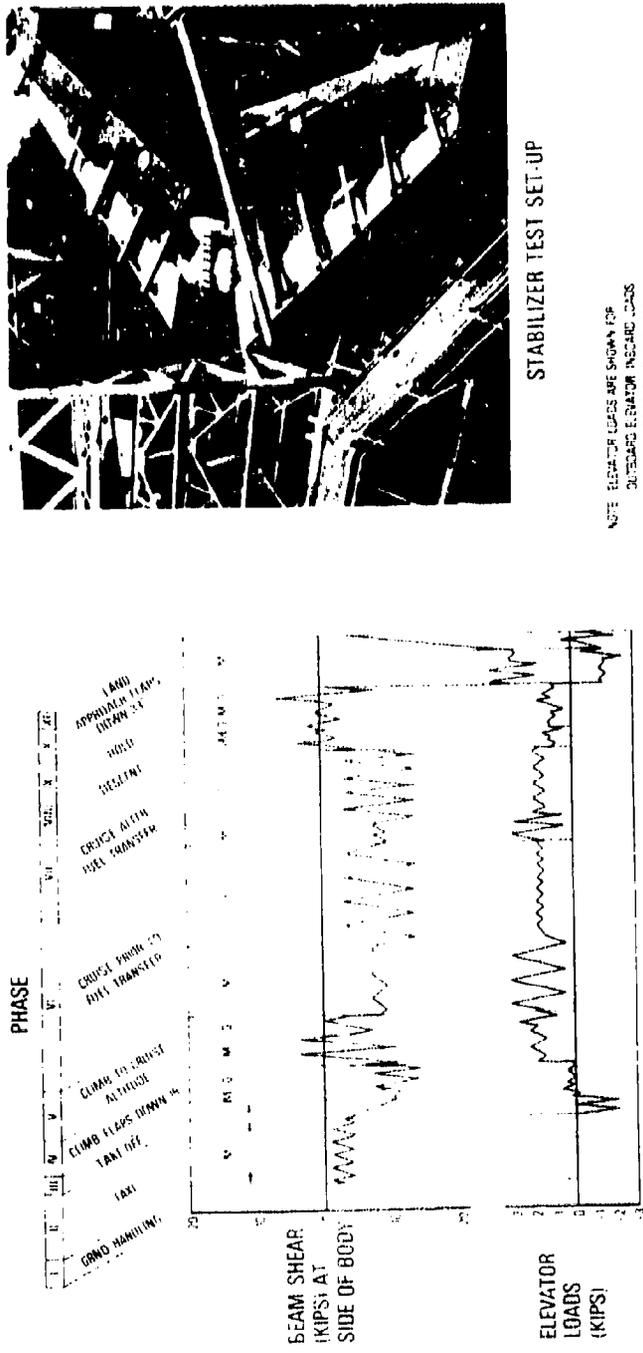


Figure 6. Cumulative Distribution of Fatigue Lives Using a Two-Parameter Weibull Distribution



TEST IS SCHEDULED FOR EQUIVALENT OF 2*60000 = 120000 HOURS IN MIXTURE OF FLIGHTS

Figure 7. Typical Component Fatigue Test

The SAIFF logic simulates the fatigue test by assuming that the fatigue test failure occurs after a test period equal to the actual average fatigue life determined in Block 1 divided by the fatigue test acceleration factor. If the actual average fatigue life is less than twice the service life when a fatigue test failure occurs, a production modification is developed. If the actual average fatigue life is less than the service life, a retrofit modification is developed for those aircraft already in service, and the inspection frequency of the particular element is increased from the time the element reaches 80% of its actual average fatigue life to the time that the element is either modified or repaired. The interval between the time that a fatigue test failure occurs and the time that the element modification is installed is the lead time required to design the modification, procure materials and/or parts, and fabricate the modification. The lead time also includes the time required to fatigue test the modification, if such testing has been specified. Whether or not a modification must be so tested is a decision that is part of the data input required at the start of the simulation.

If a modification is tested, it is assumed that it will be redesigned and retested until the actual average life is at least equal to the predicted average life. If the modification is not tested, then it is assumed that the actual average life will be subject to the same uncertainties as the original design and, therefore, must be determined by the same distribution as discussed above and indicated in Block 1 and Figure 5. Once the actual average fatigue life is determined, the logic returns to Block 1, where the actual fatigue life of each modified element is determined as previously discussed.

3. Reduce Fatigue Life Because of Production, Service, or Corrosion Defects (Block 3)

The previous blocks provide the means of determining the fatigue life that could be expected of each individual element under ideal conditions. However, the effect of production defects, service damage, and corrosion must be accounted for. Since these factors cannot be realistically duplicated in a laboratory or during a controlled experiment, MRR/SDR data was used to construct their occurrence rates. From this information, the following may be defined: (1) the rate at which production defects occur, (2) the rate at which service damage occurs, (3) the rate at which corrosion occurs, (4) the rate at which corrosion grows, (5) the effect of production defects on fatigue life, and (6) the effect of service damage on fatigue life.

Figure 8 shows the distribution of fatigue lives for elements that have been subject to production damage. This figure indicates that the average fatigue life has been substantially reduced. Therefore, when it has been determined that an element has been subject to production damage, the SAIFF logic selects a revised fatigue life for that individual element by applying the Monte Carlo method to the distribution shown in Figure 8.

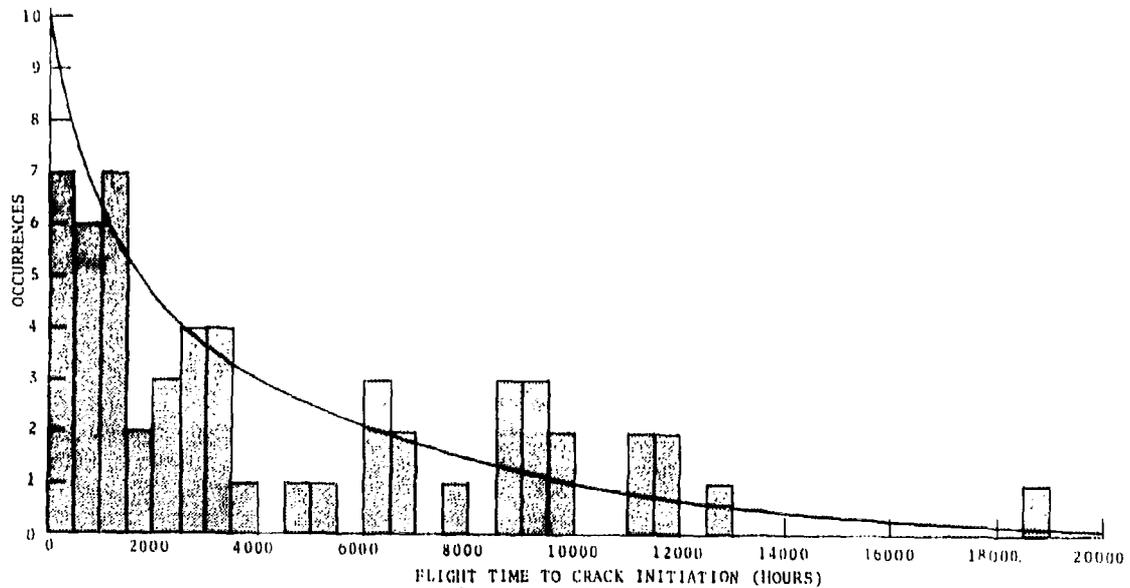


Figure 8. Histogram of Crack Occurrences on Production-Damaged Elements

Figure 9 is a histogram of time to service damage occurrence constructed from MRR/SDR data. This figure indicates that service damage is a uniformly occurring random event independent of aircraft service time. The Monte Carlo method is used to generate time to service damage occurrence from a uniform distribution. The SAIPE logic treats service damage and the resulting crack initiation as occurring simultaneously.

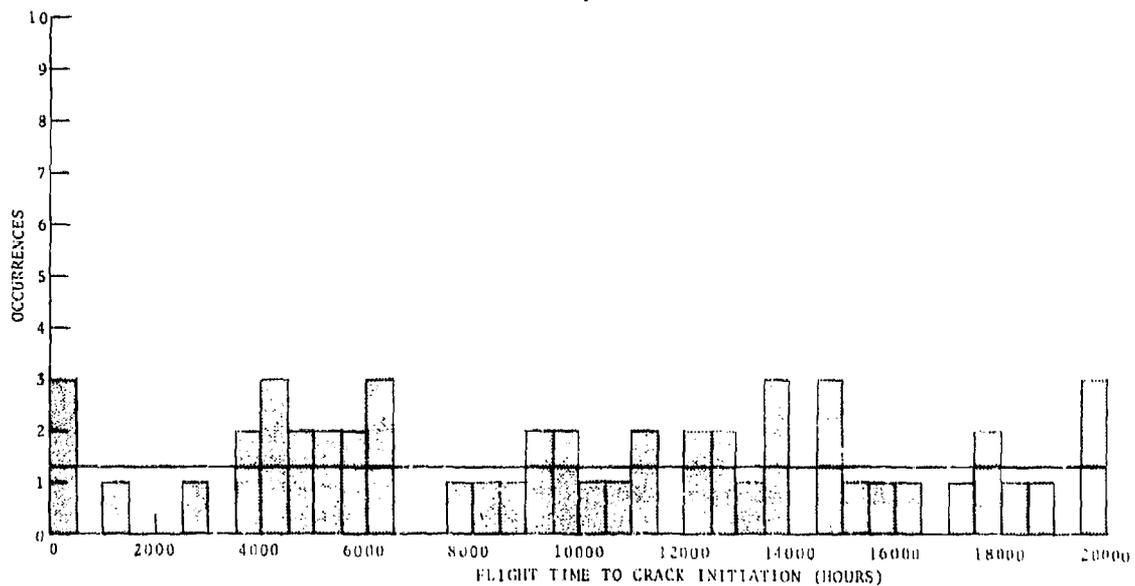


Figure 9. Histogram of Crack Occurrences on Service-Damaged Elements

A study conducted by the Naval Air Engineering Center (Reference 7) provides the means for determining the effect of corrosion defects on fatigue life. This study, which compared the fatigue lives of wing spars taken from previously operational HU-16 aircraft with the fatigue lives of newly manufactured spars, concluded that approximately 30% of the fatigue life reduction in the corroded spars was due to operational usage. In spars with surface pitting and/or light exfoliation, there was no fatigue life reduction due to corrosion; but, in spars with severe exfoliation, the fatigue life reduction was at least 40%. The study further indicates that severe exfoliation is found almost exclusively in stress concentrations such as those at fastener holes.

For each of the documented corrosion occurrences in the MRR/SDR data, the reported corrosion size was plotted as a function of the corrosion detection time. A corrosion growth rate was then postulated by constructing a line between the origin and one of the data points such that parallel growth rate lines passing through each of the other data points yield no negative times to corrosion initiation. This is a somewhat conservative approach in that it allows corrosion to initiate as soon as an aircraft enters service. Knowing the growth rate and time of detection, the number of corrosion occurrences versus time of initiation may be plotted. A typical cumulative distribution of times to corrosion initiation is shown in Figure 10. With such a distribution, the Monte Carlo method was used to generate a time to corrosion initiation for each of the structural elements.

The fatigue life reduction of a structural element resulting from corrosion depends on the state of stress in the corroded area. The probability that corrosion exists in a stress concentration is equal to the ratio of the number of corrosion occurrences found in stress concentrations to the total number of corrosion occurrences identified in that structural element type within the fleet. For each incident of corrosion, if a random number drawn from a uniform distribution is less than the appropriate probability of corrosion occurrence in a stress concentration, the corrosion is assumed to occur in a stress concentration; otherwise, it is assumed to occur in a uniform stress field.

4. Reduce Strength Because of Crack or Corrosion Growth/Predict Time to Failure (Block 4)

The previous blocks provide the means for establishing the fatigue life, the time of crack initiation, for each element. In Block 4 after the growth of the crack and the growth of possible corrosion are considered, the resulting strength reduction is compared with the loads expected on the airframe. The crack growth rate is determined from specimen and large-component tests conducted on typical airframe sections. This rate depends on design, material selection, and load environment. All of these factors are accounted for by selecting an average growth rate from a component test that closely resembles the design of the given

element and then by considering that each individual element falls within a normal distribution. The validity of this procedure was proved by Eggwertz (Reference 8).

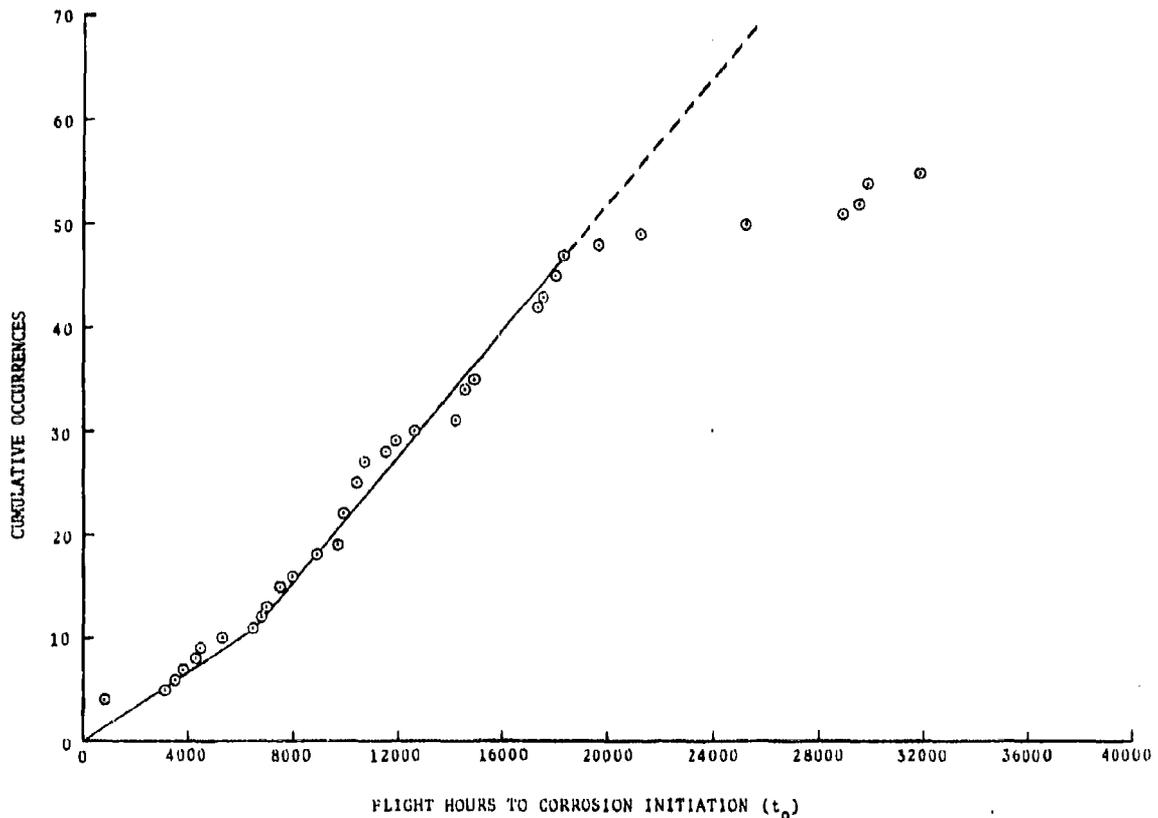


Figure 10. Typical Cumulative Distribution of Corrosion Occurrence

The Navy study with wing spars (Reference 7) concluded from tensile strength tests that the ultimate strength of the spar was not affected by corrosion. This conclusion is also supported by Jackman's investigation (Reference 9). It may be assumed, therefore, that corrosion on commercial transports will always be detected before the ultimate strength is affected. The only instances of structural failure being attributed to corrosion have occurred on prop or turboprop aircraft that were not protected by advanced corrosion resistant materials and preventive coatings.

As indicated in the foregoing discussion, the strength reduction due to fatigue cracking is compared with the load environment to determine the time of element failure. The load environment is the sum of gust and maneuver acceleration loads on the wing and fuselage elements. The flight loads used in SAIPE are based on 2000 flight hours of VGH (airspeed, normal acceleration, altitude) data recorded on commercial transport aircraft and reported by NASA (Reference 10).

The time to failure of each element is calculated by the reliability formula, Equation (15), discussed in Section III.4. If the time to failure is greater than the aircraft service life, the simulation retires the aircraft from service and returns to Block 1.

5. Periodic Inspection of Elements/Aircraft Deleted from Fleet (Block 5)

This block covers the periodic inspection of a commercial transport aircraft. It includes four levels of inspection. As each inspection level is called during the simulation, a decision on whether or not an existing defect, either crack or corrosion, is found depends on the probability-of-detection curves in Figures 11 and 12 and on a random number selection. The formulation of these curves was based on data obtained from a survey of maintenance inspectors and on an analysis of actual defects detected in MRR/SDR data. If a defect is detected, the logic proceeds directly to Block 6; if a defect is not detected, the simulation performs additional scheduled inspections. The detection sequence is repeated at each subsequent inspection until a defect is found, the aircraft is retired from service, or a structural failure occurs. If a defect is detected, the logic goes to the repair block; if a structural failure occurs, the aircraft is deleted from the fleet.

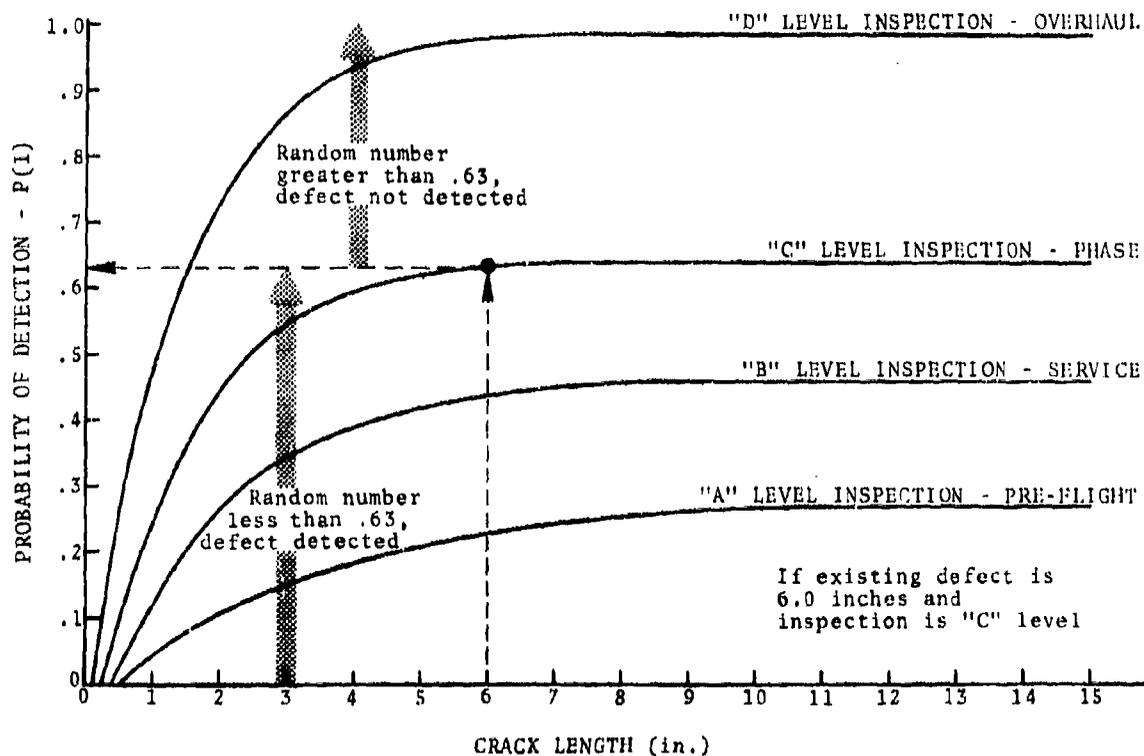


Figure 11. Probability of Crack Detection During a Periodic Inspection

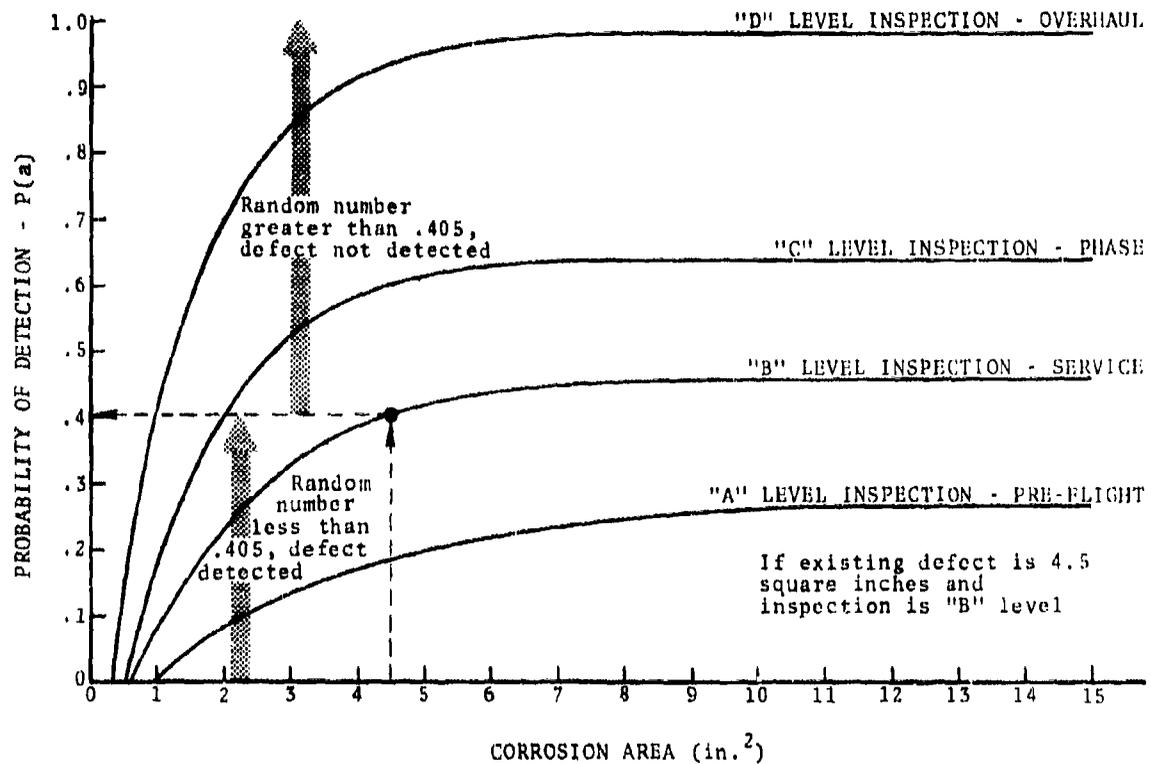


Figure 12. Probability of Corrosion Detection During a Periodic Inspection

6. Repair Element to Original Strength (Block 6)

When a defect is detected, the logic first determines whether an element modification is pending. If it is, the modification is installed, and a new fatigue life for that individual element is determined by applying the Monte Carlo method to the distribution previously defined in Block 1. The logic in Block 8 determines the actual average fatigue life of the given element when the decision is made to modify the element.

If an element modification is not pending, the element is restored to its original actual average fatigue life, and the fatigue life of the individual element is determined by applying the Monte Carlo method. If an element has multiple defects when repaired, these defects are also corrected, even if they were not detected during the original inspection. It is assumed that once one defect is found, the element will be carefully reinspected and all other existing defects will be found.

7. Special Inspections, Increase Inspection Frequency (Block 7)

The decision to conduct a special inspection and/or increase the periodic inspection frequency for each aircraft in the fleet is

based on the size of the previously detected defects. If a structural failure occurs, fail-safe damage occurs, or if an element has a crack whose propagation would lead to a one-half strength reduction before the next inspection, then both the special inspection and the increased periodic inspection frequency are scheduled. This scheduling is also effected if the sum of the percentages of strength reductions due to defects in all aircraft of the fleet exceeds 20 percent of the average fleet strength.

Conducted immediately after it is called for, the special inspection is considered complete when all aircraft in the fleet have been inspected. Also instituted immediately after it is called for, the increased frequency of inspection remains in effect until a modification is required as indicated by service experience or fatigue testing. As each aircraft has the modification installed, the original inspection frequency is resumed on an individual basis.

8. Develop Modifications Because of Service Experience
(Block 8)

Modifications suggested because of service experience are initiated only after weighing the one-time cost of modification against the recurring costs of an increased inspection frequency and of repairing elements, some repeatedly. SALFE determines which of the two costs is less and selects the course of action associated with the lesser cost. This comparison is illustrated in Figure 13.

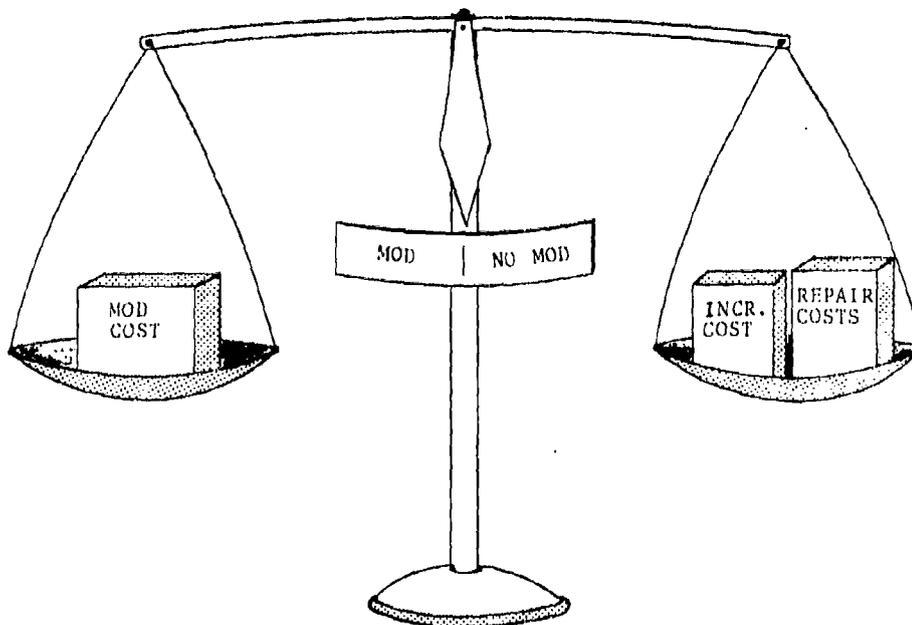


Figure 13. Service Modification Decision Logic

Additional modifications may also be warranted if a previous modification sustains defects while in service. The logic for an additional modification is based on the same type of cost comparison discussed above. The cost of inspections, repairs, and modifications is based on a study presented at an ATA Maintenance Conference and documented in Reference 11.

Once the decision has been made to develop a modification, the logic determines, according to simulation input data, whether the modification had been fatigue tested before its incorporation in the fleet. If the modification had been tested, the actual average fatigue life of the modified element is considered to be equal to the fatigue life predicted in Block 1 for the original design. If the modification had not been tested, the predicted average fatigue life of the modified element is considered to be equal to the fatigue life predicted in Block 1 for the original design, and the actual average fatigue life of the modified element is determined from Figure 5 similarly as the actual average fatigue life of the original element was determined.

After the actual average fatigue life of the modified element has been determined, each modified element has a fatigue life assigned when it is installed in an aircraft.

V. PARAMETRIC STUDY

1. Background

As discussed earlier, the major advantage of a simulation is that it permits study of the real system without actual modification of that system in any way. For many real systems, major experimentation involves very high risks. The SAIFE simulation permits experimentation with an aircraft inspection program without jeopardizing the actual fleet. Various inspection program parameters can be modified, and the corresponding effect on aircraft safety observed. While there are many variables by which aircraft safety can be gauged, structural element failure rate is the most revealing.

Ideally, failure rate is calculated directly from observed failures. Consider n aircraft placed in service with a common retirement life t_{ret} . Assume that r failures are observed with $r \leq n$, and that the observed failure times are $t_1 \leq t_2 \leq t_3 \leq \dots \leq t_{ret}$. Then the failure rate, λ , can be calculated by

$$\lambda = \frac{r}{T} \quad (17)$$

where T , the accumulated service life is

$$T = \sum_{i=1}^r t_i + (n - r) t_{ret} \quad (18)$$

To run the SAIFE program with all of the defined structural elements in the aircraft requires a great deal of computer time. Thus, any extensive parametric study will be very costly from a computer standpoint. An economical alternative is to run samples of elements from each of the element types. But, sample runs normally result in no structural failures appearing in the output. This makes it impossible to calculate failure rate directly. However, there are statistical reliability techniques by which the failure rate can be estimated.

2. Estimation Technique

Recall the general expression for the reliability of a system

$$R(t) = e^{-\int \lambda(t) dt} \quad (19)$$

where $R(t)$ = the reliability or probability of survival of the system through time t

$\lambda(t)$ = the hazard rate, or probability that a failure will occur in the next instant of time assuming previous survival

For most systems, failure is a reflection of individual part failure. Known as a serial reliability configuration, it can be represented as

$$R_s(t) = R_1(t) \cdot R_2(t) \cdot \dots \cdot R_n(t)$$

where $R_s(t)$ = the series (system) reliability

$R_i(t)$ = probability of surviving the i^{th} failure mode through time t

This technique can be applied to a fleet of aircraft to estimate the aircraft failure rate for the fleet. Consider the fleet as the system under consideration with each aircraft in the fleet representing a failure mode. Let P_i be the probability of survival of the i^{th} aircraft through the time interval of interest. Then the probability, $R_s(t)$, of there being no structural failures throughout the fleet is

$$R_s(t) = \prod_{i=1}^n P_i \quad (20)$$

where $R_s(t)$ = fleet (system) reliability

P_i = reliability of i^{th} aircraft

n = number of aircraft in the fleet

Recall that fleet reliability can also be expressed by the generalized reliability equation

$$R_s(t) = e^{-\int \lambda(t) dt} \quad (21)$$

If it can be assumed that the hazard rate of our system now remains constant over a practical interval of time, and that $\lambda(t) = \lambda_s = \text{constant}$, expected number of random failures per unit of operating, i.e., the failure rate, then Equation (21) can be expressed as

$$R_s(t) = e^{-\lambda_s t} \quad (22)$$

where λ_s = constant element failure rate for the fleet
 t = total flight hours for the fleet

Equation (22) can then be solved for λ_s .

$$\lambda_s = - \frac{\ln[R_s(t)]}{t} \quad (23)$$

That λ_s is constant is not an unwarranted assumption when the fleet is considered to be a single complex system with a constant failure rate regardless of the failure pattern of individual aircraft. The mixing of part ages when individual elements are replaced or repaired causes the fleet over a period of time to approach a stable state.

Next, the average element failure rate for a given element type can be formed.

$$\hat{\lambda}_s = \frac{\sum_{k=1}^n \lambda_{sk}}{m} \quad (24)$$

where $\hat{\lambda}_s$ = average element failure rate for a given element type

λ_{sk} = failure rate for k^{th} sample element from a given element type

m = number of sample elements from a given element type

and the element type failure rate is then

$$\lambda_{sT} = u \hat{\lambda}_s \quad (25)$$

where λ_{sT} = element type failure rate

u = number of elements in population for a given element type

The estimated aircraft failure rate for the fleet can now be calculated.

$$\text{A/C failure rate} = \sum_{j=1}^w \lambda_{sT_j} \quad (26)$$

where λ_{sT_j} = element type failure rate for j^{th} element type
 w = number of element types in an aircraft

Initial use of the foregoing feature indicated that very long cracks resulted in P_i values $\rightarrow 1.0$ and $R_s(t) \rightarrow 0$. When used in equation (23) this resulted in unrealistically high λ_s values. Consequently for the AFS-510 demonstration described in Book Two of Volume IV, this feature in the program was changed as described below.

2. Consider the fleet of aircraft a system with constant failure rate and multiple failure modes. Each aircraft in the fleet represents a failure mode. Then, $R(t)$, the fleet reliability is

$$R(t) = \prod_{i=1}^n P_i \quad (27)$$

where P_i = probability of surviving the i^{th} failure mode or non-failure of the i^{th} aircraft
 n = number of failure modes or aircraft in the fleet

While the failure rate for each failure mode is not constant, the assumption of constant failure rate for the fleet allows us to write directly from probability theory the following,

$$R(t) = \prod_{i=1}^n P_i = e^{-\lambda t} \quad (28)$$

where λ is the constant fleet failure rate. Equation (28) is easily solved for λ ,

$$\lambda = - \frac{\ln \left[\prod_{i=1}^n P_i \right]}{t} \quad (29)$$

Summing the P_i is not strictly correct since it is possible that the sum will be greater than one, which violates the definition of a probability function.

However, if one chooses to call the P_i the probable number of failures per i^{th} aircraft in the fleet, then summing them will yield the probable number of failures in the fleet for a single SAIFE run. To calculate failure rate, the accumulated exposure time is required. Simply using the number of aircraft multiplied by the aircraft retirement life overestimates the exposure time and underestimates the failure rate. Direct calculation of failure rate is

$$\lambda = \frac{r}{T} = \text{A/C failure rate} \quad (30)$$

where r is the number of failures and T , the accumulated exposure time, is

$$T = \sum_{i=1}^r t_i + (n - r) t_{\text{ret}} \quad (31)$$

where $t_i = i^{\text{th}}$ failure time
 $n =$ number of aircraft in fleet
 $t_{\text{ret}} =$ aircraft retirement life

It is easily seen that the error introduced becomes greater as r increases or the t_i decreases but this is small and can be neglected.

3. Output

The original standard SAIFE outputs are shown in Tables 1 and 2. To enhance the program's parametric study capability, these two outputs have been expanded as shown in Tables 3 and 4. Note in Table 3, that for each crack that occurs in a particular element during the sample run, the aircraft number, the airframe flight hours, the crack length, and its corresponding $1-P_i$ are printed. The aircraft number for each corrosion or production defect that occurs is printed. The estimated element failure rate, λ_s , as calculated by Equation (23) is also printed.

In Table 4, the element summary for a particular element type, the additional output consists of: the estimated element type failure rate, λ_{sT} , as calculated by Equation (25), the sample crack length mean and standard deviation used to define the log-normal distribution of crack lengths, and the crack length vs $1-P_i$ curve fit constants.

While the outputs shown in Tables 3 and 4 are adequate for identifying trends, a thorough analysis of some parametric modifications or of a particular feature of a particular run may require a more complete service history of selected elements and aircraft. This service history is available for every element in the aircraft and every aircraft in the fleet. It consists of every structurally significant event that occurs during the simulation. It is so voluminous, however, that this long list history should be output for only selected aircraft. The aircraft of interest are selected from the standard output, and the simulation is run a second time for specific elements with the long list option in effect. This means that the two runs must be identical. That is, the random number generators must deliver the same sequences of numbers each time. To avoid having to run all the elements a second time, just to see a long list of one or two elements, the program permits the user to input the random number generator seeds for each element of interest.

TABLE 3. EXPANDED SAFE OUTPUT FOR AN INDIVIDUAL ELEMENT

AIRCRAFT TYPE: HYBRID
 NUMBER OF AIRCRAFT IN FLEET: 500 AIRCRAFT SERVICE LIFE: 60000 HOURS
 STRUCTURAL ELEMENT: FUS-MFR-BOT-1020
 PREDICTED AVERAGE FATIGUE LIFE: 197580 HOURS ACTUAL AVERAGE FATIGUE LIFE: 251039 HOURS
 FATIGUE TEST LIFE: 343036 HOURS

NUMBER AND TIME TO INITIATION OF AIRCRAFT DEFECTS

	FIRST CRACK	CORROSION	SERVICE DAMAGE	PRODUCTION DEFECTS
OCCURRENCES	3	0	0	0
MIN(HRS)	14873	0	0	---
MAX(HRS)	58472	0	0	---
AVG(HRS)	42707	0	0	---

NUMBER AND LENGTH OF CRACKS DETECTED AT EACH LEVEL OF INSPECTION

	A-LEVEL	B-LEVEL	C-LEVEL	D-LEVEL	SPECIAL
OCCURRENCES	1	0	0	0	0
MIN(IN)	11.39	0.	0.	0.	0.
MAX(IN)	11.39	0.	0.	0.	0.
AVG(IN)	11.39	0.	0.	0.	0.

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	200	1000	2000	0	24
2	25	200	1125	3000	0	17
3	25	200	1266	4500	0	12
4	25	200	1424	6750	0	9
5	25	200	1602	10125	0	7
6	25	200	1802	15188	0	6
7	25	200	2253	18984	0	7
8	25	200	2816	23730	0	8
9	25	200	3520	29663	0	9

AIRCRAFT NO.	CRACK LENGTHS AND CORRESPONDING CUMULATIVE PROBABILITY OF FAILURE FLT. HOURS	CRK.LGT.	PROR. OF FAILURE
281	60000	.53	4.2E-08
371	55253	11.39	2.6E-06
477	60000	.12	1.3E-08

NUMBER OF SPECIAL INSPECTIONS CONDUCTED: 0
 NUMBER OF STRUCTURAL MODIFICATIONS: 0
 FINAL ACTUAL AVERAGE MODIFIED FATIGUE LIFE: 251039 HOURS
 NUMBER OF AIRCRAFT MODIFIED IN SERVICE: 0
 ESTIMATED ELEMENT FAILURE RATE: 0.04E-14/HR.

STRUCTURAL FAILURES		RESIDUAL STRENGTH EQUALS FAIL-SAFE STRENGTH	
AIRCRAFT NO.	FLT. HOURS	AIRCRAFT NO.	FLT. HOURS
-----	-----	-----	-----

TABLE 4. EXPANDED SAIFE OUTPUT FOR AN ELEMENT TYPE

AIRCRAFT TYPE: HYBRID					
NUMBER OF AIRCRAFT IN FLEET: 500			AIRCRAFT SERVICE LIFE: 40000 HOURS		
SUMMARY OF STRUCTURAL ELEMENT: FUS-MFR-40T					
NUMBER AND TIME TO INITIATION OF AIRCRAFT DEFECTS					
	FIRST CRACK	CORROSION	SERVICE DAMAGE	PRODUCTION DEFECTS	
	-----	-----	-----	-----	
OCCURRENCES	7	0	0	0	
MIN(HRS)	14473	0	0	-----	
MAX(HRS)	50472	0	0	-----	
AVG(HRS)	48766	0	0	-----	
NUMBER AND LENGTH OF CRACKS DETECTED AT EACH LEVEL OF INSPECTION					
	A-LEVEL	B-LEVEL	C-LEVEL	D-LEVEL	SPECIAL
	-----	-----	-----	-----	-----
OCCURRENCES	1	0	0	0	0
MIN(IN)	11.39	0.	0.	0.	0.
MAX(IN)	11.39	0.	0.	0.	0.
AVG(IN)	11.39	0.	0.	0.	0.
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)					
INITIAL	25	200	1000	2000	
SHORTEST	25	200	1000	2000	
LONGEST	25	200	3520	29663	
NUMBER OF SPECIAL INSPECTIONS CONDUCTED: 0					
NUMBER OF STRUCTURAL MODIFICATIONS: 1					
NUMBER OF AIRCRAFT MODIFIED IN SERVICE: 0					
ESTIMATED ELEMENT TYPE FAILURE RATE: 3.42E-12/HR.					
CRK. LGT. VS PROBABILITY CURVE FIT CONST: A = 0.					
			SAMPLE CRK. LGT. MEAN(IN)	2.37	SAMPLE STD. DEV. 3.8
			R =	-.0000	
STRUCTURAL FAILURES			RESIDUAL STRENGTH EQUALS FAIL-SAFE STRENGTH		
AIRCRAFT NO.	FLT. HOURS	STA. NO.	AIRCRAFT NO.	FLT. HOURS	STA. NO.
-----	-----	-----	-----	-----	-----

VI. SUMMARY AND CONCLUSIONS

- (1) Although the SAIFE simulation logic for evaluating proposed inspection programs is very complex, it can indicate the number, extent, flight time, and criticality of the defects that would occur in a given inspection program.
- (2) Except for limited data on wide-body aircraft, data detailing the service years and flight hours of the U.S. commercial transport fleet is currently available to only the air carriers or the airframe manufacturers.
- (3) SAIFE is a flexible program that can be used to evaluate the inspection requirements for an entire aircraft, a large segment of an aircraft, or a single element.
- (4) The information available on MRR/SDR's is useful for evaluating the rate of occurrence of production defects, service damage, and corrosion. However, the quantitative engineering type of data required for an in-depth analysis of these parameters is currently lacking.
- (5) Because of the flexibility provided by the input parameters, SAIFE can be used to evaluate inspection programs on both fail-safe and safe-life design aircraft.

REFERENCES

1. Anderjaska, A.E., A PLAN FOR DEVELOPING AN AIRCRAFT STRUCTURAL INSPECTION PROGRAM, a master's thesis submitted to the faculty of the School of Engineering and Applied Science of the George Washington University, February 1973.
2. Raithby, K.D., A COMPARISON OF PREDICTED AND ACHIEVED FATIGUE LIVES OF AIRCRAFT STRUCTURES, Royal Aircraft Establishment, Technical Note No. Structures 301, Ministry of Aviation, London, July 1961.
3. Freudenthal, A.M., THE EXPECTED TIME TO FIRST FAILURE, Ohio State University Research Foundation, Technical Report AFML-TR-66-37, Air Force Materials Laboratory, Wright-Patterson AFB, Ohio, February 1966.
4. Abelkis, P.R., FATIGUE STRENGTH DESIGN AND ANALYSIS OF AIRCRAFT STRUCTURES, PART 1, SCATTER FACTORS AND DESIGN CHARTS, Douglas Aircraft Company, Inc., Technical Report AFFDL-TR-66-197, Air Force Flight Dynamics Laboratory (FDTR), Wright-Patterson AFB, Ohio, June 1967.
5. Stone, M.E., and Heap, H.F., DEVELOPING THE DC-10 STRUCTURAL INSPECTION PROGRAM, presented at the 7th Annual FAA International Aviation Maintenance Symposium, Oklahoma City, Oklahoma, December 1971.
6. BOEING 747 FATIGUE INTEGRITY PROGRAM, REVISION 1, The Boeing Company, 747 Division, Everett, Washington, January 1971.
7. Shaffer, I.S., and Sebastian, J.C., CORROSION AND FATIGUE EVALUATION OF SPAR CAP SPECIMENS FROM HU-16 WINGS, Naval Air Engineering Center; Report No. NAEC-AML-2538, Coast Guard Aircraft Repair and Supply Center, Elizabeth City, North Carolina, U.S. Coast Guard Requisition No. Z70099-6081-0771, September 1967.
8. Eggwertz, S., and Lindsjo, G., STUDY OF INSPECTION INTERVALS FOR FAIL-SAFE STRUCTURES, The Aeronautical Research Institute of Sweden, FAA Report 120, Stockholm, 1970, AD 723111.
9. Excerpts from STRESS-CORROSION CRACKING RESISTANCE OF HIGH-STRENGTH ALUMINUM ALLOYS AND HIGH-STRENGTH FASTENER MATERIALS, MC1C 73-19, a paper presented at the Tri-Service Conference on Corrosion, Houston, Texas, December 1972.
10. Hunter, P.A., and Fetner, M.W., AN ANALYSIS OF VGH DATA COLLECTED FROM ONE TYPE OF FOUR-ENGINE TURBOJET TRANSPORT AIRPLANE, NASA Technical Note D-4529, Langley Research Center, Hampton, Virginia, May 1968.
11. Excerpts from the Air Transport Association of America (ATA) Annual Engineering and Maintenance Conference, held in Phoenix, Arizona, September 1968.

BIBLIOGRAPHY

Davidson, J.R., RELIABILITY AND STRUCTURAL INTEGRITY, NASA-Langley Research Center, Technical Note X-71934, National Aeronautics and Space Administration, Washington, D.C., November 1973.

DC-8 INSPECTION AND MAINTENANCE PROGRAM, VOLUME ONE, Air Transport Association of America (ATA), New York Avenue, N.W., Washington D.C., October 1957.

Eggwertz, S., INSPECTION PERIODS DETERMINED FROM DATA OF CRACK DEVELOPMENT AND STRENGTH REDUCTION OF AN AIRCRAFT STRUCTURE USING STATISTIC ANALYSIS, The Aeronautical Research Institute of Sweden, Wright Air Development Division of the Air Research and Development Command, U.S. Air Force, June 1961, AD-631-351.

FAA STATISTICAL HANDBOOK OF AVIATION, 1973 Edition, Department of Transportation, Federal Aviation Administration, Washington, D.C.

FAA STATISTICAL HANDBOOK OF AVIATION, 1970 Edition, Department of Transportation, Federal Aviation Administration, Washington, D.C.

Gould, A.J., CORROSION FATIGUE, FREQUENCY, Session 4, Paper 2: TEMPERATURE AND ENVIRONMENT, presented at the International Conference on Fatigue of Metals, London, September 1956.

Harmsworth, C.L., EFFECT OF CORROSION ON THE FATIGUE BEHAVIOR OF 2024-T4 ALUMINUM ALLOY, ASD Technical Report 61-121, Directorate of Materials and Processes, Aeronautical Systems Division, Wright-Patterson AFB, Ohio, July 1961.

Lundberg, B.K.O., and Eggwertz, S., A STATISTICAL METHOD FOR FAIL-SAFE DESIGN WITH RESPECT TO AIRCRAFT FATIGUE, THE REDUCED STATIC STRENGTH CRITERION APPLIED TO A DIFFUSE WING STRUCTURE, The Aeronautical Research Institute of Sweden, FAA Report No. 99, presented at the ICAS Congress in Zurich, September 1960.

Whittaker, I.C., and Saunders, S.C., EXPLORATORY DEVELOPMENT ON APPLICATION OF RELIABILITY ANALYSIS TO AIRCRAFT STRUCTURES CONSIDERING INTERACTION OF CUMULATIVE FATIGUE DAMAGE AND ULTIMATE STRENGTH, The Boeing Company, Technical Report AFML-TR-72-283, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, January 1973.