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The Fatigue in Aircraft Corrosion Testing (FACT) Programme

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(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.713

THE FATIGUE IN AIRCRAFT CORROSION TESTING (FACT) PROGRAMME

by

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PREFACE

In accordance with the mission of AGARD the Structures and Materials Panel (SMP) has always kept an open eye for the possibility of sponsoring collaborative programmes of research. AGARD is unique in its ability to realise the cooperation of laboratories in up to sixteen nations. In this way AGARD distinguishes itself from other international scientific and technical organisations.

In the 1970s the SMP decided to embark on collaborative research activities in the area of fatigue. One of the first activities was the Corrosion Fatigue Cooperative Testing Programme (CFCTP), the precursor to the Fatigue in Aircraft Corrosion Testing (FACT) programme. Both programmes are described in this report.

Failure by fatigue and degradation by corrosion continue to be major considerations in aircraft design. Environmental effects influence both initiation and propagation of fatigue cracks, and dynamic loading may cause more rapid deterioration of corrosion protection systems. Therefore the conjoint action of dynamic loading and environmental attack, i.e. corrosion fatigue, requires special attention.

Many corrosion fatigue tests have been done on aluminium alloys. However, few included critical structural details like joints, under realistic cyclic load histories and in service-like environments. Even fewer used practical corrosion protection systems. These aspects are specifically addressed by the CFCTP and FACT progammes. The results provide a significant contribution to the understanding of aircraft corrosion fatigue and should encourage further investigation in this difficult and challenging area of aerospace technology.

H.P. VAN LEEUWEN
Chairman, Subcommittee on
Fatigue in Aircraft
Corrosion Testing (FACT)

* * *

Conformément à la mission de l'AGARD, le Panel des Structures et Matériaux (SMP) a toujours veillé aux possibilités de parrainage de programmes collaboratifs de recherche.

La capacité d'AGARD de coordonner des programmes de coopération entre laboratoires dans les seize pays membres de l'OTAN est unique. Ainsi, AGARD se distingue de tous les autres organismes scientifiques et techniques internationaux.

Au cours des années 1970, le Panel SMP a pris la décision d'entreprendre des activités de recherche collaborative dans le domaine de la fatigue. L'une des premières initiatives dans ce sens a été le Programme Collaboratif d'Essais de Fatigue sous Corrosion (CFCTP), précurseur du Programme d'essais des interactions fatigue/corrosion des matériaux constitutifs des avions (FACT). Ce rapport donne la description des deux programmes.

La rupture de fatigue et la dégradation sous corrosion sont toujours des questions d'actualité dans la conception des aéronefs. Les conditions d'ambiance influent sur le début et la propagation de la fissure, et l'imposition des charges dynamiques peut conduire à la déterioration accelérée des systèmes de protection contre la corrosion. Il s'ensuit que l'action conjointe de charges dynamique et de conditions d'ambiance aggréssives, c'est à dire la fatigue sous corrosion, demande une attention particulière.

De nombreux essais de fatigue sous corrosion ont été effectués sur des alliages d'aluminium, mais très peur sur les éléments de structure critiques tels que les assemblages dans des conditions qui simulent les conditions réelles de service, en appliquant des séquences de charges réelles. L'emploi de systèmes pratiques de protection contre la corrosion s'avère même plus rare. Ce sont précisement ces aspects qui sont examinés par les programmes CFCTP et FACT. Les résultats obtenus représentent une contribution importante à l'effort consacré à l'analyse de la corrosion sous fatigue des matériaux aérospatiaux, et ils devraient conduire à des travaux de recherche plus approfondis dans ce domaine difficile et exigeant de la technologie aérospatiale.

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ACRONYMS AND TRADE NAMES

AFWAL : Air Force Wright Aeronautical Laboratories
AGARD : Advisory Group for Aerospace Research and Development
ALCOA : ALuminium COmpany of America
Alodine : chromate conversion coating on aluminium, produced by chemical reaction
AMLGUARD : water displacing corrosion preventive compound
ARALL : Aramid Reinforced ALuminium Laminates
ASTM : American Society for Testing and Materials
CCT : Centre Cracked Tension (type of fatigue specimen)
Celloseal : sealant for corrosion protection
CFCTP : Corrosion Fatigue Cooperative Testing Programme
DFVLR : Deutsche Forschungs- und Versuchsanstalt für Luft-und Raumfahrt
DTD : Directorate of Technical Development (U.K.)
EFFGRO : EFfective Flaw GROwth (computer program for fatigue crack growth prediction)
FACT : Fatigue in Aircraft Corrosion Testing
FALSTAFF : Fighter Aircraft Loading STAndard For Fatigue (manoeuvre spectrum load sequence
FFA : Flygtekniska Försöksanstalten
F+W : Eidgenössisches Flugzeugwerk
Hi-Lok : aircraft fastener system
Hi-Tigue : aircraft fastener system
IABG : Industrieanlagen-Betriebsgesellschaft
I.A.C.S. : International Annealed Copper Standard
ICAF : International Committee on Aeronautical Fatigue
Koroflex : flexible, elastomeric primer coating
LBF : Laboratorium für betriebsfestigkeit
LRTH : Luchtvaart- en Ruimtevaarttechniek, Technische Hogeschool, Delft
LT : Load Transfer
LTV : Ling-Temco-Vought (see VOUGHT)
MBB : Messerschmitt-Bolköw-Blohm
MIDAS : Magnetic tape Input Digital-to-Analogue Signal (controller for electro hydraulic fatigue machines)
MIL-A-83444 : Military Specification Airplane Damage Tolerance Requirements (U.S.)
MIL-C-5541 : Military Specification Chemical Conversion Coatings (U.S.)
MIL-C-81773C : Military Specification Coatings, Polyurethane, Aliphatic (U.S.)
MIL-P-23377 : Military Specification Primer Coating, Epoxy Polyamide (U.S.)
MIL-S-81733B . Military Specification Sealing and Coating Compound (U.S.)
MINITWIST : shortened version of Transport WIng STandard (gust spectrum load sequence
MRCA : Multi Role Combat Aircraft
MTS : Materials Testing Systems
NADC : Naval Air Development Centre
NAE : National Aeronautical Establishment
NATO : North Atlantic Treaty Organisation
NDRE : Norwegian Defence Research Establishment
NIVR : Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart
NLR : Nationaal Lucht- en Ruimtevaartlaboratorium
NRC : National Research Council
Permagum : non-hardening sealant
RAE : Royal Aircraft Establishment
RAF : Royal Air Force (U.K.)
RRA : Retrogression and Reage (metallurgical heat treatment)
SAAB : Svenska Aeroplan Aktien Bolaget
SBR : Secondary Bending Ratio
SCANIA : originally independent automobile manufacturer
SIFFRL : Structural Integrity, Fatigue and Fracture Research Laboratories
SLEEVbolt : interference fit aircraft fastener system
SMP : Structures and Materials Panel of AGARD
SPATE : Stress Pattern Analysis by measurement of Thermal Emission
STP : Special Technical Publication of the American Society for Testing and Materials
TOR : Terms Of Reference for setting up an AGARD activity
VOUGHT : division of the Ling-Temco-Vought Aerospace and Defence Company

PART I

PROGRAMME OBJECTIVES AND DEFINITION

1. INTRODUCTION

Aircraft structures are susceptible to corrosion and fatigue. Corrosion can occur under both static conditions and during missions. Thus the conjoint action of corrosion and cyclic loading, i.e. corrosion fatigue, is possible. Corrosion begins when the applied protection systems become degraded and damaged. Degradation occurs owing to exposure, e.g. to ultraviolet light and ozone, and moisture-induced leaching of inhibitors from primers and sealants. Damage may be incidental, for example as a consequence of impact by foreign objects, or may occur as cracking due to service loads or because the underlying metal has cracked.

Corrosion and fatigue damage tend to concentrate at joints, which in conventional aluminium alloy structures possess most or all of the following detrimental features:

- stress concentrations and faying surface contacts that crack and wear away the protection systems
- crevices for moisture entrapment
- possible galvanic couples when steel or titanium fasteners are used
- fatigue critical locations, e.g. fastener holes and their vicinities.

In the past a variety of corrosion fatigue tests have been conducted with aluminium alloys. Nearly always the results have indicated environmental effects to be significant. However, few investigations have included the testing of critical structural details, such as joints, under realistic cyclic load histories and in simulated service environments. Even fewer have considered the effectiveness of various corrosion protection systems. Consequently, a data base for assessing the influence of corrosion on the fatigue life of aircraft structures has not been acquired.

In recognition of this state of affairs it was decided at the 44th Meeting of the AGARD Structures and Materials Panel in April 1977 to form a Sub-Committee and appoint European and North American coordinators for a cooperative programme on corrosion fatigue of aerospace materials of particular interest to the NATO countries. At that time the objectives of the programme were formulated as follows:

- assessment of the effectiveness of state-of-the-art protection schemes for aluminium alloys with respect to corrosion fatigue and corrosion + fatigue
- stimulation of the development of new protection products, procedures and techniques
- bringing together researchers on both sides of the Atlantic in a common testing effort that would result in a better understanding of the corrosion fatigue phenomenon and the means of mitigating it for aerospace structural materials
- enabling participating laboratories to add to their fatigue testing capabilities by using a controlled atmospheric corrosion environment.

The cooperative programme was planned to be carried out in two stages. The first stage was to be a core programme of round-robin testing to establish whether participants could obtain confidence in one another's fatigue testing capabilities. At the same time this core programme was designed to be sufficiently straightforward to encourage participation, particularly by those with relatively little experience of corrosion fatigue testing.

Originally there were eight participants to the core programme, which was completed in 1981 and published as an AGARD report, reference (1). However, since that time two more participants have carried out core programme testing. The results, together with "fine tuning" of the statistical methods used to analyse the core programme data, warrant a reassessment of the core programme. This reassessment is presented in Part II of this report.

The second stage of the cooperative programme was to consist of supplemental testing directed to the requirements of individual participants but still with much commonality. This second stage also involved ten participants, four of whom had not taken part in the core programme, and was completed in 1985. The results, in the form of contributions by the participants, are presented in Part III of this report.

A summary evaluation of the entire programme is given in Part IV. In this part the coordinators have endeavoured to establish common trends from the results in order to place them in a broader context. Recommendations for further investigation are made also.

2. OVERVIEW OF THE CORE PROGRAMME (CFCTP)

The core programme of round-robin testing was entitled the Corrosion Fatigue Cooperative Testing Programme, hereinafter referred to as the CFCTP. An overview of the CFCTP is given in table 1. The CFCTP specified identical conditions for the following parameters:

- material and heat treatment: 7075-T76 aluminium alloy sheet
- specimen configuration: 1½ dogbone joint
- protection system: chromate conversion, primer and topcoat
- mechanical testing: static prestressing and fatigue (constant amplitude only)
- environments: pre-exposure, fatigue and corrosion fatigue.

To achieve these identical conditions it was necessary to obtain a batch of 7075-T76 aluminium alloy from one heat, to manufacture all prior-to-assembly specimen parts at one location, to apply the protection system and assemble the specimens at one location, and to prepare a technical manual for mechanical and environmental testing.

The technical manual was published in reference (1). An impression of its scope and the kind of detail necessary to try and ensure identical testing conditions is provided by the summary in table 2. Most of the chapter headings are self-evident, but the cold box requires some explanation. This is an environmental chamber for statically loading the specimens at low temperature in order to crack the protection system (paint) near the fasteners.

As indicated in the introduction, the main purpose of the CFCTP core programme was to establish whether participants could obtain confidence in one another's fatigue testing capabilities, with the added dimension of a controlled atmospheric corrosion environment. That is to say, results from all participants were to be analysed to determine whether one or more laboratories had obtained data significantly different from those of the remaining laboratories.

3. OVERVIEW OF THE SUPPLEMENTAL PROGRAMME (FACT)

The supplemental programme was entitled Fatigue in Aircraft Corrosion Testing (FACT). This programme was included so that individual participants could investigate corrosion fatigue problems of particular relevance to their own interests and yet within a broader context. To achieve this it was emphasized that testing should be done with as much commonality as possible. In particular, it was recommended that

- the same specimen configuration (1½ dogbone joint) be used as for the CFCTP core programme
- mechanical testing conditions be identical
- environmental conditions (pre-exposure, fatigue and corrosion fatigue) be identical to those for the CFCTP
- efforts be made to obtain materials of mutual interest from one heat.

Concerning the first three points the technical manual required for the CFCTP also included supplemental testing guidelines for specimen manufacture, application of protection systems, specimen assembly, pre-exposure, and fatigue and corrosion fatigue under flight simulation loading, see table 2.

An overview of the FACT programme is given in table 3. There were ten participants. Four had not taken part in the CFCTP core programme, namely

(1) SAAB-SCANIA Aerospace Division, Linköping, Sweden.

(2) Delft University of Technology LRTH, Delft, The Netherlands.

(3) Industrieanlagen-Betriebsgesellschaft IABG, Ottobrunn, Germany.

(4) National Research Council NRC, Ottawa, Canada.

Table 3 shows similarities and commonalities in the individual programmes. Most participants tested 1½ dogbone specimens under nominally identical mechanical and environmental conditions. The fatigue loadings were constant amplitude, as in the CFCTP, the manoeuvre spectrum FALSTAFF (references 2-4) and the gust spectrum MINITWIST (reference 5). The environmental conditions generally included two or more of those in the CFCTP. Notable exceptions were in the SAAB and NRC programmes.

The main interest of several participants was to compare - in their individual programmes - the environmental fatigue properties of a number of aluminium alloys in various tempers. However, owing to the calibratory function of the CFCTP and the participants' active cooperation in obtaining the many similarities and commonalities within the FACT programme, it was possible to make inter-participant comparisons of materials, protection systems and fasteners as well. Furthermore, the total testing effort provided many data for comparing environmental fatigue effects under constant amplitude and FALSTAFF loading, the latter being a realistic cyclic load history for tactical aircraft.

In retrospect we consider the objectives of the CFCTP and FACT programmes to have been achieved, though much remains to be done to increase the understanding of aircraft corrosion fatigue and the effectiveness of protection systems. We hope this report will encourage further investigation in this difficult and challenging area of aerospace technology.

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3. "Description of a Fighter Aircraft Loading STAndard For Fatigue evaluation", Combined Report of the F+W, LBF, NLR and IABG, March 1976.

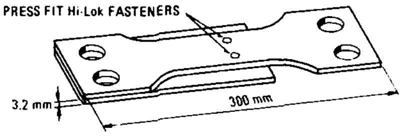
4. J.B. de Jonge, "Additional information about FALSTAFF", NLR Technical Report TR 79056 U, June 1979.

5. H. Lowak, J.B. de Jonge, J. Franz and D. Schütz, "MINITWIST. A shortened version of TWIST", Combined Report of the LBF and NLR, NLR Miscellaneous Publication MP 79018 U, May 1979.

TABLE 1: OVERVIEW OF THE CFCTP CORE PROGRAMME

CFCTP CORE PROGRAMME

MATERIAL
- 3.2 mm thick 7075-T76 aluminium alloy sheet

SPECIMEN
- 

PROTECTION SYSTEM
- Chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat

PROTECTION SYSTEM DAMAGE
- Two stress cycles at low temperature (209 ± 10 K) to crack primer and paint around the fastener heads

FATIGUE LOADING
- Constant amplitude, $S_{min}/S_{max} = 0.1$

FATIGUE ENVIRONMENTS
- Laboratory air; 5 % aqueous NaCl salt spray with pH 4 at 295 K

STATIC PRE-EXPOSURE
- 72 hours in 5 % aqueous NaCl + SO_2 at 315 K

TEST PROGRAMME
-

SCHEDULES	NUMBER OF SPECIMENS		CYCLE FREQUENCY
	S_{max} = 210 MPa	S_{max} = 144 MPa	
Fatigue in air	4	4	2 Hz
Pre-exposure + fatigue in air	4	4	
Fatigue in salt spray	4	4	0.5 Hz
Pre-exposure + fatigue in salt spray	4	4	

STATISTICAL ANALYSIS
- Fatigue lives and primary fatigue origins

PARTICIPANTS
- (1) Naval Air Development Centre NADC, Warminster, Pennsylvania USA.
  (2) University of Saskatchewan, Saskatoon, Canada.
  (3) Vought Corporation, Dallas, Texas, USA.
  (4) Air Force Wright Aeronautical Laboratories AFWAL, Dayton, Ohio, USA.
  (5) National Aerospace Laboratory NLR, Emmeloord, The Netherlands.
  (6) Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfahrt DFVLR, Cologne, Germany.
  (7) Norwegian Defence Research Establishment NDRE, Kjeller, Norway.
  (8) Royal Aircraft Establishment RAE, Farnborough, United Kingdom.
  (9) University of Toronto SIFFRL, Toronto, Canada.
  (10) University of Pisa, Pisa, Italy.

TABLE 2: SUMMARY OF THE TECHNICAL MANUAL FOR THE CFCTP CORE PROGRAMME AND ALSO SUPPLEMENTAL TESTING (THE FACT PROGRAMME)

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TABLE 3: OVERVIEW OF THE FACT SUPPLEMENTAL PROGRAMME

PARTICIPANTS	IDENTICAL MATERIALS	CFCTP CORE PROGRAMME PROTECTION SYSTEM	MAIN ASPECTS OF THE INDIVIDUAL PROGRAMMES						
			MATERIAL COMPARISONS		PROTECTION SYSTEM COMPARISONS	FASTENER COMPARISONS	FATIGUE LOADING COMPARISONS (C.A. - CONSTANT AMPLITUDE)	ENVIRONMENTS OTHER THAN THOSE IN THE CFCTP CORE PROGRAMME	TYPES OF TESTS
			DIFFERENT MATERIALS	DIFFERENT HEAT TREATMENTS					
VOUGHT		●					C.A. with marker loads	● salt spray at various temperatures	single dogbone fatigue life and crack propagation
SAAB	● 7075-T76	●	● 7075-T6 clad		● 7075-T6 clad with and without anodising		C.A. only	● pre-exposure outdoors for 7075-T6; fatigue with repeated condensation or alternate immersion in distilled water	unnotched and 14 dogbone fatigue life
NADC	● 7075-T76	●			● standard and flexible primers	● press and interference fit Hi-Loks	C.A. only		14 dogbone fatigue life
AFWAL	● 7075-T76	●			● Hi-Loks with and without sealant	● press fit Hi-Loks, SLEEVbolts	● C.A., FALSTAFF		
NDRE	◑ 7075-T6	●		● 7075 in T76 and T6RRA conditions			● C.A., FALSTAFF		
NLR/LRTH	◑ 7075-T6 ○ 7475-T761 clad		● 2024 T3 Alclad 2024-T3/aramid fibre laminates, 7075-T6, 7475-T761 clad		● F 28, NF-5 systems; F-16 system with and without sealant		● C.A., FALSTAFF, MINITWIST		
IABG	● 7075-T76 ◑ 7075-T6 ○ 7475 T761 clad	●	● 7075-T6, 7075-T76, 7475-T761 clad		● CFCTP core programme and MRCA systems		FALSTAFF only		
RAE	◑ 7075-T6				● inhibited and non-inhibited primers		● C.A. only		
				● 7010 in T7651 and T7451 conditions			● C.A., FALSTAFF		fatigue strength
			● 7010-T7X51, 7475 T7351, 7050-T7451	● 7010 in T7651 and T7451 conditions			● C.A., FALSTAFF		fatigue crack propagation
NRC				● 7075 in T651, T6RRA and T7351 conditions			C.A. only	● argon, 3.5 % aqueous NaCl	

PART II

REASSESSMENT OF THE CFCTP CORE PROGRAMME

1. INTRODUCTION

The CFCTP core programme consisted of round-robin testing whose primary purpose was to establish whether participants could obtain confidence in one another's fatigue testing capabilities with the added dimension of a controlled atmospheric corrosion environment. The programme was designed to be sufficiently straightforward to encourage participation, particularly by those with relatively little experience of corrosion fatigue testing.

Originally there were eight participants to the CFCTP. The results were published in an AGARD report in 1982 (reference 1). Since then two more participants completed the core programme. The results have been included in a reassessment of the CFCTP. This reassessment involves "fine tuning" of the statistical methods originally used to analysed the CFCTP data and is presented here.

2. DESCRIPTION OF THE CFCTP CORE PROGRAMME

An overview of the CFCTP core programme is given in table 1. The CFCTP specified identical conditions for the following parameters: material and heat treatment, specimen configuration, protection system, mechanical testing and environmental conditions. These parameters are discussed in more detail in sections 2.1 - 2.4. Summaries of the test procedure and statistical methods for analysing the results are given in sections 2.5 and 2.6.

2.1 *Material and Specimen Configuration*

The material was 3.2 mm thick 7075-T76 bare aluminium alloy sheet from one heat and supplied by ALCOA especially for the CFCTP. The engineering properties were specified as follows:

0.2 % YIELD STRESS	UTS	ELONGATION	CONDUCTIVITY
479 MPa (max) 455 MPa (min)	550 MPa (max) 541 MPa (min)	11.0 %	38 % I.A.C.S.

Figure 1 shows the specimen configuration. This was recommended for the FACT supplemental programme also. The specimen is a 1½ dogbone mechanically fastened by cadmium plated steel Hi-Loks. It was designed to simulate the load transfer and secondary bending characteristics of runouts of stiffeners attached to the outer skin of an airframe structure. The design goals were a load transfer of 40 % and a secondary bending ratio of 0.5 (reference 2). These characteristics have been checked and the actual values are generally lower, see Appendix I.

All prior-to-assembly specimen blanks for the CFCTP were manufactured in one batch by the U.S. Air Force Wright Aeronautical Laboratories AFWAL. The fastener holes of all specimens for the first eight participants listed in table 1 were drilled to press fit dimensions in one batch at the U.S. Naval Air Development Centre NADC. However, to enable the remaining two participants to complete the core programme it was necessary to disassemble some interference fit supplemental programme specimens, redrill to press fit dimensions and reassemble. It turned out that this procedure significantly influenced the fatigue results, as will be discussed in section 3.2.

2.2 Protection System and Specimen Assembly

Application of the CFCTP protection system and specimen assembly were done by the NADC as follows:

- chromate conversion coating on all surfaces
- inhibited epoxy polyamide primer on all surfaces except fastener holes
- assembly of fatigue specimen -1 and half plate -2 with Hi-Lok fasteners and collars, see figure 1
- inhibited epoxy polyamide primer on fastener head and collar areas
- aliphatic polyurethane topcoat on all exterior surfaces.

The specimens were then wrapped individually and shipped in batches to the participants.

2.3 Mechanical Testing Conditions (Static Prestressing and Fatigue)

All stresses were defined in terms of the total cross-section of the fatigue specimen -1 at the location of the centreline between the Hi-Lok fasteners, i.e. the fastener holes were included in the cross-sectional area.

Before environmental exposure and fatigue testing the CFCTP specimens were prestressed in cold boxes at 209 ± 10 K by applying two quasi-static load cycles up to a maximum stress of 215 MPa. The purpose was to crack the primer and paint realistically in the fastener head areas.

Fatigue testing was done using constant amplitude sinusoidal loading with a stress ratio $R = S_{min}/S_{max}$ of 0.1. It was decided to test at two stress levels giving nominal fatigue lives of 20,000 and 100,000 cycles for uncorroded specimens fatigued in laboratory air. From pilot tests (reference 1) the following fatigue stress levels were established for the CFCTP:

NOMINAL UNCORRODED FATIGUE LIFE	S_{max}	S_{min}
20,000 cycles	210 MPa	21 MPa
100,000 cycles	144 MPa	14.4 MPa

2.4 Environmental Conditions (Pre-exposure, Fatigue and Corrosion Fatigue)

There were four testing schedules for the CFCTP, see also table 1:

- fatigue in air, cycle frequency 2 Hz
- pre-exposure + fatigue in air at 2 Hz
- fatigue in salt spray, cycle frequency 0.5 Hz
- pre-exposure + fatigue in salt spray at 0.5 Hz.

Specimens to be pre-exposed and/or fatigued in salt spray were sealed at faying surface side edges and Hi-Lok collars in order to prevent corrosion except in the fastener head areas. Pre-exposure was for 72 hours in 5 % aqueous NaCl salt solution to which a predetermined amount of SO_2 gas was added by reacting Na_2SO_3 pellets with H_2SO_4. This reaction was accomplished in vented test tubes suspended above the salt solution, which was maintained at a temperature of 315 ± 2 K.

For fatigue testing all specimens were electrically insulated from the loading grips and bolts by polymeric liners and bushings. The environments were laboratory air and 5 % aqueous NaCl salt spray acidified with H_2SO_4 to pH 4, both at a nominal temperature of 295 K. The salt spray tests were done in specially constructed cabinets, fully described in reference (1).

2.5 Summary of the Test Procedure

A schematic summary of the CFCTP test procedure is shown in figure 2. This gives some idea of the complexity of even a fairly straightforward programme, which is why a technical manual was prepared as already mentioned in Part I of this report. The technical manual is published in reference (1).

One part of the test procedure was modified after analysis of results from the original eight participants. The technical manual had specified fatigue testing as soon as possible after pre-exposure and cleaning, with desiccator storage only if delay were unavoidable. However, this was later amended to require desiccator storage for at least one week after cleaning, in order to ensure the specimens were completely dry before fatigue testing.

2.6 Summary of the Statistical Methods for Data Analysis

A detailed description of the statistical methods used to analyse the CFCTP fatigue life and primary fatigue origin data is given in Appendix II. Statistical analysis was done with the primary purpose of checking whether participants could have confidence in one another's fatigue testing capabilities, i.e. the results were analysed primarily to determine whether one or more laboratories had obtained data significantly different from those of the remaining laboratories. The statistical analysis also had several secondary purposes, namely to determine

- whether pre-exposure was significant for subsequent fatigue life in air or salt spray
- whether the effect of fatigue in salt spray, with or without pre-exposure, was significant compared to fatigue in air with or without pre-exposure
- whether there were significant differences between laboratories in the relative effects of pre-exposure and/or fatigue in salt spray (this is part of the primary purpose)
- whether the sample size (4 specimens per test condition per participant) was sufficient and whether there were noticeable differences in data scatter between laboratories and fatigue testing schedules
- whether there were relationships between the locations of primary fatigue origins, fatigue stress levels, environmental conditions and fatigue lives.

A survey of the statistical methods and procedure is given in figure 3. The fatigue life data were first checked for normality and homogeneity of variances (approximate compliance with these conditions is sufficient) as a prerequisite to further treatment. The main statistical analysis was multiple factor analysis of variance. This was followed by "fine tuning" using the least significant difference test or Duncan's new multiple range test (references 3, 4). To avoid possible misuse the least significant difference test was applied only when analysis of variance indicated significant effects. In addition, scatter in the data was used to check for adequate sample size (four specimens per test condition per participant) according to a method described in reference (5).

The primary fatigue origin data were analysed using the χ^2 test of independence, Yates' corrected χ^2 test or Fisher's exact test, whichever was appropriate. For these tests it is sufficient to assume only that the data constitute a random sample (reference 6). These tests were also used (as appropriate) to check whether there were significant correlations between fatigue lives and primary origins for each test condition.

3. RESULTS

The CFCTP core programme fatigue life and primary fatigue origin results are compiled in table 2, which also indicates the originally interference fit specimens that were disassembled, redrilled to press fit dimensions and reassembled. The primary fatigue origin data are those obtained by one of the programme coordinators (R.J.H.W.), who also supplied the remarks concerning fatigue fracture surfaces of pre-exposed specimens tested in air.

The fatigue life results are presented and statistically analysed in sections 3.1 and 3.? respectively. This is followed by presentation and statistical analysis of the primary fatigue origin data in section 3.3. Correlations between fatigue lives and primary fatigue origins are discussed in section 3.4.

3.1 Presentation of Fatigue Life Data

The fatigue life data are presented in figures 4 and 5 in terms of log mean life and data range for each fatigue testing schedule and for each participant. There is a clear separation of the data with respect to stress level, as expected. Figure 5 shows a general tendency for shorter lives owing to fatigue in salt spray with or without pre-exposure, though individual trends vary.

3.2 Statistical Analysis of Fatigue Life Data

3.2.1 Checking for normality

In checking for normality the CFCTP core programme data were considered to belong to eight different populations corresponding to each of the four fatigue testing schedules in combination with each of the two stress levels. The χ^2 test for goodness of fit (references 6, 7 and see Appendix II) showed that data for six of the populations were log-normally distributed and data for the other two (fatigue in air with $S_{max} = 210$ MPa and pre-exposure + fatigue in air with $S_{max} = 144$ MPa) were approximately log-normal. A subjective impression of these results is provided by the logarithmic normal probability plots in figure 6. Because of the log-normal distributions all further statistical treatment of the data used the logarithms of the fatigue lives.

3.3.2 Checking for homogeneity of variances

As shown in figure 3, the Box test (reference 8) was used to check for interlaboratory differences in variances. To do this the data from different laboratories were considered to come from different populations. This resulted in eighty populations corresponding to data from each of the ten participants for each of the four fatigue testing schedules in combination with each of the two stress levels. The Box test results are summarised in table 3. There were two very slight violations and one moderate violation of the criterion for homogeneity of variances.

The Bartlett test (reference 8) was used to check for differences in variances between fatigue test conditions. To do this the data for each fatigue testing schedule and stress level were treated as coming from the same population, i.e. no distinction was made between the data from different laboratories. In view of the Box test results this assumption is not strictly correct. However, it is considered justified. The Barlett test results are summarised in table 4. There were three moderate violations of the criterion for homogeneity of variances.

As mentioned in section 2.6, approximate compliance with the requirement of homogeneity of variances is sufficient for further statistical analysis. In the present work the main technique of statistical analysis was multiple factor analysis of variance. This is a very robust, i.e. "forgiving", technique. Thus the results summarised in tables 3 and 4 were considered sufficient for continuing the statistical treatment of the fatigue life data.

3.2.3 Main statistical analysis: analysis of variance

Multiple factor (three-way) analysis of variance was used to compare the CFCTP core programme fatigue life data in terms of the experimental variables of stress level, fatigue testing schedule (environmental effects) and laboratory. The results are shown in table 5.

According to the analysis the main variables of stress level, fatigue testing schedule and performing laboratory all had significant effects on the fatigue lives of the specimens. The significant effect attributable to stress level and fatigue testing schedule were anticipated from the way the CFCTP core programme was planned. However, determination of whether there were significant effects attributable to differences between laboratories was the primary purpose of the core programme.

A significant effect was also indicated for the interaction between stress level and fatigue testing schedule. This means that the stress level and fatigue testing schedule significantly affected the fatigue lives.

3.2.4 *"Fine tuning" with the least significant difference test*

As shown in figure 3, significant effects indicated by analysis of variance were investigated in more detail ("fine tuning") using the least significant difference test. However, this was not necessary for the effect of stress level: since there were only two stress levels it is obvious that the significant difference is between them. Thus the significant effects investigated were

- environment
- laboratory
- stress: environment.

In the first instance the fatigue life data from all ten participants were analysed. This showed that data from two participants (SIFFRL and the University of Pisa) were significantly different from the rest. Because SIFFRL and the University of Pisa were the only participants to have tested specimens that had been disassembled, redrilled to press fit dimensions and reassembled (see table 2) it was decided to conduct an additional analysis omitting the data for these specimens. The results are given in table 6. Note that omission of data for reassembled specimens resulted in unequal sample sizes, so that a modified version of the least significant difference test had to be used. This modified version of the test is also discussed in Appendix II.

Table 6 shows the following:

(1) The effects of different fatigue testing schedules (environmental effects) were significant and consistent at both stress levels. The effect of pre-exposure was similar to that of changing the fatigue environment from air to salt spray.

(2) The SIFFRL and University of Pisa data were significantly different from the other participants' data.

(3) A significant interlaboratory difference was also found between the AFWAL data and those for the University of Saskatchewan, Vought, DFVLR and NDRE.

3.2.5 "Fine tuning" with Duncan's new multiple range test

As shown in figure 3, Duncan's new multiple range test was used to investigate in more detail the experimental variables (in the present case their interactions) that were not found to be significant by analysis of variance. These interactions were

- stress: laboratory
- environment: laboratory
- stress: environment: laboratory.

As before, it was found that the SIFFRL and University of Pisa data were significantly different from the rest. Thus the fatigue life data were analysed both with and without data for specimens that had been disassembled, redrilled to press fit dimensions and reassembled (see table 2). Table 7 lists significant differences indicated by Duncan's test, which in the case of omitting data for reassembled specimens was modified because of unequal sample sizes. This modified version of the test is also discussed in Appendix II.

Table 7 shows the following:

(1) A clear indication that the SIFFRL and University of Pisa data were significantly different from the other participants' data.

Excluding the SIFFRL and University of Pisa data,

(2) At S_{max} = 144 MPa there were significant differences between the AFWAL total log mean fatigue life and those for the DFVLR and NDRE.

(3) There were some significant differences in log mean fatigue lives for the fatigue testing schedules of pre-exposure + fatigue in air and fatigue in salt spray. In more detail these significant differences were found only for S_{max} = 210 MPa.

3.2.6 Checking for adequate sample size and differences in data scatter

Scatter in the CFCTP core programme fatigue life data was used to check for adequacy of sample size (four specimens per test condition per participant). The method used is due to Lipson and Sheth (reference 5) and involves selecting an acceptable error level, usually 5 % or 10 %, and finding the required sample size for a particular confidence level. The sample size check has two purposes, namely

- to find the combination of error and confidence levels for which the actual sample size was sufficient
- to give an indication of differences in data scatter between laboratories and fatigue test conditions.

The actual sample size was sufficient for the combination of 10 % error and 90 % confidence levels except for one case: pre-exposure + fatigue in air at S_{max} = 144 MPa by the University of Pisa. There was thus a generally low scatter in the data and high reproducibility of the specimens and testing conditions for each participant.

To indicate differences in data scatter the required sample sizes were determined for the combination of 5 % error and 90 % confidence levels and are shown in table 8. The shaded regions denote exceedance of the actual sample size, and since a larger required sample size reflects greater scatter the results indicate

(1) More persistent scatter for the RAE data.

(2) The amount of scatter tended to increase with complexity of testing. This is particularly noticeable for pre-exposure + fatigue in salt spray.

(3) For pre-exposure + fatigue in air there was much more scatter at the higher maximum stress level of 210 MPa.

3.3 Presentation of Primary Fatigue Origin Data

As mentioned at the beginning of section 3, the primary fatigue origin data are compiled in table 2. In the last column of this table there are remarks concerning specimens pre-exposed and fatigued in air. Some of these specimens had corroded fracture surfaces near and at the primary fatigue origins. This indicated that an aqueous solution was present inside the specimens during fatigue testing, even though a detailed cleaning and drying procedure was specified to follow pre-exposure (reference 1).

Table 9 classifies the fatigue life and primary fatigue origin data for all specimens pre-exposed and fatigued in air. For both stress levels the log mean fatigue lives of corroded specimens were significantly shorter than those for uncorroded specimens. This was confirmed by statistical analysis that omitted the data for interference fit specimens disassembled, redrilled to press fit dimensions and reassembled. The statistical techniques used were a variance-ratio test to check for homogeneity of variances and the t-statistic evaluation to compare two means. These tests are described in references (9, 10).

It is concluded that an aggressive aqueous solution was present inside the specimens with corroded fracture surfaces. Most probably this was acidified aqueous NaCl remaining from pre-exposure. Information on time delays between cleaning and drying pre-exposed specimens and fatigue testing in air was supplied by the participants. There was no strong correlation between time delays and subsequent fatigue lives and corroded fracture surfaces. However, from the NLR and AFWAL information it appeared that storing the specimens for several days in desiccators resulted in relatively long fatigue lives and uncorroded fracture surfaces, see table 2. This was considered sufficient ground for amending the cleaning procedure to require desiccator storage for at least one week, as mentioned in section 2.5 and specified in detail in reference (1). This amendment was made only after CFCTP core programme data had been received from the original eight participants. Of the remaining two, SIFFRL included desiccator storage but the University of Pisa fatigue tested the specimens immediately after cleaning. Table 2 shows that corroded fracture surfaces were not found for the SIFFRL specimens but were present in four of the University of Pisa specimens. This is additional evidence that desiccator storage was effective in drying the specimens completely.

Despite the significant effect of insufficient drying on the fatigue lives of specimens pre-exposed and fatigued in air, table 9 shows there was no essential difference in the locations of primary fatigue origins in specimens with corroded and uncorroded fracture surfaces. Thus it was felt that all the fatigue origin data in table 2 could be classified together.

3.3.1 Classification of all primary fatigue origins

The primary fatigue origin data are classified in table 10. The table has four sub-divisions, which will be discussed consecutively:

(1) Listing the total numbers of each type of primary fatigue origin shows

- most failures began in the bores (E/Q) or at the bore/faying surface corners (F/R) of fastener holes: there was no evident preference with respect to outer (E,F) or inner (Q,R) sides of the holes
- failures at faying surfaces (G/S) occurred mainly to the outside of fastener holes (G) probably because the proximity of free edges facilitated relative displacements between the fatigue specimen -1 and half plate -2 (see figure 1), thereby promoting fretting fatigue initiation
- very few failures initiated in the countersink areas: most were at the surface edges to the outsides of fastener holes (B).

(2) Listing the primary fatigue origins for specimens tested by each participant reveals some interlaboratory differences. Possibly the most significant difference is that specimens tested by SIFFRL and the University of Pisa had more bore/faying surface corner (F/R) primary origins than specimens from other participants.

(3) The third part of table 10 gives a complete breakdown of the locations of primary fatigue origins with respect to stress level and fatigue testing schedule.

(4) The last part of table 10 adds up the total numbers of primary fatigue origins per stress level and fatigue environment.

The data distribution in parts (3) and (4) of table 10 reveals a predominant effect of stress level on the locations of primary fatigue origins. Thus stress level has been treated as the primary variable in preparing figure 7, which supplements table 10. The table and figure show that

- stress level had a major effect:
  - for S_{max} = 210 MPa the primary fatigue origins were mainly in the bores of fastener holes
  - for S_{max} = 144 MPa the primary fatigue origins were mainly at the bore/faying surface corners and the faying surfaces
- the effect of fatigue environment was significant: changing from fatigue in air to fatigue in salt spray promoted initiation in the bores or at the bore/faying surface corners of fastener holes and reduced the number of failures initiating at the faying surfaces
- pre-exposure resulted in several effects:
  - relatively more primary fatigue origins in the bores of fastener holes
  - a few primary fatigue origins at the surface edges of countersinks
  - slightly fewer primary fatigue origins at the bore/faying surface corners of fastener holes
  - reduction of the number of failures initiating at the faying surfaces.

The effects of pre-exposure and/or fatigue in salt spray may be summarised as especially promoting failure initiation in the bores of fastener holes.

3.3.2 Statistical analysis of primary fatigue origin data

The χ^2 test of independence and the Yates' corrected χ^2 test were used to determine whether there was a significant association between the locations of primary fatigue origins and the experimental variables of stress level and fatigue testing schedule (environmental effects). The SIFFRL and University of Pisa data were omitted because they were considered non-representative. The results are summarised in table 11. This confirms the impression gained from table 10 and figure 7 that both stress level and fatigue testing schedule had significant effects on the primary fatigue origin locations.

Note that for S_{max} = 210 MPa there is no significant association between environmental effects and primary fatigue origin locations. This is because the higher stress level and changing from fatigue in air to pre-exposure and/or fatigue in salt spray had similar effects on the primary fatigue origin locations, i.e. promotion of failure initiation in the bores of fastener holes.

3.4 Correlation of Fatigue Lives and Primary Origins of Fatigue

Owing to the results of the statistical analysis of fatigue lives, section 3.2, it was decided to omit the SIFFRL and University of Pisa data from the correlation of fatigue lives and primary origins of fatigue.

Correlations of the fatigue lives and primary fatigue origins for the original eight participants in the CFCTP core programme are given in table 12 and figures 8 and 9. Note that the two failures at the surface edges of countersinks (B) for pre-exposure + fatigue in air at S_{max} = 210 MPa have been omitted from figure 8 since there were no similar failures for other fatigue testing schedules at the same stress level. The correlations indicate the following:

(1) From figure 8 it is seen that there are no generally consistent relations between primary fatigue origin locations and the fatigue lives for each test condition. However,

- for fatigue in air and pre-exposure + fatigue in air at S_{max} = 210 MPa the initiation of failures in the bores and at the bore/faying surface corners of fastener holes tended to result in shorter lives than failure initiation at other locations.
- for fatigue in salt spray and pre-exposure + fatigue in salt spray at S_{max} = 144 MPa the initiation of failures at the bore/faying surface corners of fastener holes tended to result in shorter lives than failure initiation at other locations.

(2) From figure 9 it is seen that for S_{max} = 144 MPa the effect of pre-exposure and/or fatigue in salt spray in reducing fatigue life was more pronounced for specimens in which failure initiated at the bore/faying surface corners of fastener holes as compared to other locations.

Yates' corrected χ^2 test (reference 11) and Fisher's exact test (reference 12) were used to determine whether there were statistically significant associations between the locations of primary fatigue origins and the fatigue lives for each test condition, i.e. each combination of stress level and fatigue testing schedule. The results are summarised in table 13. A significant association between primary fatigue origin locations and fatigue lives was found only for fatigue in salt spray at S_{max} = 144 MPa. This agrees with one of the trends noted from figure 8. It is concluded that the other three trends, namely an association between primary fatigue origin locations and fatigue lives for fatigue in air and pre-exposure + fatigue in air at S_{max} = 210 MPa and pre-exposure + fatigue in salt spray at S_{max} = 144 MPa, are not sufficiently well-founded.

4. DISCUSSION

4.1 Primary Purpose of the CFCTP Core Programme

As mentioned at the beginning of this Part of the report, the primary purpose of the CFCTP core programme was to establish whether participants could obtain confidence in one another's fatigue testing capabilities with the added dimension of a controlled atmospheric corrosion environment.

Statistical analysis showed that the SIFFRL and University of Pisa fatigue life results were significantly different from those of the original eight participants. A partial explanation is available. To supply the University of Pisa with CFCTP-type specimens it was necessary to disassemble interference fit specimens, redrill to press fit dimensions and reassemble. This procedure apparently caused significant reductions in the fatigue lives, especially at the lower stress level of S_{max} = 144 MPa. These fatigue life reductions may well be related to an increased tendency for failure to initiate at bore/faying surface corners of fastener holes in the University of Pisa specimens, see table 10.

In the case of the SIFFRL specimens, only six had been disassembled, redrilled and reassembled. The rest should have been nominally identical to the first batch of specimens delivered to the original eight participants, but it appears they were not. It is worth noting that the SIFFRL fatigue life data were significantly different from those of the original eight participants mainly on the basis of straightforward fatigue testing in air, see figure 4 and tables 2 and 7. This means that the source of the difference is unlikely to have been different environmental conditions (pre-exposure and/or fatigue in salt spray).

Excluding the SIFFRL and University of Pisa fatigue life data does not remove all the significant differences found by statistical analysis. However, the remaining significant differences were few and not consistently found:

(1) The least significant difference test indicated a significant interlaboratory difference between the AFWAL data and those for the University of Saskatchewan, Vought, DFVLR and NDRE, table 6.

(2) Duncan's new multiple range test indicated a significant interlaboratory difference between the AFWAL data with S_{max} = 144 MPa and those for the DFVLR and NDRE, table 7.

(3) In more detail, Duncan's test (table 7) indicated significant differences for

- pre-exposure + fatigue in air at S_{max} = 210 MPa between Vought and the NADC and DFVLR; and between the NLR and the NADC, University of Saskatchewan, DFVLR, NDRE and RAE
- fatigue in salt spray at S_{max} = 210 MPa between Vought and the University of Saskatchewan, DFVLR and RAE.

An important factor in the significant differences found for pre-exposure + fatigue in air at S_{max} = 210 MPa was insufficient drying of some specimens after pre-exposure, resulting in shorter fatigue lives and corroded fracture surfaces. The relevant data have been re-analysed by separating out the specimens with corroded fracture surfaces. The results are given in table 14. All of the previously indicated significant differences have been eliminated.

In view of there being only a very few unexplained significant differences found by statistical analysis and the generally low data scatter (see section 3.2.6) it is concluded that

- with the exception of the unamended cleaning and drying procedure after pre-exposure, the first batch of CFCTP core programme specimens and the mechanical and environmental testing conditions were highly reproducible
- the original eight participants in the CFCTP core programme can have confidence in each other's results.

In other words, with the exception of the two later participants, SIFFRL and the University of Pisa, the primary purpose of the CFCTP core programme has been achieved.

It is most unfortunate that the SIFFRL and University of Pisa results were significantly different from the rest. However, on the positive side these later results emphasize how important and necessary it was to do the CFCTP core programme, to provide a detailed technical manual for mechanical and environmental testing, and to supply the original eight participants with specimens from one batch.

4.2 Environmental Effects

Statistical analysis of the CFCTP core programme fatigue life data showed that the effects of different fatigue testing schedules (environmental effects) were significant and consistent at both stress levels. Both pre-exposure and fatigue in salt spray significantly reduced the fatigue lives, especially in combination. An overall impression of these results is provided by figure 10, which also separates out the data for specimens found to have uncorroded fracture surfaces after pre-exposure + fatigue in air. Figure 10 shows two additional trends:

(1) Environmental effects were relatively greater for the higher S_{max} of 210 MPa: many environmental fatigue data in the literature show that the reverse trend would be expected.

(2) The statistical result that the effect of pre-exposure was similar to that of changing the fatigue environment from air to salt spray (see table 6) is a consequence of including data for specimens that had corroded fracture surfaces after pre-exposure + fatigue in air.

4.2.1 Dependence of environmental effects on stress level

In sections 3.3.1 and 3.3.2 it was shown that stress level was a major variable controlling the locations of primary fatigue origins, see figure 7 and tables 10 and 11. For S_{max} = 210 MPa most failures began in the bores of fastener holes. On the other hand, for S_{max} = 144 MPa most failures began at bore/faying surface corners and the faying surfaces.

Pre-exposure and/or fatigue in salt spray especially promoted failure initiation in the bores of fastener holes. It is most likely that environmental effects will be greater when they promote characteristic failure modes. This explains why the observed environmental effects were relatively greater for S_{max} = 210 MPa.

There is an important conclusion to be drawn from this explanation of why the environmental effects were relatively greater for a higher stress level, in contrast to many other data in the literature. Correct assessment of environmental effects requires the specimens to be realistic. The CFCTP core programme specimens were designed to closely simulate a fatigue critical structural joint and their behaviour is more likely to be representative than that of simple coupons, which constitute the majority of specimens used in environmental fatigue testing.

4.2.2 Environmental effects and fatigue life data scatter

As table 8 shows, there was a general trend for fatigue life data scatter to increase with complexity of testing, i.e. when the environmental variables of pre-exposure and fatigue in salt spray were included in the testing schedules.

For pre-exposure + fatigue in air there was much more scatter in the fatigue life data at the higher S_{max} of 210 MPa. This is an unusual result, since scatter usually decreases with increasing stress level. The explanation lies in the variable effect of insufficient drying of some specimens after pre-exposure. Insufficient drying caused significantly reduced fatigue lives and corroded fracture surfaces, and there were many more such specimens fatigue tested at S_{max} = 210 MPa, see table 9.

4.3 Primary Fatigue Origin Locations

As discussed previously, stress levels and fatigue testing schedules (environmental effects) had significant effects on the locations of primary fatigue origins in the CFCTP core programme specimens. This is shown in figure 7 and tables 10 and 11. Also, there were some indications that for a given fatigue testing schedule the initiation of failures in the bores and at the bore/faying surface corners of fastener holes resulted in shorter fatigue lives than failure initiation at other locations, see figure 8 and table 13.

It is evident that examination with respect to primary fatigue origins and fracture surfaces was essential for understanding the fatigue behaviour of the CFCTP core programme specimens. In fact, such examination should always be done when investigating the fatigue behaviour of realistic specimens.

5. CONCLUSIONS

The CFCTP core programme of round-robin testing has demonstrated that

(1) The original eight participants may be confident in one another's environmental fatigue testing capabilities.

(2) With the exception of the unamended cleaning and drying procedure after pre-exposure, the first batch of CFCTP core programme specimens and the mechanical and environmental testing conditions were highly reproducible. (The amended cleaning and drying procedure is reproducible and should be adopted in further tests).

(3) Environmental effects on fatigue lives were significant and consistent.

(4) Realistic specimens are necessary for correct assessment of environmental effects.

(5) Examination with respect to fatigue origins and fracture surfaces is essential.

Finally we conclude that, for at least the original eight participants, supplemental testing programmes directed to the requirements of individual participants may be carried out with confidence that the results from different laboratories can be compared.

6. ACKNOWLEDGEMENTS

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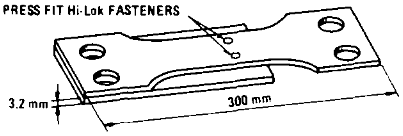
TABLE 1: OVERVIEW OF THE CFCTP CORE PROGRAMME

CFCTP CORE PROGRAMME

MATERIAL

- 3.2 mm thick 7075-T76 aluminium alloy sheet

SPECIMEN

- 

PROTECTION SYSTEM

- Chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat

PROTECTION SYSTEM DAMAGE

- Two stress cycles at low temperature (209 ± 10 K) to crack primer and paint around the fastener heads

FATIGUE LOADING

- Constant amplitude, $S_{min}/S_{max} = 0.1$

FATIGUE ENVIRONMENTS

- Laboratory air; 5 % aqueous NaCl salt spray with pH 4 at [illegible]

STATIC PRE-EXPOSURE

- 72 hours in 5 % aqueous NaCl + SO_2 at 315 K

TEST PROGRAMME

-

SCHEDULES	NUMBER OF SPECIMENS		CYCLE FREQUENCY
	S_{max} = 210 MPa	S_{max} = 144 MPa	
Fatigue in air	4	4	2 Hz
Pre-exposure + fatigue in air	4	4	
Fatigue in salt spray	4	4	0.5 Hz
Pre-exposure + fatigue in salt spray	4	4	

STATISTICAL ANALYSIS

- Fatigue lives and primary fatigue origins

PARTICIPANTS

- (1) Naval Air Development Centre NADC, Warminster, Pennsylvania USA.
(2) University of Saskatchewan, Saskatoon, Canada.
(3) Vought Corporation, Dallas, Texas, USA.
(4) Air Force Wright Aeronautical Laboratories AFWAL, Dayton, Ohio, USA.
(5) National Aerospace Laboratory NLR, Emmeloord, The Netherlands
(6) Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfahrt DFVLR, Cologne, Germany.
(7) Norwegian Defence Research Establishment NDRE, Kjeller, Norway
(8) Royal Aircraft Establishment RAE, Farnborough, United Kingdom.
(9) University of Toronto SIFFRL, Toronto, Canada.
(10) University of Pisa, Pisa, Italy.

TABLE 2: FATIGUE LIFE AND PRIMARY ORIGIN DATA FOR THE CFCTP CORE PROGRAMME

PARTICIPANTS	FATIGUE LIFE TO FAILURE (CYCLES AND LOG MEAN CYCLES)/LOCATIONS OF PRIMARY ORIGINS OF FATIGUE*								REMARKS CONCERNING FATIGUE FRACTURE SURFACES OF PRE-EXPOSED SPECIMENS TESTED IN AIR
	S_{max} = 210 MPa				S_{max} = 144 MPa				
	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	
[illegible]	18,705 Q 25,606 F 25,894 Q 28,134 S 24,304	4,997 F 6,33[illegible] [illegible] 10,970 F 16,458 F 8,675	11,737 E 11,360 Q 7,935 E 7,563 E 9,457	16,770 Q 8,015 Q 4,603 E 8,354 E 8,479	76,186 F 133,611 R 147,107 F 199,893 G 131,533	96,085 G 106,206 S 109,712 S 234,4[illegible] F 12[illegible],282	143,434 G 150,663 Q 122,092 [illegible] 73,92[illegible] R 118,1[illegible]	[illegible] R [illegible] F [illegible] G [illegible] B [illegible]	corroded fracture surfaces for three specimens tested at 210 MPa
[illegible] OF [illegible] MEAN	9,180 Q 13,800 Q,R 21,850 Q,R 26,950 R 16,527	18,310 F 7,985 [illegible] 10,093 E 13,023 E 11,772	12,626 E,F 18,577 F 17,893 Q 10,298 E 14,418	8,841 F 5,352 Q 5,006 E 8,129 Q 6,624	419,690 F 59,710 G 109,340 G 107,050 S 130,869	111,470 S 122,340 F 82,483 S 126,596 R [illegible]	78,088 G 104,090 F 46,046 F 145,818 R 85,951	[illegible] E [illegible] G 65,121 G [illegible] G [illegible]	corroded fracture surfaces for three specimens tested at 210 MPa
	12,165 R 25,841 Q 20,494 E 24,235 E 19,878	28,562 G 20,1[illegible]8 F [illegible] E [illegible] F [illegible]	7,163 E 4,933 Q 6,373 E [illegible] R 6,172	3,763 E 7,791 E 9,395 Q 9,538 E 7,158	176,242 R [illegible] F [illegible] S [illegible] S [illegible]	119,0[illegible] G [illegible] F [illegible] [illegible] F [illegible]	122,468 Q 54,920 R [illegible] 35,331 R 83,884	[illegible] Q [illegible] B [illegible] R [illegible] F [illegible]	corroded fracture surfaces for one specimen tested at 210 MPa and one at 144 MPa
	22,300 Q 32,500 E [illegible] G [illegible] S [illegible]	12,[illegible] F [illegible] [illegible] [illegible] R 15,[illegible]	[illegible] E,R [illegible] R 9,560 E [illegible] E [illegible]	6,120 E 4,350 E 9,830 R 7,590 G 6,698	[illegible] 244,600 G [illegible] 293,800 F [illegible]	[illegible] G 11[illegible] G [illegible] G [illegible] F [illegible]	68,120 222,600 S 28,530 [illegible] 173,270 [illegible] 114,8[illegible]	[illegible] E [illegible] F [illegible] [illegible] R [illegible]	very slight corrosion near primary origin for one specimen tested at 210 MPa
	[illegible] Q 24,822 E [illegible] G [illegible] E [illegible]	[illegible] R [illegible] [illegible] [illegible] [illegible]	[illegible] Q 11,[illegible] Q 11,386 R [illegible] Q [illegible]	5,215 E 10,030 E,F 11,393 E 16,186 F 9,910	114,910 G 173,[illegible] 162,942 G 197,[illegible] [illegible]	[illegible] F [illegible] 186,[illegible] F [illegible] S [illegible]	[illegible] F 177,344 F 87,008 F 36,824 F [illegible]	[illegible] R [illegible] E 31,116 R [illegible] Q [illegible]	no corrosion on fracture surfaces
	[illegible] [illegible] F [illegible] F,Q [illegible] S [illegible]	5,393 F 16,254 G 6,268 E 8,478 G 8,261	[illegible] F 18,910 E [illegible] F [illegible] F [illegible]	5,652 Q 15,177 E 5,782 E 6,898 E [illegible],722	105,9[illegible] G 111,862 [illegible] 181,364 [illegible] 109,060 G 123,11[illegible]	[illegible] E 134,[illegible] [illegible] F [illegible] R [illegible]	[illegible] F 147,749 [illegible] F [illegible],341 F [illegible]	[illegible] R [illegible] R [illegible] F [illegible] Q [illegible]	corroded fracture surfaces for two specimens tested at 210 MPa; very slight corrosion near primary origin for another; corroded fracture surfaces for two specimens tested at 144 MPa
	[illegible] E [illegible] Q,R [illegible] E [illegible] G [illegible]	24,551 B,Q 18,670 R 12,200 F 3,930 Q 12,176	13,626 E,F 9,106 Q 11,026 F 10,137 F 10,8[illegible]	10,100 Q 11,426 E 7,093 Q 8,794 E 9,211	175,510 R 81,170 R 111,500 G 146,240 G 123,455	[illegible] B [illegible] B 72,111 R [illegible] F [illegible]	[illegible] F 82,561 G [illegible] G 121,584 – 80,539	[illegible] R [illegible] E [illegible] R [illegible] – [illegible]	corroded fracture surface for one specimen tested at 210 MPa; slight corrosion near primary origins for two specimens tested at 144 MPa
	[illegible] R [illegible] G [illegible] S [illegible] Q [illegible]	14,492 Q 18,542 E 4,565 F 8,768 E 10,184	11,940 E 11,105 R 12,047 E 26,799 R 14,384	10,272 F 6,330 F 19,523 F 11,345 Q 10,955	153,788 S 96,362 G 68,216 G 135,859 S 108,262	78,828 F 118,805 N 102,326 G 38[illegible] S 138,858	156,1[illegible] S 139,186 G 57,088 R 223,635 – 135,756	[illegible] G 36,553 F [illegible] R [illegible] R [illegible]	corroded fracture surfaces for three specimens tested at 210 MPa; corrosion near primary origin for one specimen tested at 144 MPa
	38,1[illegible] S [illegible] F 14,430 E [illegible] F [illegible]	10,290 F 11,427 E 8,000• F 12,230• Q 10,355	9,570 Q 7,310 E,F 6,830 E 14,670 E 9,150	7,840 F 8,200 E,F 8,900 F 11,460 E 8,999	125,340 G 50,740 R 115,630 F 69,390• S 84,519	91,980 G 107,880 G 80,350• F 57,850• F 82,410	54,040 G 70,380 Q 49,970 R 76,780 R 61,494	88,720 G 15,[illegible] Q 46,5[illegible] P 41,32[illegible]• P [illegible]	no corrosion on fracture surfaces
[illegible]	9,9[illegible]• R 17,342• E,Q 11,[illegible]• F [illegible],826• R 11,484	3,104• F 3,342• F 4,896• R 12,758• F 5,045	17,569• E 20,470• R 12,848• E 7,586• R 13,679	8,130• Q 8,413• F 9,000• E 22,629• E 10,864	84,870• R 181,310• F 68,490• F 67,020• R 91,675	87,920• S 270,626• G 22,116• R 45,564• F 64,975	33,013• D 45,558• F 26,479• F 35,044• F 34,377	[illegible]• P 38,[illegible]• F [illegible]• R 41,[illegible]• S [illegible]	corroded fracture surfaces for three specimens tested at 210 MPa and one at 144 MPa

• [illegible] fit specimens disassembled, redrilled to press fit dimensions and reassembled

* [illegible] surfaces unavailable for examination

EY TO LOCATIONS
FATIGUE ORIGINS

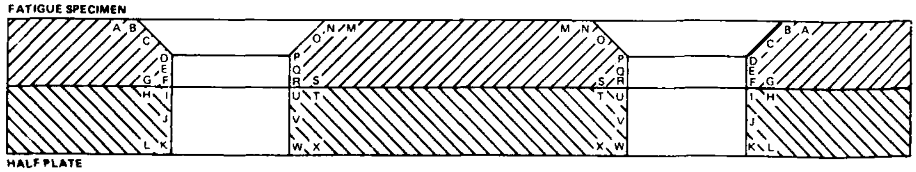


TABLE 3: SUMMARY OF BOX TEST RESULTS (95 % CONFIDENCE)

FATIGUE TESTING SCHEDULES	S_{max} (MPa)	F_o	HOMOGENEITY OF VARIANCES ($F_o < F_{0.05;9;739}$ = 1.880)	REMARKS
fatigue in air	210 144	1.925 1.984	no no	very slight violation very slight violation
pre-exposure + fatigue air	210 144	1.249 3.795	yes no	moderate violation
fatigue in salt spray	210 144	0.736 0.816	yes yes	
pre-exposure + fatigue in salt spray	210 144	0.655 0.836	yes yes	

TABLE 4: SUMMARY OF BARTLETT TEST RESULTS (95 % CONFIDENCE)

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	S_{max} (MPa)	χ^2_o	HOMOGENEITY OF VARIANCES ($\chi^2_o < \chi^2_{0.05;1}$ = 3.841)	REMARKS
fatigue in air/ pre-exposure + fatigue in air	210 144	5.151 0.366	no yes	moderate violation
fatigue in air/ fatigue in salt spray	210 144	-0.021 2.459	yes yes	
fatigue in air/pre-exposure + fatigue in salt spray	210 144	0.066 2.189	yes yes	
pre-exposure + fatigue in air/ fatigue in salt spray	210 144	5.403 0.921	no yes	moderate violation
pre-exposure + fatigue in air/ pre-exposure + fatigue in salt spray	210 144	6.495 0.757	no yes	moderate violation
fatigue in salt spray/pre-exposure + fatigue in salt spray	210 144	0.040 0.012	yes yes	

TABLE 5: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE)

SOURCE OF VARIATION	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES (F_o > F DISTRIBUTION VALUE)
● MAIN EFFECTS			
- stress	3.89	1572.877	yes
- environment	2.65	45.055	yes
- laboratory	1.93	5.763	yes
● 2-WAY INTERACTIONS			
- stress:environment	2.65	2.662	yes
- stress:laboratory	1.93	1.637	no
- environment:laboratory	1.54	1.397	no
● 3-WAY INTERACTIONS			
- stress:environment:laboratory	1.54	1.478	no

TABLE 6: RESULTS OF THE LEAST SIGNIFICANT DIFFERENCE TEST (95 % CONFIDENCE)

● ENVIRONMENTS

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	FATIGUE LIFE DATA FROM ALL TEN PARTICIPANTS		OMISSION OF FATIGUE LIFE DATA FOR REASSEMBLED SPECIMENS	
	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SIGNIFICANT DIFFERENCE (DIFFERENCE > $LSD_{0.05} = 0.061$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;210} = 1.972$)
fatigue in air/pre-exposure + fatigue in air	0.182	yes	5.156	yes
fatigue in air/fatigue in salt spray	0.227	yes	7.279	yes
fatigue in air/pre-exposure + fatigue in salt spray	0.354	yes	11.650	yes
pre-exposure + fatigue in air/fatigue in salt spray	0.045	no	2.026	yes
pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	0.172	yes	6.368	yes
fatigue in salt spray/pre-exposure + fatigue in salt spray	0.127	yes	4.412	yes

● LABORATORIES

FATIGUE LIFE DATA FROM ALL TEN PARTICIPANTS			OMISSION OF FATIGUE LIFE DATA FOR REASSEMBLED SPECIMENS	
SIGNIFICANT DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES (DIFFERENCE > $LSD_{0.05} = 0.096$)			SIGNIFICANT DIFFERENCE ($t > t_{0.025;210} = 1.972$)	
SIFFRL/NADC : 0.147	SIFFRL/RAE : 0.182	PISA/DFVLR : 0.171	SIFFRL/NADC : 3.413	SIFFRL/NDRE : 2.515
SIFFRL/SASK. : 0.111	PISA/NADC : 0.209	PISA/NDRE : 0.164	SIFFRL/SASK. : 2.695	SIFFRL/RAE : 4.112
SIFFRL/AFWAL : 0.207	PISA/SASK. : 0.173	PISA/RAE : 0.244	SIFFRL/VOUGHT : 2.375	AFWAL/SASK. : 2.024
SIFFRL/NLR : 0.171	PISA/VOUGHT : 0.157	AFWAL/VOUGHT : 0.112	SIFFRL/AFWAL : 4.611	AFWAL/VOUGHT : 2.361
SIFFRL/DFVLR : 0.109	PISA/AFWAL : 0.269	AFWAL/DFVLR : 0.098	SIFFRL/NLR : 3.893	AFWAL/DFVLR : 2 066
SIFFRL/NDRE : 0.102	PISA/NLR : 0.233	AFWAL/NDRE : 0.105	SIFFRL/DFVLR : 2.655	AFWAL/NDRE : 2.214

● STRESSES ENVIRONMENTS

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	FATIGUE LIFE DATA FROM ALL TEN PARTICIPANTS				OMISSION OF FATIGUE LIFE DATA FOR REASSEMBLED SPECIMENS			
	$S_{max} = 210$ MPa		$S_{max} = 144$ MPa		$S_{max} = 210$ MPa		$S_{max} = 144$ MPa	
	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SIGNIFICANT DIFFERENCE (DIFFERENCE > $LSD_{0.05} = 0.086$)	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SIGNIFICANT DIFFERENCE (DIFFERENCE > $LSD_{0.05} = 0.086$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;210} = 1.972$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;210} = 1.972$)
fatigue in air/pre-exposure + fatigue in air	0.268	yes	0.095	yes	5.554	yes	1.992	yes
fatigue in air/fatigue in salt spray	0.271	yes	0.181	yes	6 909	yes	3.619	yes
fatigue in air/pre-exposure + fatigue in salt spray	0.393	yes	0 313	yes	9 705	yes	6 747	yes
pre-exposure + fatigue in air/fatigue in salt spray	0.003	no	0.086	no	1.256	no	1.587	no
pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	0.125	yes	0.218	yes	4.011	yes	4.706	yes
fatigue in salt spray/pre-exposure + fatigue in salt spray	0.122	yes	0.132	yes	2.795	yes	3.175	yes

TABLE 7: SIGNIFICANT DIFFERENCES INDICATED BY DUNCAN'S NEW MULTIPLE RANGE TEST (95 % CONFIDENCE)

	FATIGUE LIFE DATA FROM ALL TEN PARTICIPANTS					OMISSION OF FATIGUE LIFE DATA FOR REASSEMBLED SPECIMENS		
	S_{max} - 210 MPa	S_{max} - 144 MPa				S_{max} - 210 MPa	S_{max} - 144 MPa	
● STRESSES: LABORATORIES	SIFFRL/NLR PISA/AFWAL PISA/NLR PISA/RAE	SIFFRL/NADC SIFFRL/SASK. SIFFRL/VOUGHT SIFFRL/AFWAL	SIFFRL/NLR SIFFRL/RAE PISA/NADC PISA/SASK.	PISA/VOUGHT PISA/AFWAL PISA/NLR PISA/DFVLR	PISA/NDRE PISA/RAE AFWAL/DFVLR AFWAL/NDRE	SIFFRL/NLR	SIFFRL/NADC SIFFRL/SASK. SIFFRL/VOUGHT SIFFRL/AFWAL	SIFFRL/NLR SIFFRL/RAE AFWAL/DFVLR AFWAL/NDRE

	FATIGUE LIFE DATA FROM ALL TEN PARTICIPANTS						OMISSION OF FATIGUE LIFE DATA FOR REASSEMBLED SPECIMENS		
	fatigue in air		pre-exposure + fatigue in air		fatigue in salt spray		fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray
● ENVIRONMENTS: LABORATORIES	SIFFRL/AFWAL SIFFRL/VOUGHT SIFFRL/NLR SIFFRL/DFVLR PISA/NADC PISA/VOUGHT PISA/AFWAL	PISA/NLR PISA/DFVLR PISA/NDRE PISA/RAE	SIFFRL/NLR PISA/NADC PISA/SASK. PISA/VOUGHT PISA/AFWAL PISA/NLR PISA/RAE	AFWAL/DFVLR NLR/NADC NLR/DFVLR NLR/NDRE	SIFFRL/DFVLR SIFFRL/RAE PISA/AFWAL PISA/DFVLR PISA/RAE VOUGHT/AFWAL VOUGHT/DFVLR	VOUGHT/RAE NLR/RAE	SIFFRL/NADC SIFFRL/VOUGHT SIFFRL/AFWAL SIFFRL/NLR SIFFRL/DFVLR SIFFRL/NDRE SIFFRL/RAE	AFWAL/DFVLR NLR/NADC NLR/DFVLR NLR/NDRE	SIFFRL/DFVLR SIFFRL/RAE VOUGHT/AFWAL VOUGHT/DFVLR VOUGHT/RAE NLR/RAE

	FATIGUE LIFE DATA FROM ALL TEN PARTICIPANTS							OMISSION OF FATIGUE LIFE DATA FOR REASSEMBLED SPECIMENS				
	S_{max} - 210 MPa				S_{max} - 144 MPa			S_{max} - 210 MPa			S_{max} - 144 MPa	
	fatigue in air	pre-exposure + fatigue in air		fatigue in salt spray	fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	fatigue in salt spray	pre-exposure + fatigue in salt spray
● STRESSES: ENVIRONMENTS: LABORATORIES	SIFFRL/AFWAL PISA/NADC PISA/AFWAL PISA/NLR PISA/DFVLR PISA/RAE	SIFFRL/NLR SIFFRL/PISA PISA/SASK. PISA/VOUGHT PISA/AFWAL PISA/NLR PISA/NDRE PISA/RAE VOUGHT/DFVLR	NLR/NADC NLR/SASK. NLR/DFVLR NLR/NDRE NLR/RAE	VOUGHT/SASK. VOUGHT/DFVLR VOUGHT/RAE VOUGHT/PISA	SIFFRL/AFWAL SIFFRL/VOUGHT	SIFFRL/RAE PISA/NADC PISA/SASK. PISA/VOUGHT PISA/AFWAL PISA/NLR PISA/DFVLR PISA/NDRE PISA/RAE	SIFFRL/NADC SIFFRL/AFWAL PISA/NADC PISA/AFWAL	SIFFRL/AFWAL	VOUGHT/NADC VOUGHT/DFVLR NLR/NADC NLR/SASK. NLR/DFVLR NLR/NDRE NLR/RAE	VOUGHT/SASK. VOUGHT/DFVLR VOUGHT/RAE	SIFFRL/RAE	SIFFRL/NADC SIFFRL/AFWAL

TABLE 8: REQUIRED SAMPLE SIZES FOR 5 % ERROR AND 90 % CONFIDENCE LEVELS

PARTICIPANTS	S_{max} = 210 MPa				S_{max} = 144 MPa			
	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray
NADC	3	6	3	6	4	4	3	4
UNIVERSITY OF SASKATCHEWAN	5	4	3	4	7	2	4	6
VOUGHT	4	5	2	5	2	2	6	4
AFWAL	3	3	5	4	4	2	5	3
NLR	3	3	4	5	3	4	4	6
DFVLR	3	5	3	5	3	4	5	5
NDRE	3	10	3	3	3	2	4	7
RAE	3	7	5	5	3	6	5	5
SIFFRL	8	3	4	3	4	3	3	7
UNIVERSITY OF PISA	3	8	4	5	4	12	3	2

TABLE 9: FATIGUE LIFE AND PRIMARY ORIGIN DATA FOR CFCTP CORE PROGRAMME SPECIMENS PRE-EXPOSED AND FATIGUE TESTED IN AIR

S_{max} = 210 MPa					
FRACTURE SURFACE CONDITION	FATIGUE LIFE TO FAILURE (CYCLES)	LOCATIONS OF PRIMARY ORIGINS			
		E/Q	F/R	G/S	B/N
corroded	3,104 •		x		
	3,342 •		x		
	3,930	x			
	4,565		x		
	4,896 •		x		
	4,997	x			
	5,393		x		
	6,268	x			
	6,337	x			
	7,980	x			
	8,353		x		
	8,478	x			
	8,768	x			
	10,093	x			
	10,970		x		
	13,023	x			
	14,492	x			
	15,600	x			
uncorroded	8,000 •		x		
	10,290	x			
	11,420	x			
	12,200		x		
	12,230 •	x			
	12,300		x		
	12,758 •		x		
	15,700	x			
	16,254	x			
	16,458	x			
	18,310		x		
	18,542	x			
	18,670		x		
	19,000		x		
	19,873				x
	20,168	x			
	20,332	x			
	20,628	x			
	24,551	x			x
	24,7[illegible]8	x			
	28,562			x	
	32,887			x	

FRACTURE SURFACE CONDITION	LOG MEAN FATIGUE LIFE (CYCLES)	NUMBERS OF EACH TYPE OF PRIMARY ORIGIN			
		E/Q	F/R	G/S	B/N
corroded	6,987	11	7	0	0
uncorroded	16,928	12	7	2	2

S_{max} 144 MPa							
FRACTURE SURFACE CONDITION	FATIGUE LIFE TO FAILURE (CYCLES)	LOCATIONS OF PRIMARY ORIGINS					
		E/Q	F/R	G/S	B/N	C/O	D/P
corroded	22,116 •		x				
	44,498		x				
	72,111		x				
	76,120	x					
	78,828						x
	85,912		x				
	86,862	x					
uncorroded	45,564 •		x				
	57,850 •		x				
	71,820				x		
	71,920				x		
	80,350 •		x				
	82,483			x			
	83,246		x				
	83,273	x					
	87,920 •			x			
	91,980			x			
	95,243			x			
	96,085			x			
	102,326			x			
	105,261		x				
	106,206			x			
	107,880			x			
	109,712			x			
	110,280			x			
	111,470			x			
	112,900			x			
	116,596		x				
	118,805				x		
	119,047			x			
	122,390		x				
	122,800					x	
	129,100		x				
	134,522	x					
	153,600			x			
	186,964				x		
	196,915				x		
	234,427		x				
	270,626 •			x			
	387,955			x			

FRACTURE SURFACE CONDITION	LOG MEAN FATIGUE LIFE (CYCLES)	NUMBERS OF EACH TYPE OF PRIMARY ORIGIN					
		E/Q	F/R	G/S	B/N	C/O	D/P
corroded	61,096	2	4	0	0	0	1
uncorroded	112,726	2	9	16	5	1	0

• Interference fit specimens disassembled, redrilled to press fit dimensions and reassembled

TABLE 10: CLASSIFICATION OF CFCTP CORE PROGRAMME PRIMARY FATIGUE ORIGINS

● TOTAL NUMBERS OF EACH TYPE OF PRIMARY ORIGIN

BORE OF FASTENER HOLE E/Q	BORE/FAYING SURFACE CORNER F/R	FAYING SURFACE G/S	SURFACE EDGE OF COUNTERSINK B/N	COUNTERSINK C/O	COUNTERSINK/ BORE TRANSITION D/P
68/59	58/60	48/20	9/2	3/0	2/1

● NUMBERS OF PRIMARY ORIGINS PER PARTICIPANT

PARTICIPANTS	E/Q	F/R	G/S	B/N	C/O	D/P
NADC	14	9	7	1	1	0
SASKATCHEWAN	14	12	9	0	0	0
VOUGHT	16	10	5	1	0	0
AFWAL	11	10	10	0	2	1
NLR	15	8	7	3	0	0
DFVLR	15	12	6	0	0	0
NDRE	15	11	4	3	0	0
RAE	8	8	11	3	0	1
SIFFRL	12	16	6	0	0	0
PISA	7	22	3	0	0	1

● NUMBERS OF PRIMARY ORIGINS PER STRESS LEVEL AND FATIGUE TESTING SCHEDULE

FATIGUE TESTING SCHEDULES	S_{max} = 210 MPa				S_{max} = 144 MPa					
	E/Q	F/R	G/S	B/N	E/Q	F/R	G/S	B/N	C/O	D/P
fatigue in air	23	14	8	0	0	15	25	0	0	0
pre-exposure + fatigue in air	23	14	2	2	4	13	16	5	1	1
fatigue in salt spray	28	16	0	0	7	19	10	0	1	1
pre-exposure + fatigue in salt spray	33	9	0	0	9	18	7	4	1	1
all schedules	107	53	10	2	20	65	58	9	3	3

● NUMBERS OF PRIMARY ORIGINS PER STRESS LEVEL AND FATIGUE ENVIRONMENT

FATIGUE ENVIRONMENT	S_{max} = 210 MPa				S_{max} = 144 MPa					
	E/Q	F/R	G/S	B/N	E/Q	F/R	G/S	B/N	C/O	D/P
fatigue in air (with and without pre-exposure)	46	28	10	2	4	28	41	5	1	1
fatigue in salt spray (with and without pre-exposure)	61	25	0	0	16	37	17	4	2	2

TABLE 11: SUMMARY OF χ^2 TEST OF INDEPENDENCE AND YATES' CORRECTED χ^2 TEST FOR THE CFCTP CORE PROGRAMME PRIMARY FATIGUE ORIGINS (95 % CONFIDENCE) OMITTING THE SIFFRL AND UNIVERSITY OF PISA DATA

SOURCE OF ASSOCIATION	FATIGUE TESTING SCHEDULES	$\chi^2_{0.05;(r-1)(c-1)}$	χ^2_o OR χ^2_c	SIGNIFICANT ASSOCIATION BETWEEN STRESS LEVEL AND PRIMARY FATIGUE ORIGINS (χ^2_o OR $\chi^2_c > \chi^2_{0.05;(r-1)(c-1)}$)
STRESS LEVEL	fatigue in air	$\chi^2_{0.05;2} = 5.99$	$\chi^2_0 = 28.40$	yes
	pre-exposure + fatigue in air	$\chi^2_{0.05;2} = 5.99$	$\chi^2_0 = 10.80$	yes
	fatigue in salt spray	$\chi^2_{0.05;2} = 5.99$	$\chi^2_0 = 17.48$	yes
	pre-exposure + fatigue in salt spray	$\chi^2_{0.05;1} = 3.84$	$\chi^2_0 = 10.27$	yes

SOURCE OF ASSOCIATION	S_{max}(MPa)	$\chi^2_{0.05;(r-1)(c-1)}$	χ^2_o	SIGNIFICANT ASSOCIATION BETWEEN ENVIRONMENT AND PRIMARY FATIGUE ORIGINS ($\chi^2_o > \chi^2_{0.05;(r-1)(c-1)}$)
ENVIRONMENT (FATIGUE TESTING SCHEDULE)	210	$\chi^2_{0.05;3} = 7.81$	7.18	no
	144	$\chi^2_{0.05;6} = 12.59$	28.56	yes

TABLE 12: CFCTP CORE PROGRAMME PRIMARY FATIGUE ORIGINS CORRELATED WITH FATIGUE LIVES, OMITTING THE SIFFRL AND UNIVERSITY OF PISA DATA

S_{max} (MPa)	LOCATIONS OF PRIMARY ORIGINS	NUMBERS OF PRIMARY FATIGUE ORIGINS AND LOG MEAN FATIGUE LIFE (CYCLES)			
		fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray
210	E/Q	20 : 22,606	20 : 12,219	22 : 10,583	28 : 8,153
	F/R	9 : 21,207	9 : 10,914	13 : 11,342	5 : 8,937
	G/S	7 : 29,699	2 : 30,648	0 : –	0 : –
	B/N	0 : –	2 : 22,089	0 : –	0 : –
144	E/Q	0 : –	4 : 92,770	6 : 124,192	8 : 76,019
	F/R	9 : 162,489	9 : 100,472	13 : 65,701	13 : 55,010
	G/S	23 : 129,873	12 : 119,938	10 : 116,807	5 : 80,906
	B/N	0 : –	5 : 117,704	0 : –	4 : 84,035
	C/O	0 : –	1 : 122,800	1 : 122,092	1 : 73,840
	D/P	0 : –	1 : 78,828	0 : –	1 : 73,840

TABLE 13: SUMMARY OF χ^2 TESTS FOR COMPARISON BETWEEN CFCTP CORE PROGRAMME PRIMARY FATIGUE ORIGINS AND FATIGUE LIVES (95 % CONFIDENCE) OMITTING THE SIFFRL AND UNIVERSITY OF PISA DATA

FATIGUE TESTING SCHEDULES	S_{max} (MPa)	TYPE OF TESTS	SIGNIFICANT ASSOCIATION BETWEEN PRIMARY FATIGUE ORIGINS AND FATIGUE LIVES
fatigue in air	210	χ^2_c	no
	144	Fisher's exact test	no
pre-exposure + fatigue in air	210	χ^2_c	no
	144	χ^2_c	no
fatigue in salt spray	210	χ^2_c	no
	144	Fisher's exact test	yes
pre-exposure + fatigue in salt spray	210	Fisher's exact test	no
	144	χ^2_c	no

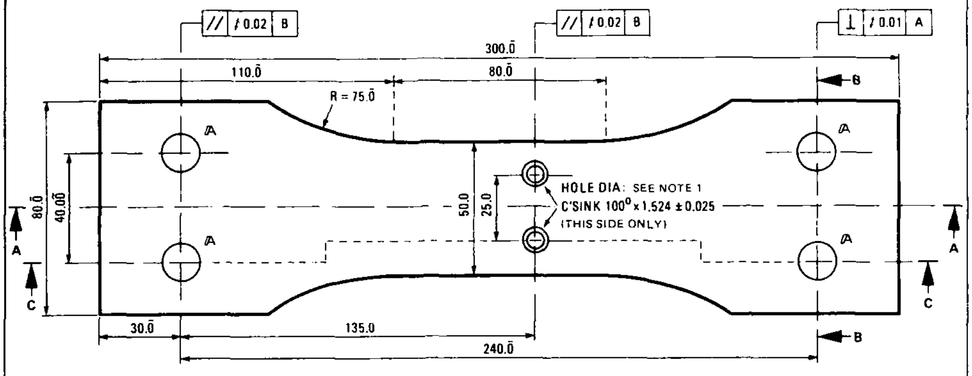
TABLE 14: RE-ANALYSIS OF SIGNIFICANT DIFFERENCES INDICATED BY STATISTICAL ANALYSIS OF FATIGUE LIFE DATA FOR PRE-EXPOSURE + *FATIGUE IN AIR AT* S_{max} = *210 MPa*

- FATIGUE LIFE DATA

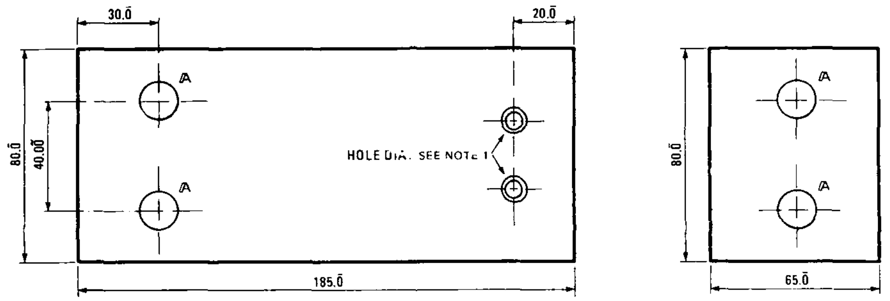
FRACTURE SURFACE CONDITION	FATIGUE LIFE TO FAILURE (CYCLES AND LOG MEAN CYCLES)						
	NADC	SASK.	VOUGHT	NLR	DFVLR	NDRE	RAE
corroded	4,997 6,337 10,970 7,030	7,980 10,093 13,023 10,160	8,353 8,353	— -	5,393 6,268 8,478 6,593	3,930 3,930	14,492 4,565 8,768 8,340
uncorroded	16,458 16,458	18,310 18,310	28,562 20,168 20,332 22,710	19,873 20,628 24,778 32,887 24,041	16,254 16,254	24,551 18,670 12,200 17,750	18,542 18,542

- SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST FOR UNCORRODED SPECIMENS (95 % CONFIDENCE)

COMPARISONS	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_i n_j}{n_i+n_j}}$	SHORTEST SIGNIFICANT RANGE (SSR)	SIGNIFICANT DIFFERENCE $(\bar{x}_i-\bar{x}_j)\sqrt{\frac{2n_i n_j}{n_i+n_j}} > SSR$
VOUGHT/NADC	0.171	0.411	no
VOUGHT/DFVLR	0.178	0.413	no
NLR/NADC	0.209	0.413	no
NLR/SASK.	0.149	0.406	no
NLR/DFVLR	0.215	0.415	no
NLR/*NDRE*	0.244	0.411	no
NLR/RAE	0.143	0.398	no

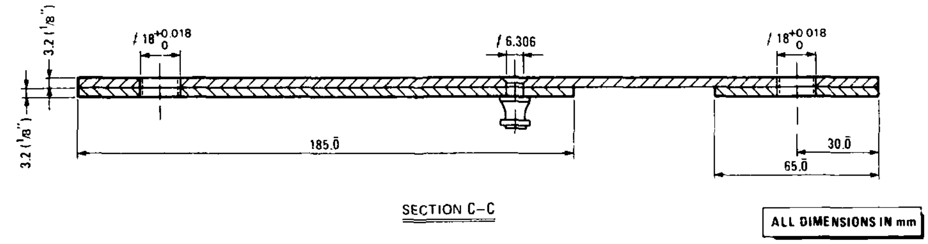


1) FATIGUE SPECIMEN



2) HALF PLATE

3) SPACER



SECTION C–C

NOTES

(1) HOLE DIAMETERS 6.306 ± 0.044 mm FOR CORE PROGRAMME SPECIMENS (SLIGHT PRESS FIT).
HOLE DIAMETERS 6.248 ± 0.0127 mm (INTERFERENCE FIT) OR 6.306 ± 0.044 mm (SLIGHT PRESS FIT) FOR SUPPLEMENTAL TESTING SPECIMENS.

(2) ALL HOLES MARKED THUS " Ⱥ " ARE $18^{+0.018}_{0}$ mm DIAMETER.

(3) SPECIAL TOLERANCE INDICATIONS ARE: 25.0 = 25 ± 0.05
25.0̄ = 25 ± 0.1
25.0̃ = 25 ± 0.2

Fig. 1 The CFCTP core programme and recommended FACT supplemental programme specimens

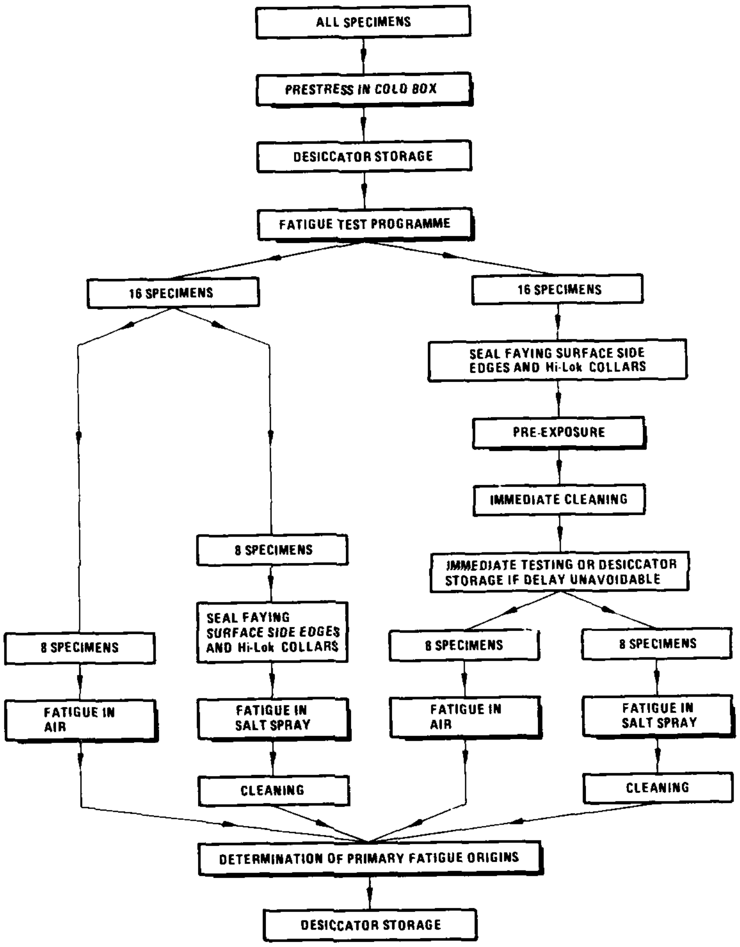


Fig. 2 Schematic summary of the CFCTP test procedure

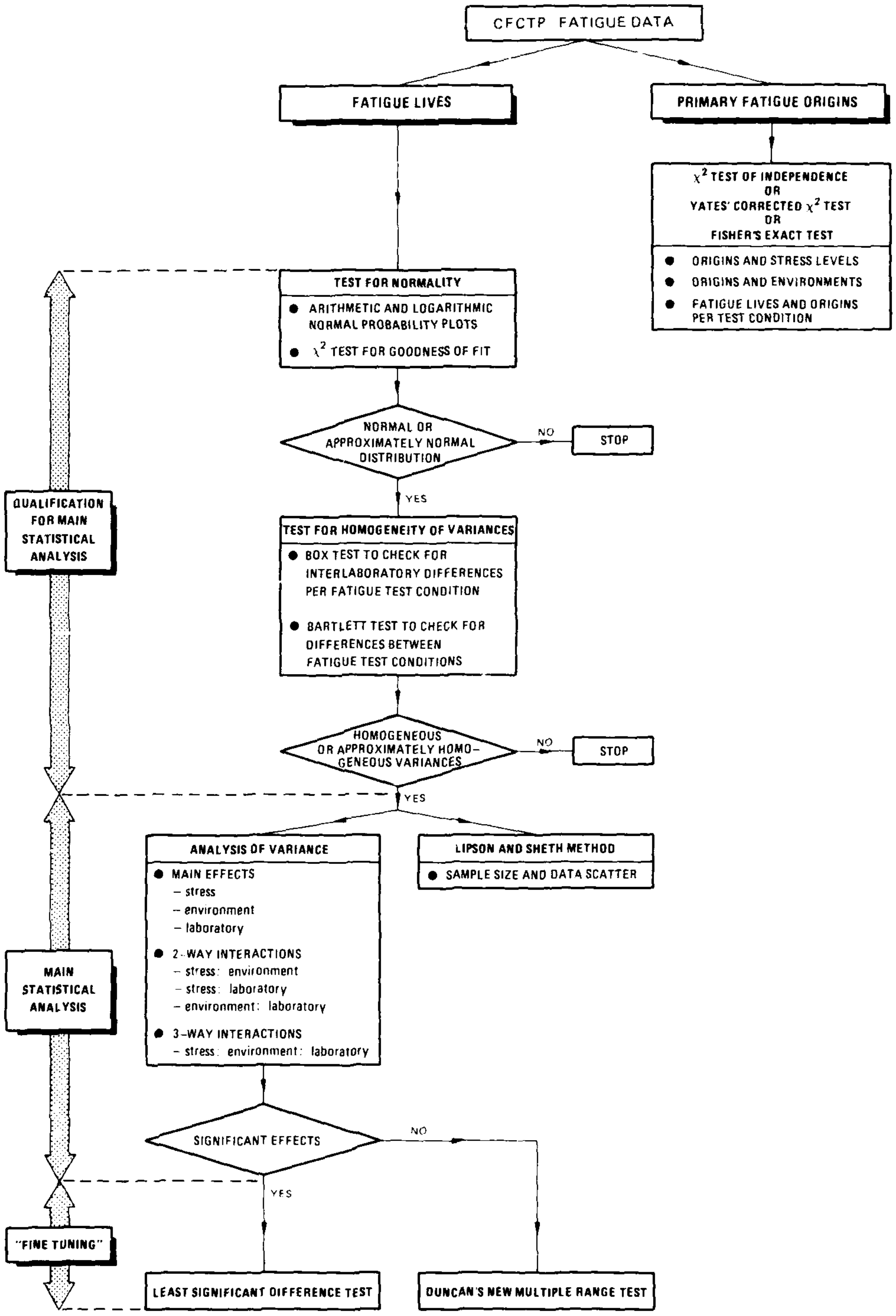


Fig. 3 Survey of statistical methods for analysing the CFCTP fatigue life and primary fatigue origin data

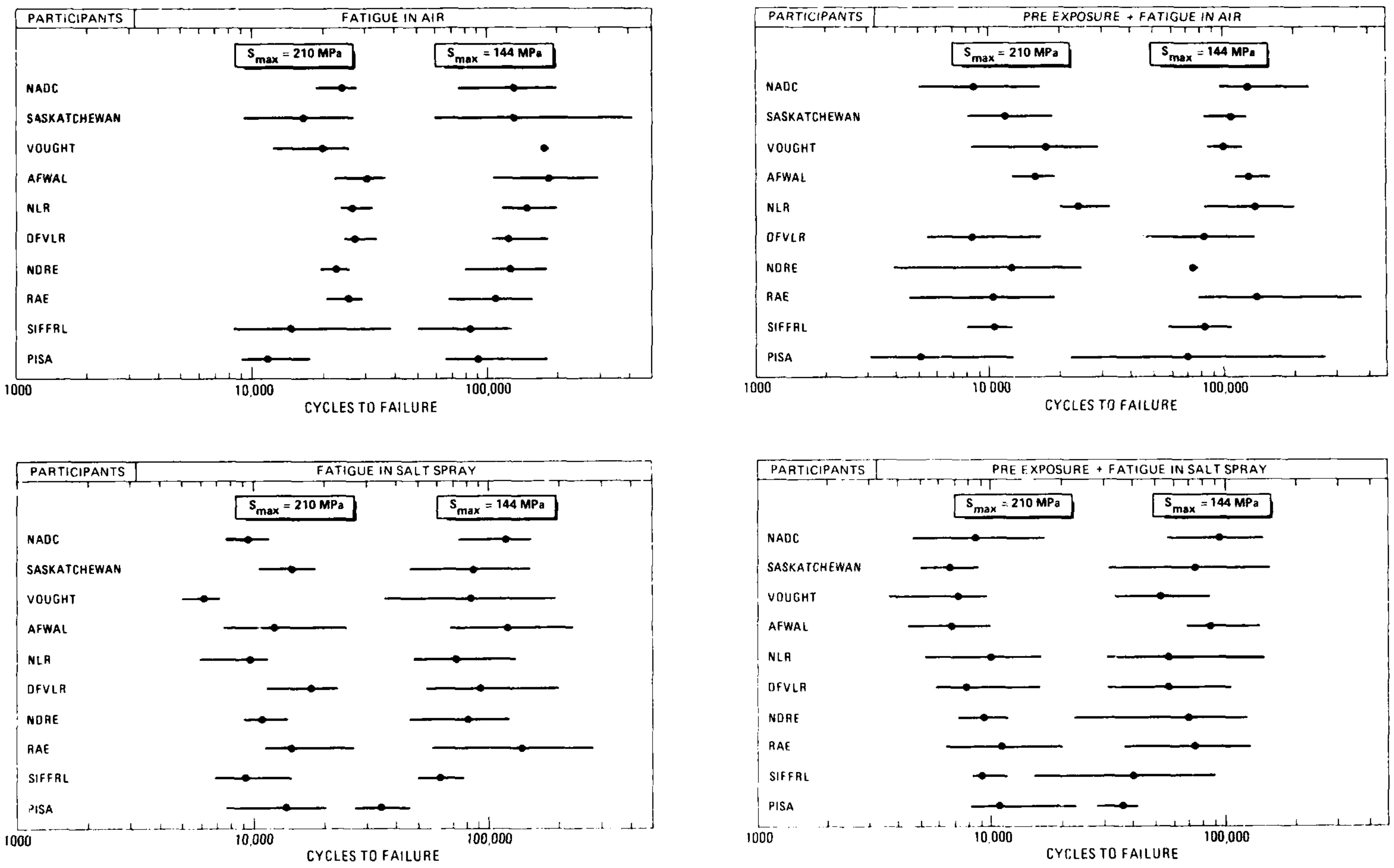


Fig. 4 CFCTP core programme fatigue life data per testing schedule and participant

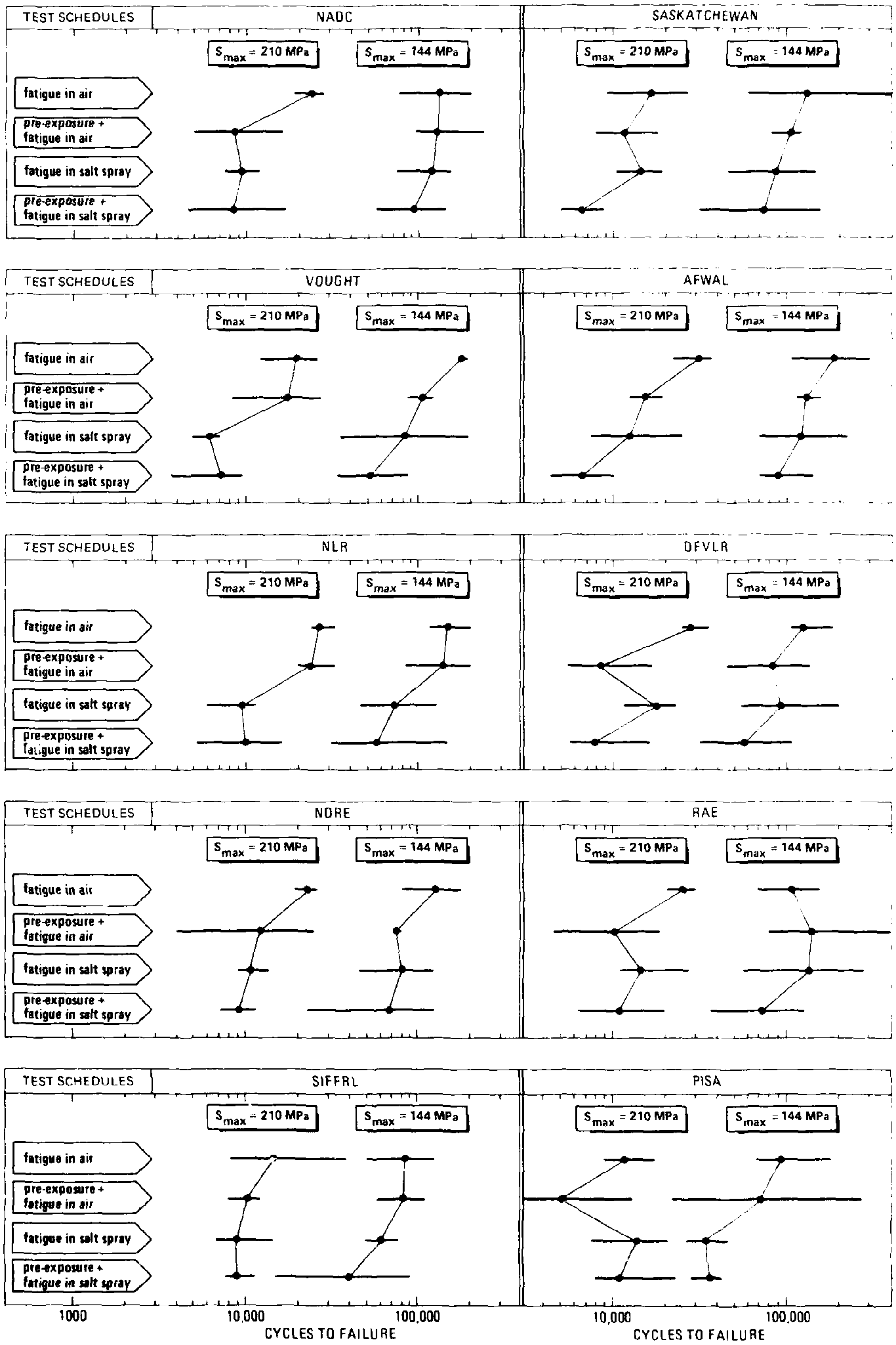


Fig. 5 CFCTP core programme fatigue life data per participant and testing schedule

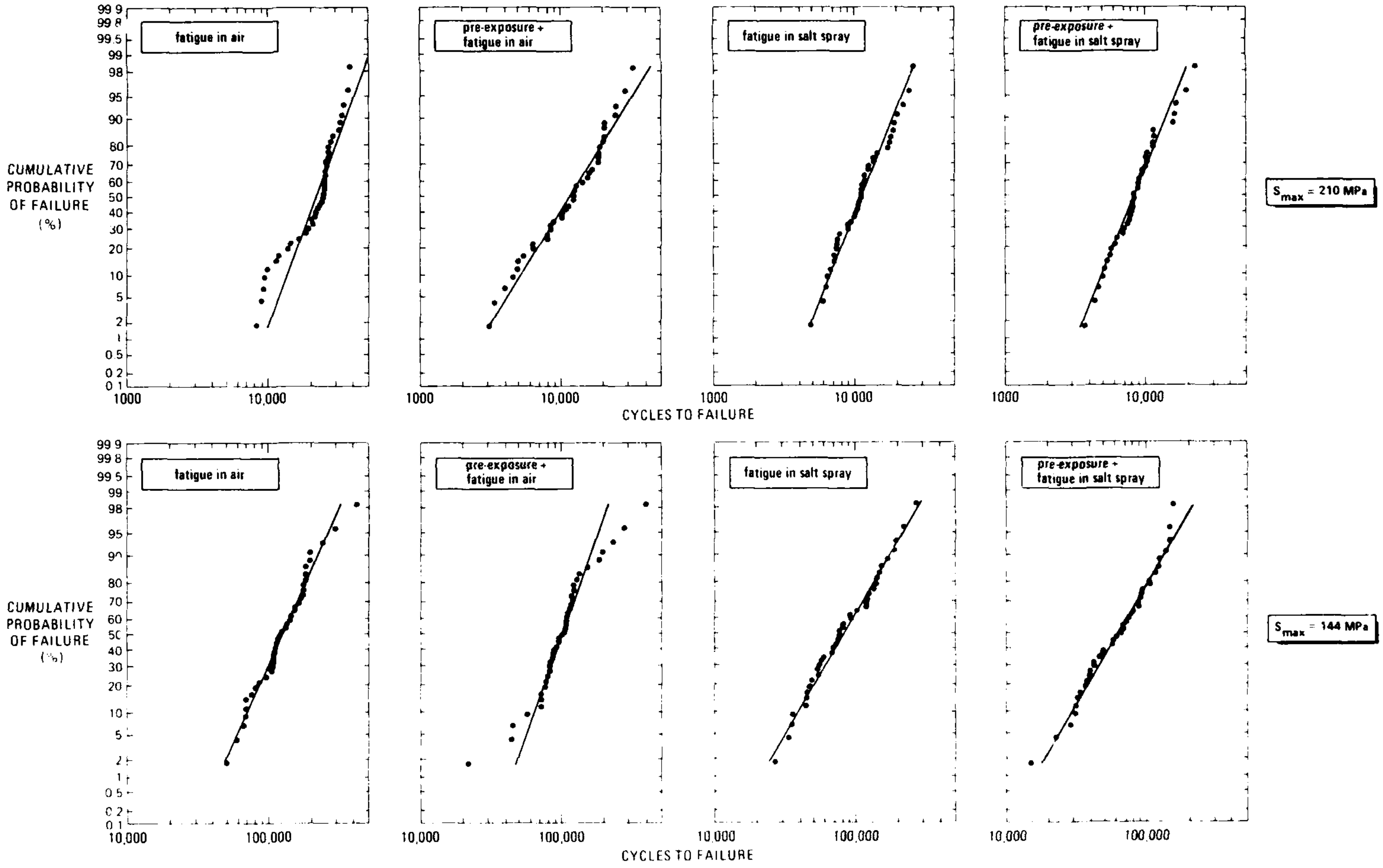


Fig. 6 Logarithmic normal probability plots of fatigue life for the CFCTP core programme specimens per test condition

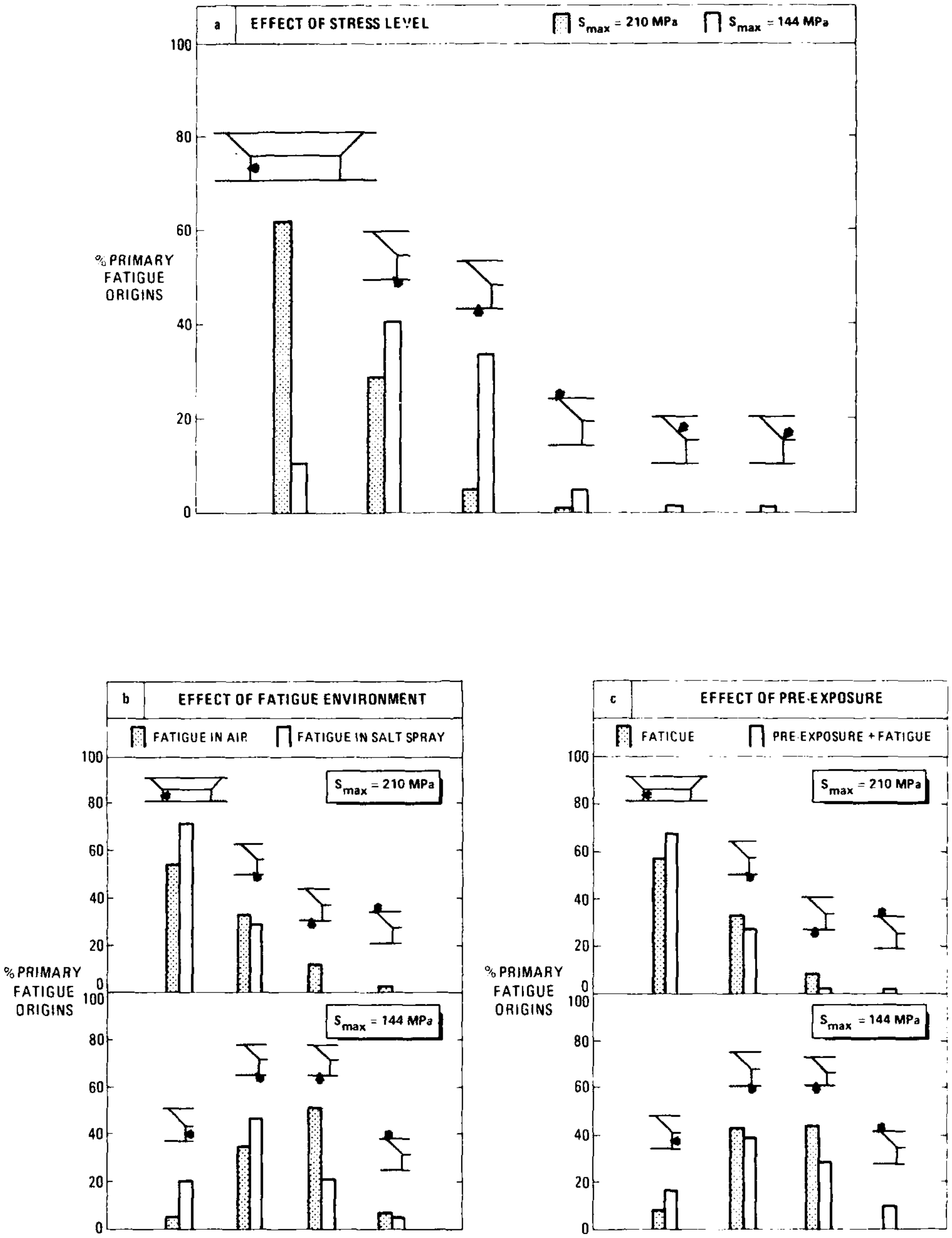


Fig. 7 Effects of stress level, fatigue environment and pre-exposure on locations of CFCTP core programme primary fatigue origins

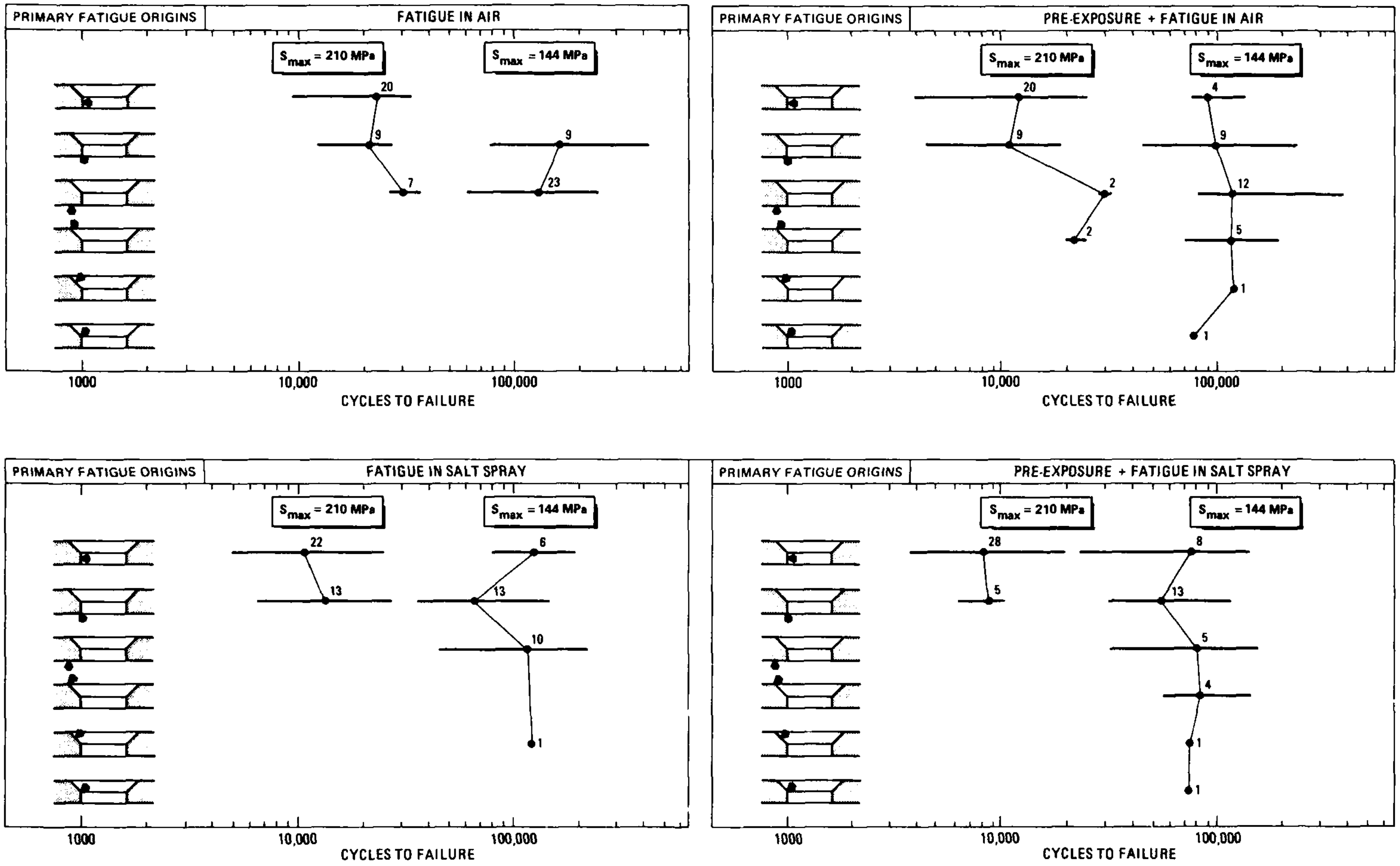


Fig. 8 CFCTP core programme fatigue life data per testing schedule and primary fatigue origin, omitting the SIFFRL and University of Pisa data

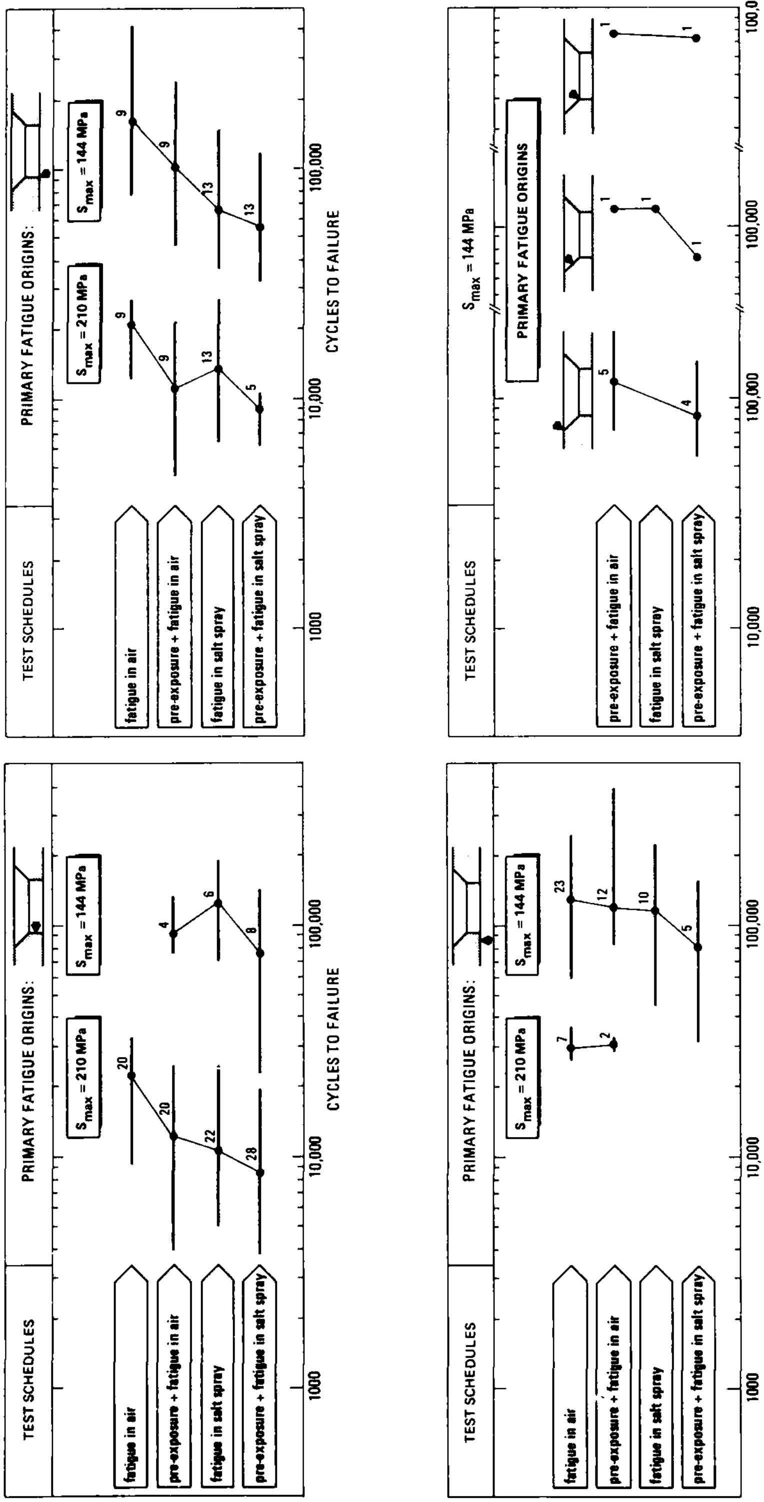


Fig. 9 CFCTP core programme fatigue life data per primary fatigue origin and testing schedule, omitting the SIFFRL and University of Pisa data

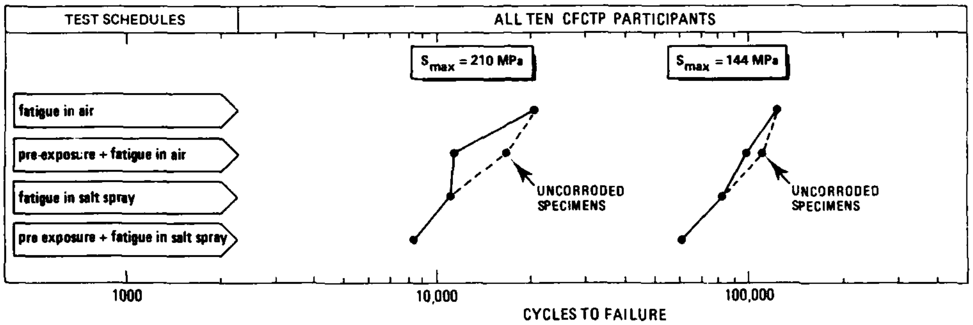


Fig. 10 Summary of the CFCTP core programme fatigue life data per testing schedule

PART III

THE FACT SUPPLEMENTAL PROGRAMME

1. INTRODUCTION

1.1 Overview

The FACT supplemental programme of fatigue testing followed on from the CFCTP core programme. The FACT programme was included so that individual participants could investigate corrosion fatigue problems of particular relevance to their own interests and yet within a broader context. To achieve this the individual programmes were set up with a high degree of commonality. This is shown in the overview in table 1.1. Most participants tested 1½ dogbone specimens (the same type of specimen used in the CFCTP) under nominally identical mechanical and environmental conditions. Concerning these aspects the technical manual required for the CFCTP (reference 1) also included supplemental testing guidelines for specimen manufacture, application of protection systems, specimen assembly, pre-exposure, and fatigue and corrosion fatigue under flight simulation loading (FALSTAFF and MINITWIST, references 2 - 5).

The individual contributions to the FACT programme will be presented in this part of the report in the same order as in table 1.1. These contributions also include summaries of the statistical methods used to analyse the results. A detailed description of these statistical methods is given in Appendix II.

It can be seen from table 1.1 that the main interest of several participants was to compare the environmental fatigue properties of a number of aluminium alloys in various tempers. However, owing to the calibratory function of the CFCTP and the participants' active cooperation in obtaining the many similarities and commonalities within the FACT programme, it has also been possible to make inter-participant comparisons of materials and the effects of different protection systems and fasteners. These inter-participant comparisons are the subject of Part IV of this report.

1.2 Recommended Specimen Configuration

The recommended specimen configuration for the FACT programme was the 1½ dogbone used in the CFCTP core programme. The specimen configuration is illustrated in figure 1.1. As mentioned in Part II of this report, the specimen was designed to simulate the load transfer and secondary bending characteristics of runouts of stiffeners attached to the outer skin of an airframe structure. The design goals were a load transfer of 40 % and a secondary bending ratio of 0.5 (reference 6). These characteristics have been checked and the actual values are generally lower, see Appendix I.

1.3 Flight Simulation Fatigue Testing

1.3.1 Short description of the manoeuvre spectrum FALSTAFF

The manoeuvre spectrum FALSTAFF (Fighter Aircraft Loading STAndard For Fatigue evaluation) was developed by several European laboratories (references 2 - 4). The spectrum is illustrated in figure 1.2. It is divided into 32 load levels. The load sequence consists of blocks of 200 different flights classified into three groups of mission types:

- flights with repetitive patterns of severe manoeuvring
- flights with severe manoeuvring
- flights with mainly moderate manoeuvring.

The sequence of flights and flight loads is random. Owing to the spectrum characteristics there are many flights containing high loads, although level 32 is reached only twice, in flights 32 and 173. An illustration of the flight-by-flight loading pattern is given in figure 1.3.

1.3.2 Short description of the gust spectrum MINITWIST

The gust spectrum MINITWIST (reference 5) is a shortened version of TWIST (Transport WIng STandard) that was developed by two European laboratories (reference 7). The spectrum is approximated for testing purposes by the stepped function shown in figure 1.4. Stresses are expressed non-dimensionally by dividing them by the stress pertaining to undisturbed cruising flight (S_{mf}). There are ten gust load levels and one ground load level.

MINITWIST consists of blocks of 4000 different flights. There are ten flight types, ranging from storm (A) to calm (J) conditions. Basic properties of the load sequence are:

- the flights and loads for each flight are applied in a random sequence except that clustering of severe flights has been avoided
- the loads within each flight are applied as a random sequence of half-cycles in such a way that a positive half-cycle is followed by a negative half-cycle of arbitrary magnitude
- load sequences have been generated individually for each flight. This means that flights of the same type generally have different load sequences.

The severest flights are 1656 (type A), 2856 (type B) and 501, 2936 and 3841 (type C). An illustration of the flight-by-flight loading pattern is given in figure 1.5.

1.4 Establishment of Fatigue Stress Levels for the 1½ Dogbone Specimen

Characteristic fatigue stress levels for the FACT programme were established on the basis of nominal target fatigue lives and pilot tests. This is illustrated in figure 1.6. The established fatigue stress levels were as follows (reference 8):

TYPE OF FATIGUE LOADING	NOMINAL UNCORRODED FATIGUE LIFE	CHARACTERISTIC STRESS LEVEL
constant amplitude, R = 0.1	100,000 cycles	S_{max} = 144 MPa
FALSTAFF	4,000 flights	S_{max} = 289 MPa
	10,000 flights	S_{max} = 238 MPa
MINITWIST	10,000 flights	S_{mf} = 101 MPa
	40,000 flights	S_{mf} = 89 MPa

There are two important points to note:

- all stresses are defined in terms of the total cross-section of the fatigue specimen -1 at the location of the centreline between the fasteners, i.e. the fastener holes are included in the cross-sectional area
- the pilot tests used representative specimens but did not take place under exactly the same conditions as definitive tests. This is because the definitive tests included prestressing the specimens at low temperature to crack the paint (if possible) around the fastener holes.

1.5 References

1. R.J.H. Wanhill and J.J. De Luccia, "An AGARD-coordinated corrosion fatigue cooperative testing programme", AGARD Report No. 695, February 1982.

2. G.M. van Dijk and J.B. de Jonge, "Introduction to a fighter aircraft loading standard for fatigue evaluation "FALSTAFF"", Paper 3.61, Problems with Fatigue in Aircraft, Proceedings of the Eighth ICAF Symposium, compiled and edited by J. Branger and F. Berger, Swiss Federal Aircraft Establishment (F + W) 1975: Emmen, Switzerland.

3. "Description of a Fighter Aircraft Loading STAndard For Fatigue evaluation", Combined Report of the F + W, LBF, NLR and IABG, March 1976.

4. J.B. de Jonge, "Additional information about FALSTAFF", NLR Technical Report TR 79056 U, June 1979.

5. H. Lowak, J.B. de Jonge, J. Franz and D. Schütz, "MINITWIST. A shortened version of TWIST", Combined report of the LBF and NLR, NLR Miscellaneous Publication MP 79018 U, May 1979.

6. D. Schütz and J.J. Gerharz, "Schwingfestigkeit von Fügungen met Sonderbefestigungselementen", Fraunhofer-institut für Betriebsfestigkeit Technische Mitteilungen TM 69/73, 1973.

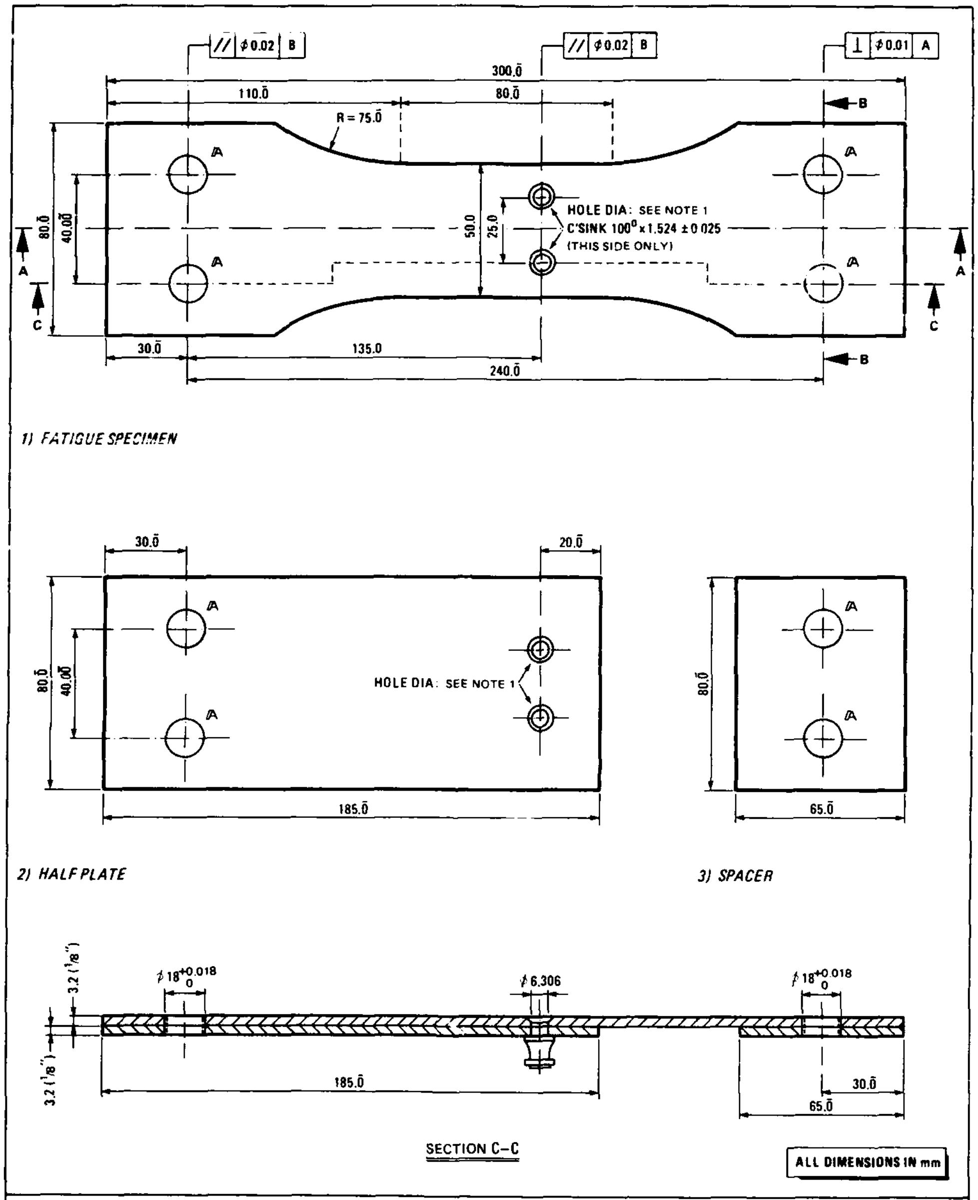
7. J.B. de Jonge, D. Schütz, H. Lowak and J. Schijve, "A standardised load sequence for flight simulation tests on transport aircraft wing structures", Combined report of the LBF and NLR, NLR Technical Report TR 73029 U, March 1973.

8. R.J.H. Wanhill, "Establishment of CFCTP stress levels for NLR core and supplemental testing programme", NLR Memorandum SM-80-034, March 1980.

TABLE 1.1: OVERVIEW OF THE FACT SUPPLEMENTAL PROGRAMME

PARTICIPANTS	IDENTICAL MATERIALS	CFCTP CORE PROGRAMME PROTECTION SYSTEM	MAIN ASPECTS OF THE INDIVIDUAL PROGRAMMES						
			MATERIAL COMPARISONS		PROTECTION SYSTEM COMPARISONS	FASTENER COMPARISONS	FATIGUE LOADING COMPARISONS C.A - CONSTANT AMPLITUDE	ENVIRONMENTS OTHER THAN THOSE IN THE CFCTP CORE PROGRAMME	TYPES OF TESTS
			DIFFERENT MATERIALS	DIFFERENT HEAT TREATMENTS					
VOUGHT		●					C.A. with marker loads	● salt spray at various temperatures	single dogbone fatigue life and crack propagation
SAAB	● 7075-T76	●	● 7075-T6 clad		● 7075 T6 clad with and without anodising		C.A. only	● pre-exposure outdoors for 7075-T6; fatigue with repeated condensation or alternate immersion in distilled water	unnotched and 1½ dogbone fatigue life
NADC	● 7075-T76	●			● standard and flexible primers	● press and interference fit Hi Loks	C.A. only		1½ dogbone fatigue life
AFWAL	● 7075-T76	●			● Hi-Loks with and without sealanr	● press fit Hi-Loks, SLEEVbolts	● C.A., FALSTAFF		
NDRE	◐ 7075-T6	●		● 7075 in T76 and T6RAA conditions			● C.A., FALSTAFF		
NLR/LRTH	◐ 7075-T6 ○ 7475-T761 clad		● 2024-T3 Alclad 2024-T3/aramid fibre laminates, 7075-T6, 7475-T761 clad		● F-28, NF-5 systems; F-16 system with and without sealant		● C.A., FALSTAFF, MINITWIST		
IABG	● 7075-T76 ◐ 7075-T6 ○ 7475-T761 clad	●	● 7075-T6, 7075-T76, 7475-T761 clad		● CFCTP core programme and MRCA systems		FALSTAFF only		
RAE	◐ 7075-T6				● inhibited and non-inhibited primers		C.A. only		
				● 7010 in T7651 and T7451 conditions			● C.A., FALSTAFF		fatigue strength
			● 7010-T7X51, 7475-T7351, 7050-T7451	● 7010 in T7651 and T7451 conditions			● C.A., FALSTAFF		fatigue crack propagation
NRC				● 7075 in T651, T6RRA and T7351 conditions			C.A. only	● argon, 3.5 % aqueous NaCl	

(1) LTV Aerospace and Defence VOUGHT, Dallas, Texas, USA.
(2) SAAB-SCANIA Aerospace Division, Linkoping, Sweden.
(3) Naval Air Development Centre NADC, Warminster, Pennsylvania, USA
(4) Air Force Wright Aeronautical Laboratories AFWAL, Dayton, Ohio, USA
(5) Norwegian Defence Research Establishment NDRE, Kjeller, Norway.
(6) National Aerospace Laboratory NLR, Emmeloord, The Netherlands.
(7) Delft University of Technology LRTH, Delft, The Netherlands.
(8) Industrieanlagen-Betriebsgesellschaft IABG, Ottobrunn, Germany
(9) Royal Aircraft Establishment RAE, Farnborough, United Kingdom.
(10) National Research Council NRC, Ottawa, Canada.



NOTES

(1) HOLE DIAMETERS 6.306 ± 0.044 mm (SLIGHT PRESS FIT) OR 6.248 ± 0.0127 mm (INTERFERENCE FIT).

(2) ALL HOLES MARKED THUS " A " ARE $18^{+0.018}_{0}$ mm DIAMETER.

(3) SPECIAL TOLERANCE INDICATIONS ARE: 25.0 = 25 ± 0.05
25.$\bar{0}$ = 25 ± 0.1
25.$\bar{\bar{0}}$ = 25 ± 0.2

Fig. 1.1 The recommended FACT supplemental programme specimen

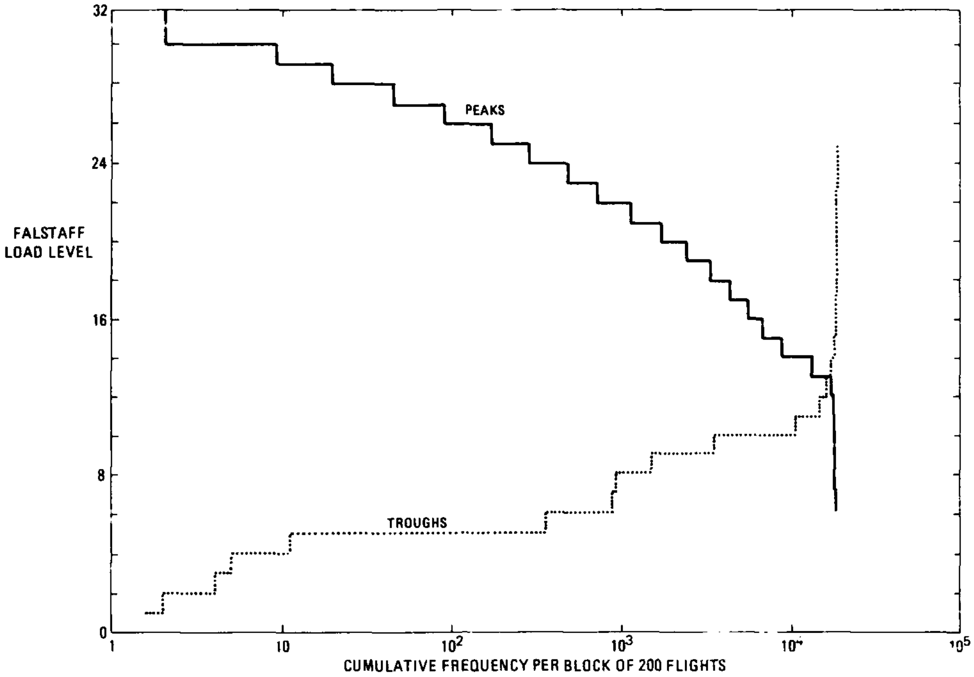


Fig. 1.2 The manoeuvre spectrum FALSTAFF

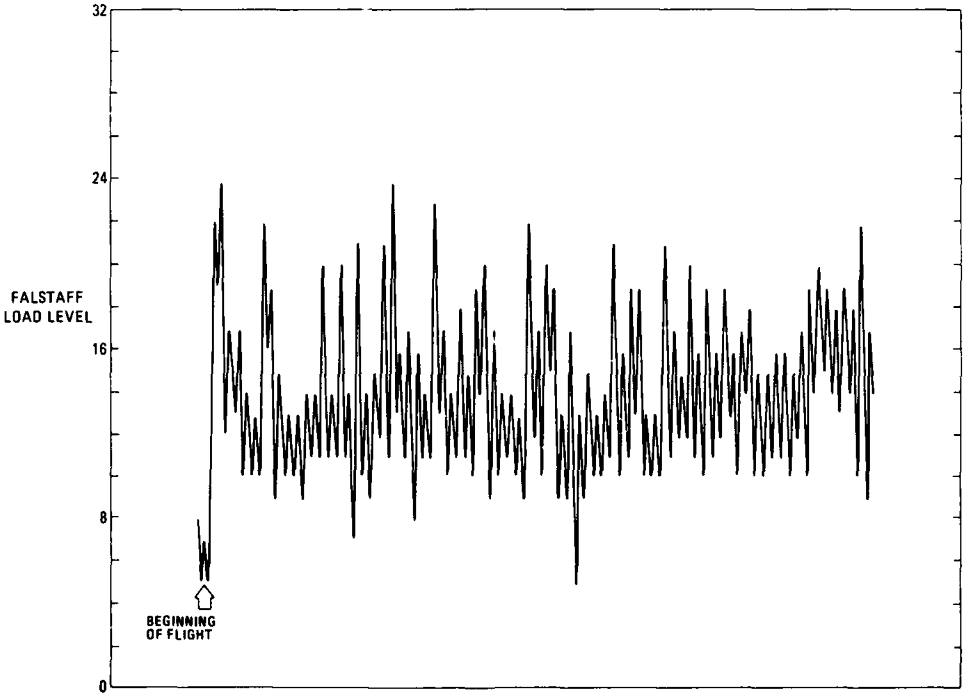


Fig 1.3 Part of FALSTAFF flight 183

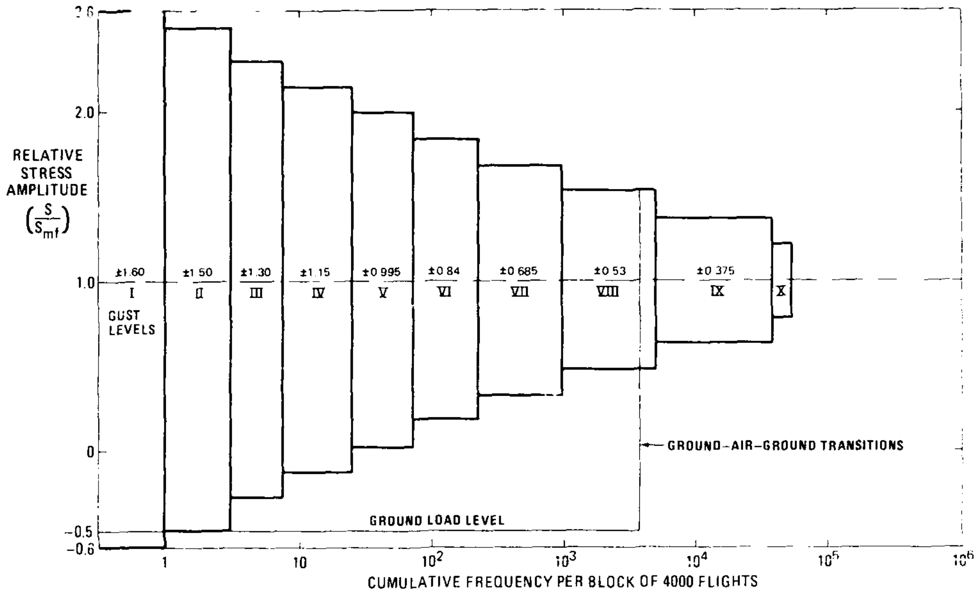


Fig. 1.4 The gust spectrum MINITWIST

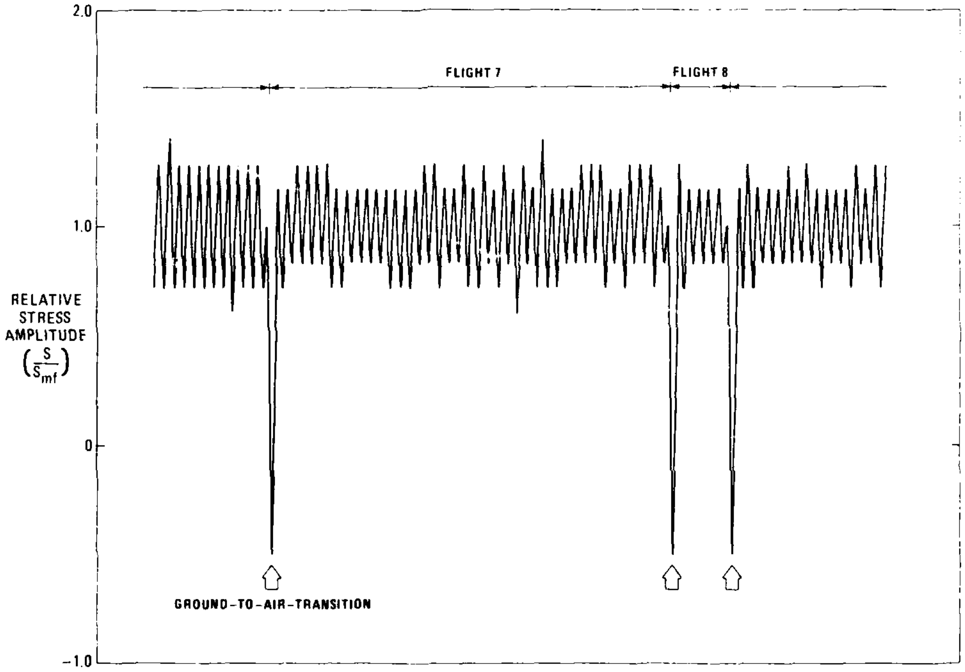


Fig. 1.5 Part of MINITWIST

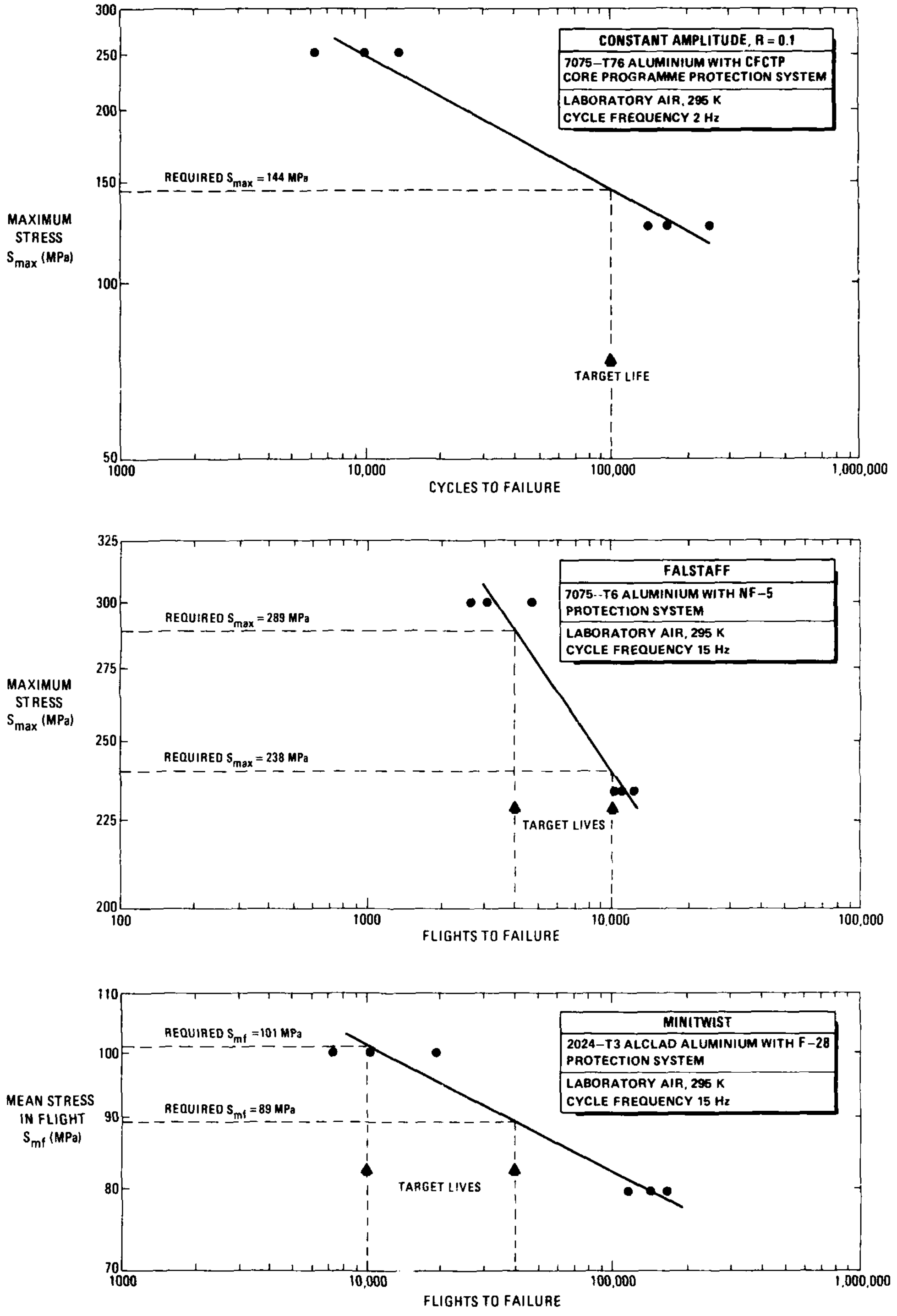


Fig. 1.6 Establishment of FACT supplemental programme fatigue stress levels for the 1½ dogbone specimen from pilot tests (●)

2. THE VOUGHT CONTRIBUTION TO THE FACT PROGRAMME

R.E. Duval and A.E. Hohman, LTV Aerospace and Defence Company, Vought Missiles and Advanced Programmes Division, Dallas, Texas, USA.

2.1 Introduction

Experience has shown that metal fatigue is a major cause of structural failures in aircraft. Also it has been known for a long time that fatigue properties of structures can be greatly influenced by the nature of the environment in which they are operating. In the past these effects were accounted for by applying safety factors to designs based on data developed in non-aggressive environments. However, increasing emphasis on lower weight, higher performance and longer lasting aircraft makes it imperative that future designs take more accurate account of the effects of adverse operating environments.

Because of the relatively short time available during the design and development of an aircraft, long term corrosion exposure to simulate the service environment is not practical. Accelerated testing procedures must be employed to provide the necessary data in a timely manner. To obtain corrosion fatigue data severe environments ranging from total immersion to salt fog have been used. However, even with these severe environments considerable testing time is required because of the slow rates of cycling that must be used.

An even greater acceleration of corrosion effects is desirable. One possible way to achieve this is to raise the temperature of the environment so that reaction rates increase. At present there is little information on temperature effects in corrosion fatigue. The primary objective of the VOUGHT contribution to FACT was to obtain a limited amount of elevated temperature corrosion fatigue data as part of a continuing investigation of corrosion fatigue testing methods.

2.2 The Test Programme

An overview of the test programme is given in table 2.1. This programme was preceded by pilot tests to check marker load characteristics predicted using the EFFGRO computer program, which is a crack growth analysis program developed at Rockwell International. Further information about the prediction of marker load characteristics and EFFGRO is given in references (1, 2).

2.2.1 Material, specimen configuration and protection system

The material was 6.35 mm thick 7075-T7651 aluminium alloy plate. Average engineering properties were as follows:

0.2 % YIELD STRESS	UTS	ELONGATION	CONDUCTIVITY
484 MPa	536 MPa	15 %	37.4 % I.C.A.S.

The specimens were of the single dogbone configuration shown in figure 2.1. The dogbones were notched by central holes with a K_t value ~ 2.7. Note that mill finish was retained on all surfaces, i.e. including the central holes. The protection system was a standard U.S. Navy paint scheme:

- chromate conversion coating type 2 class 2 (MIL-C-5541)
- inhibited epoxy polyamide primer (MIL-P-23377)
- aliphatic polyurethane topcoat. MIL-C-81773C 207-9-404

This system was applied to all surfaces except the central holes.

2.2.2 Mechanical testing conditions

All stresses were defined in terms of loads on the central cross-section of the specimen and including the central hole in the cross-sectional area. The characteristic fatigue stress levels (S_{max}) for the test programme have been given already in table 2.1. These levels were based on the results of pilot tests and the CFCTP core programme.

The fatigue load history is illustrated in figure 2.2. It consisted of blocks of 200 damage cycles (R = 0.1) and 100 marker cycles (R = 0.5) with a constant S_{max} in order to avoid crack growth retardation. The intention of this load history was to provide clearly visible marker bands which, however, should have a minimal contribution to overall crack growth. All tests were carried out with a cycle frequency of 0.5 Hz.

2.2.3 Environmental conditions

The fatigue tests were done in laboratory air at a nominal temperature of 297 K and in 5 % aqueous NaCl salt spray acidified with H_2SO_4 to pH 4. The tests in salt spray were done at several temperatures in the range 297 - 339 K, see table 2.1. The salt spray cabinet met the requirements in reference (3) but with the addition of a hot air inlet and baffles for mixing hot air with salt spray to produce elevated temperature fog. The environmental temperature was monitored by a thermistor temperature control probe located 25 mm from the specimen test section. The specimen temperature was monitored by a thermocouple, and it was found that the temperature could be maintained to within ± 0.5 K.

During testing at elevated temperatures the air pressure in the salt spray cabinet was increased to try to compensate for evaporation. However, it was found that the solution collection rates specified in ASTM standard B 117 - 73 (Standard Method of Salt Spray (Fog) Testing) could not be maintained at temperatures above about 316 K. Furthermore the salt fog became only a slight mist at 325 K and was not observed at 339 K.

2.3 Results

2.3.1 Fatigue life and fatigue crack initiation and propagation life data

Fatigue life and fatigue crack initiation and propagation life data are compiled in table 2.2. The fatigue crack initiation and propagation life data were obtained by correlating marker load bands on the fracture surfaces with numbers of cycles and tracing the markers back to crack dimensions less than 0.3 mm.

The data for fatigue in salt spray at different temperatures are presented in figure 2.3. These data were analysed statistically according to the procedure shown in figure 2.4. Owing to the limited number of data and unequal sample sizes it had to be assumed that they at least approximated to random samples from log-normally distributed populations with equal variance. Unequal sample sizes also meant that a modified version of Duncan's new multiple range test had to be used for "fine tuning" the analysis of variance results. More details of the statistical methods are given in Appendix II.

Results of the statistical analysis are summarised in tables 2.3 and 2.4. According to the analysis the temperature of the salt spray environment had no significant effect on the fatigue life and fatigue crack initiation and propagation lives.

2.3.2 Fatigue crack growth rate data

The fatigue crack growth rate data are shown in figure 2.5. Most of the data fall into two broad bands which indicate that the aggressiveness of salt spray first increased and then decreased with increasing temperature, eventually becoming no more aggressive than room temperature air.

The data for tests in salt spray at 316 K appear to represent a transition in the aggressiveness of salt spray. At high crack growth rates the environmental contribution to crack growth decreases with respect to mechanically-induced crack growth. However, this effect had a negligible effect on crack propagation life and total life.

2.4 Discussion

Owing to insufficient data for some test conditions and to data scatter the statistical analysis did not indicate a significant effect of salt spray temperature on the fatigue life and fatigue crack initiation and propagation lives. However, the data in figures 2.3 and 2.5 show the following trends:

(1) Increasing the salt spray temperature from 297 K to 316 K tended to decrease the fatigue crack initiation and propagation lives and hence total life.

(2) Further increasing the salt spray temperature from 316 K to 339 K resulted in an increase in fatigue crack initiation and propagation lives and a decrease in fatigue crack growth rates to values similar to those for fatigue in room temperature air.

In view of these trends and also the observations on collection rates and appearance of the salt spray at elevated temperatures (section 2.2.3) it seems reasonable to conclude that acceleration of salt spray corrosion fatigue testing is possible by raising the temperature of the salt spray, but only as long as the experimental set-up permits the production of a proper salt fog.

For the test set-up in this investigation it appears that the critical temperature at which a proper salt fog can still be maintained is 316 K. At this temperature the average fatigue life decreased by about 35 % compared to the room temperature fatigue life, mainly because the crack initiation life decreased. This represents a considerable reduction in testing time which, however, must be weighed against the increased complexity of salt spray fatigue testing at elevated temperatures and greater difficulty in obtaining reproducible test conditions.

2.5 Conclusions

Although statistical analysis did not indicate a significant effect of salt spray temperature on the fatigue life and fatigue crack initiation and propagation lives of notched 7075-T651 plate specimens, the following conclusions are drawn:

(1) Increasing the salt spray temperature from 297 K to 316 K tended to decrease the fatigue crack initiation and propagation lives and hence total life.

(2) Further increasing the salt spray temperature resulted in an increase in fatigue crack initiation and propagation lives and a decrease in fatigue crack growth rates because a proper salt fog could not be maintained above 316 K.

(3) Raising the salt spray temperature can result in a considerable reduction in testing time. This must be weighed against the experimental problems of obtaining and maintaining a proper salt fog at elevated temperatures.

2.6 Recommendations for Further Investigation

The effects of temperature on corrosion fatigue should be investigated for other materials and heat treatment conditions and also for specimen configurations representing typical aircraft structural joints. Other fatigue load histories should be considered, especially spectrum loading representing service usage and preferably giving marker bands that allow tracing crack growth back to small flaw sizes.

2.7 References

1. R.E. Duval, "Effect of temperature on corrosion fatigue life of 7075-T7651 aluminium alloy plate", LTV Aerospace and Defence Company, Vought Missiles and Advanced Programmes Division Report 3-41300/4R-115, 1984.

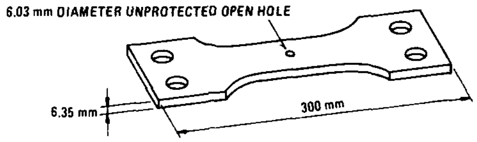
2. J.B. Chang, M. Szamossi and K.-W. Liu, "Random spectrum fatigue crack life predictions with or without considering load interactions", Methods and Models for Predicting Fatigue Crack Growth under Random Loading, ASTM STP 748, edited by J.B. Chang and C.M. Hudson, American Society for Testing and Materials, pp. 115 - 132 (1981): Philadelphia.

3. R.J.H. Wanhill and J.J. De Luccia, "An AGARD - coordinated corrosion fatigue cooperative testing programme", AGARD Report No. 695, February 1982.

TABLE 2.1: OVERVIEW OF THE VOUGHT TEST PROGRAMME FOR FACT

MATERIAL • 6.35 mm thick 7075-T7651 aluminium alloy plate

SPECIMEN •



PROTECTION SYSTEM • Chromate conversion + inhibited epoxy polyamide primer + aliphatic polyurethane topcoat (except central hole)

FATIGUE LOADING • Blocks of constant amplitude damage cycles (S_{min}/S_{max} = 0.1) and marker cycles (S_{min}/S_{max} = 0.5); cycle frequency 0.5 Hz

FATIGUE ENVIRONMENTS • Laboratory air; 5 % aqueous NaCl salt spray with pH 4 at various temperatures

TEST PROGRAMME •

SCHEDULES	ENVIRONMENTAL TEMPERATURE (°K)	S_{max} (MPa)		
		152	148	144
Fatigue in air	297	●	●	
Fatigue in salt spray at various temperatures	297			●
	311			●
	316			●
	325			●
	339			●

STATISTICAL ANALYSIS • Fatigue lives and fatigue crack initiation and propagation lives

SPECIAL CONSIDERATIONS • Fractographic determination of fatigue crack growth data from marker load bands

TABLE 2.2: FATIGUE LIFE AND FATIGUE CRACK INITIATION AND PROPAGATION LIFE DATA FOR THE VOUGHT CONTRIBUTION TO FACT

PARAMETERS	CHARACTERISTIC STRESS LEVEL	TOTAL DAMAGE + MARKER CYCLES PER SPECIMEN AND LOG MEAN VALUES					
		fatigue in air at 297 K	fatigue in salt spray at various temperatures:				
			297 K	311 K	316 K	325 K	339 K
FATIGUE LIFE	S_{max} - 152 MPa	64,874 41,388 51,817					
	S_{max} - 148 MPa	42,830					
	S_{max} - 144 MPa		63,550 53,756 34,450 49,005	34,600 42,093 29,716 35,110	33,547 29,825 31,631	46,949	50,105 61,375 55,454
FATIGUE CRACK INITIATION LIFE TO A 0.3 mm CRACK	S_{max} - 152 MPa	29,346 12,663 19,277					
	S_{max} - 148 MPa	16,884					
	S_{max} - 144 MPa		35,376 17,803 25,096	14,673 15,075 14,873	13,488	15,000	21,839 18,090 19,876
FATIGUE CRACK PROPAGATION LIFE FROM A 0.3 mm CRACK	S_{max} - 152 MPa	35,528 28,725 31,946					
	S_{max} - 148 MPa	25,946					
	S_{max} - 144 MPa		28,174 16,647 21,657	19,927 14,641 17,081	16,337	31,949	28,266 43,285 34,978

TABLE 2.3: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE)

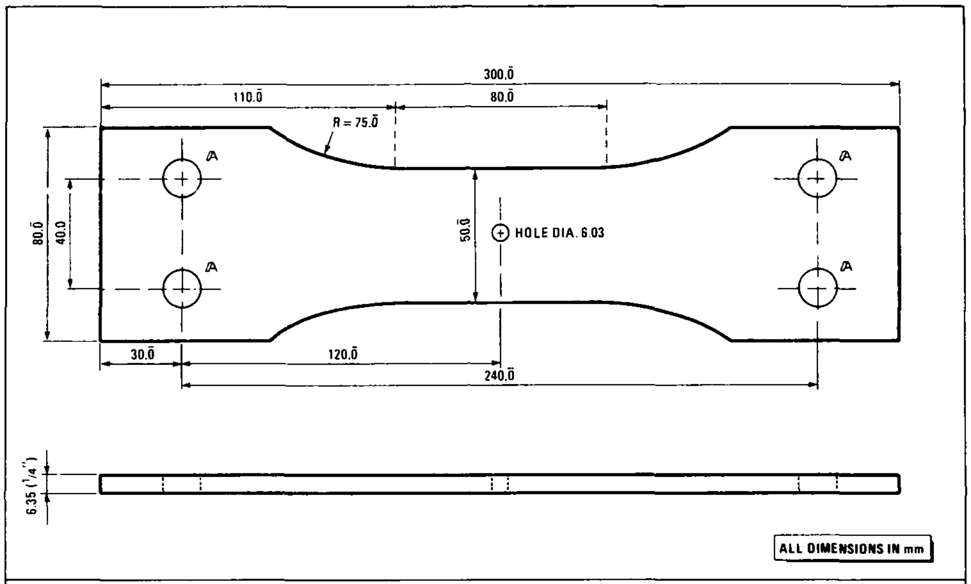
SOURCE OF VARIATION	FATIGUE LIFE PARAMETERS	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECT OF TEMPERATURE (F_o > F DISTRIBUTION VALUE)
● MAIN EFFECT - temperature	TOTAL LIFE	4.53	2.573	no
	LIFE TO A 0.3 mm CRACK	9.12	1.270	no
	LIFE FROM A 0.3 mm CRACK	9.12	2.058	no

TABLE 2.4: SUMMARY OF RESULTS USING DUNCAN'S NEW MULTIPLE RANGE TEST (95 % CONFIDENCE)

	LOG MEAN FATIGUE LIVES AND SAMPLE SIZES n				
SALT SPRAY TEMPERATURE	297 K	311 K	316 K	325 K	339 K
TOTAL LIFE	4.690 ; 3	4.545 ; 3	4.500 ; 2	4.672 ; 1	4.744 ; 2
LIFE TO A 0.3 mm CRACK	4.400 ; 2	4.172 ; 2	4.130 ; 1	4.176 ; 1	4.298 ; 2
LIFE FROM A 0.3 mm CRACK	4.336 ; 2	4.233 ; 2	4.213 ; 1	4.504 ; 1	4.544 ; 2

	p	COMPARISONS OF DATA FOR FATIGUE TESTING IN SALT SPRAY AT DIFFERENT TEMPERATURES	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_in_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i-\bar{x}_j)\sqrt{\frac{2n_in_j}{n_i+n_j}} > SSR$
TOTAL LIFE	5	339 K/316 K*	0.345	0.350	no
	4	339 K/311 K	0.308	0.347	no
	3	339 K/325 K	0.083	0.341	no
	2	339 K/297 K	0.083	0.329	no
	4	297 K/316 K	0.295	0.347	no
	3	297 K/311 K*	0.251	0.341	no
	2	297 K/325 K	0.023	0.329	no
	3	325 K/316 K	0.198	0.341	no
	2	325 K/311 K	0.155	0.329	no
	2	311 K/316 K	0.070	0.329	no
LIFE TO A 0.3 mm CRACK	5	297 K/316 K	0.311	0.569	no
	4	297 K/311 K*	0.321	0.569	no
	3	297 K/325 K	0.258	0.569	no
	2	297 K/339 K*	0.143	0.567	no
	4	339 K/316 K	0.194	0.569	no
	3	339 K/311 K*	0.178	0.569	no
	2	339 K/325 K	0.142	0.567	no
	3	325 K/316 K*	0.046	0.564	no
	2	325 K/311 K	0.004	0.567	no
	2	311 K/316 K	0.049	0.567	no
LIFE FROM A 0.3 mm CRACK	5	339 K/316 K	0.382	0.596	no
	4	339 K/311 K*	0.440	0.596	no
	3	339 K/297 K*	0.294	0.596	no
	2	339 K/325 K	0.045	0.594	no
	4	325 K/316 K*	0.291	0.596	no
	3	325 K/311 K	0.314	0.596	no
	2	325 K/297 K	0.194	0.594	no
	3	297 K/316 K	0.141	0.596	no
	2	297 K/311 K*	0.146	0.594	no
	2	311 K/316 K	0.022	0.594	no

*Owing to equal sample size these comparisons can also be made using the unmodified version of Duncan's test The same result is obtained



NOTES

(1) MILL FINISH RETAINED ON ALL SURFACES.

(2) ALL HOLES MARKED THUS "A" ARE $18^{+0.05}_{+0}$ mm DIAMETER.

(3) SPECIAL TOLERANCE INDICATIONS ARE: $25.0 = 25 \pm 0.05$
$25.\bar{0} = 25 \pm 0.1$

Fig. 2.1 Specimen configuration for the VOUGHT contribution to the FACT programme

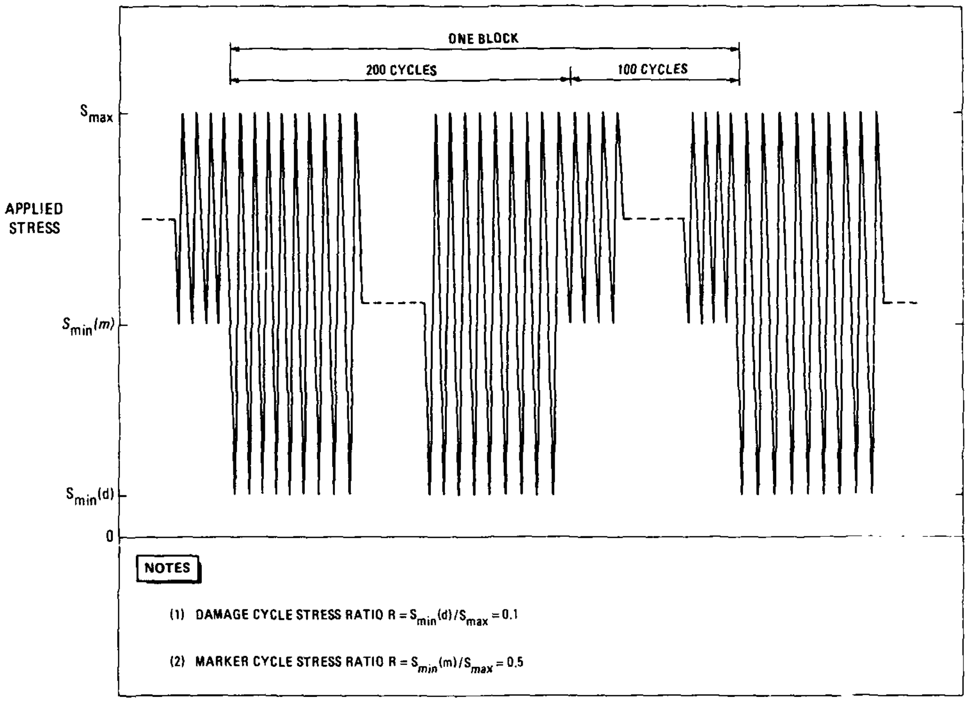


Fig. 2.2 Fatigue load history for the VOUGHT contribution to the FACT programme

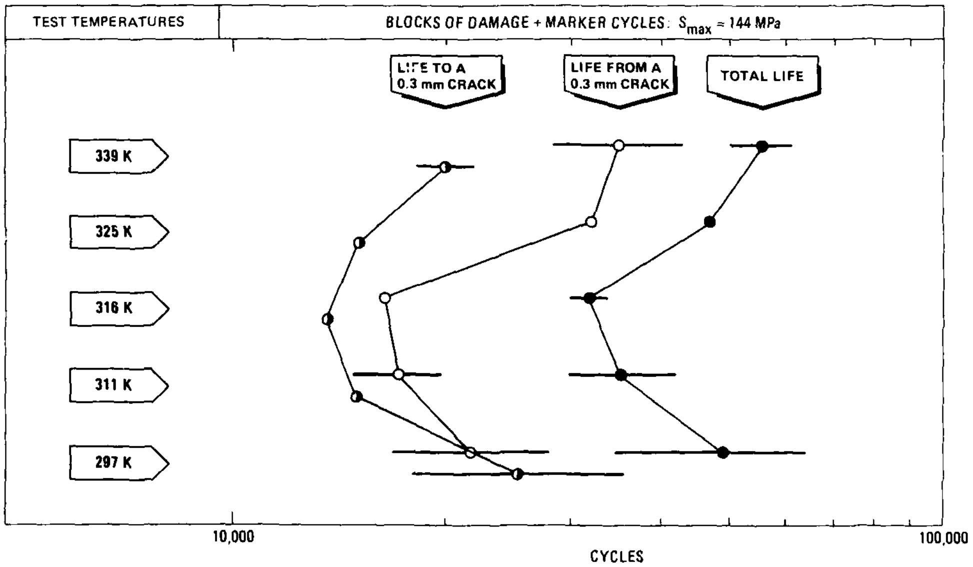


Fig. 2.3 VOUGHT salt spray fatigue life and fatigue crack initiation and propagation life data for 7075-T7651 single dogbone specimens with unprotected open holes

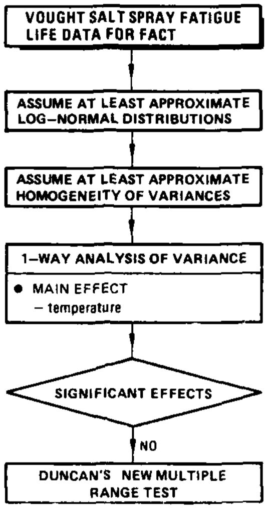


Fig. 2.4 Survey of statistical methods for analysing the VOUGHT salt spray fatigue life and fatigue crack initiation and propagation life data for FACT

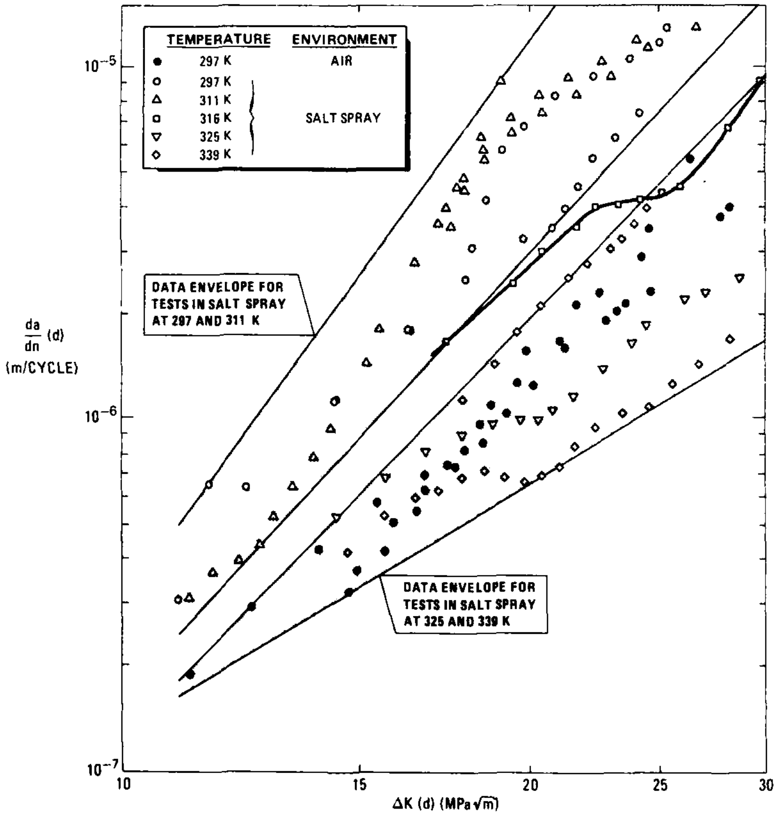


Fig. 2.5 Fatigue crack growth rate data for the VOUGHT contribution to FACT: da/dn and ΔK were calculated as though the tests were done with damage cycles only

3. THE SAAB CONTRIBUTION TO THE FACT PROGRAMME

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3.1 Introduction

The Aerospace Division of SAAB-SCANIA participated in the FACT supplemental programme with the assistance of the Structures Department of the Aeronautical Research Institute of Sweden FFA (references 1, 2). The main objectives of the SAAB contribution to FACT were to develop fatigue testing facilities for comparison of different corrosion protection systems and to compare results with those of the CFCTP core programme.

3.2 The Test Programme

An overview of the test programme is given in table 3.1. There were two types of specimen. The unnotched coupon specimens were used in an introductory study of the effects on fatigue life of outdoor pre-exposure and/or environmental fatigue in chambers specially constructed by the FFA. The 1½ dogbone specimens were from the same batch as the CFCTP core programme specimens and provided a basis for comparing the effects of environmental fatigue in the FFA chambers and the CFCTP salt spray cabinets.

3.2.1 Materials, specimen configurations and protection systems

The material for the unnotched coupon specimens was 3 mm thick clad sheet of aluminium alloy 7075-T6 from two batches (I and II). The specimen configuration is shown in figure 3.1. This has a parallel sided gauge section 25 mm x 20 mm at the centre of the specimen. Half the specimens were left as machined. The remainder were chromic acid anodised, without hot water sealing, according to SAAB-SCANIA specifications.

The 7075-T76 aluminium alloy 1½ dogbones were from the same batch as the CFCTP core programme specimens and with the same fastener hole size (press fit) and protection system, as discussed in detail in reference (3) and Part II of this report.

3.2.2 Mechanical testing conditions (static prestressing and fatigue)

All stresses were defined in terms of loads on the total cross-sections of the specimens in the gauge sections, i.e. including cladding layers (unnotched coupons) and fastener holes (1½ dogbones).

Before environmental exposure and fatigue testing the 1½ dogbone specimens were prestressed at 209 ± 10 K by applying two load cycles up to 215 MPa. The procedure for this is discussed in reference (3). The purpose of this low temperature prestressing was to ensure that the paint and primer layers were brittle and would crack around the Hi-Lok fastener holes, thereby simulating service damage that enables corrosion and corrosion fatigue to occur.

The fatigue testing of the 1½ dogbone specimens was done using an FFA-designed 50 kN load frame with MTS electrohydraulic equipment and load cell. Static calibration showed the load cell error to be within ± 1 % and ± 50 N. A strain gauged dummy coupon was used to check alignment. Bending and axial strains were determined at a tensile load of 5 kN. The in-plane bending strain was 2.3 % of the axial strain and therefore well within the 3 % limit specified in reference (3).

The fatigue load history was constant amplitude sinusoidal loading with a stress ratio $R = S_{min}/S_{max}$ of 0.1. The characteristic stress levels for the test programme have been indicated already in table 3.1. The stress level for the 1½ dogbone specimens was chosen to be the same as the lower stress level for the CFCTP core programme, i.e. $S_{max} = 144$ MPa. The tests were carried out at cycle frequencies of 1.4 Hz for the unnotched coupons and 0.5 Hz for the 1½ dogbone specimens.

3.2.3 Environmental conditions (pre-exposure, fatigue and corrosion fatigue)

Unnotched coupons scheduled for static exposure before fatigue testing (batch I) were placed on a roof in a light industry area 5 km from the centre of Stockholm for 8 months (June 1977 to January 1978). Thereafter they were wrapped and stored in a freezer until required for fatigue testing.

Half of the 1½ dogbone specimens were pre-exposed by the U.S. Naval Air Development Centre NADC before shipment to SAAB-SCANIA. The pre-exposure conditions were the same as in the CFCTP core programme, i.e. sealing of faying surface side edges and Hi-Lok collars to prevent corrosion except in the fastener head areas, followed by immersion for 72 hours in 5 % aqueous NaCl acidified by a predetermined amount of SO_2 gas and maintained at 315 ± 2 K.

Before fatigue testing all 1½ dogbone specimens were sealed at the faying surface side edges and Hi-Lok collars. The fatigue tests on unnotched coupons and 1½ dogbone specimens were done in specially constructed environmental chambers capable of being stacked to enable tests in series in the load frame. Drawings of the environmental chambers are shown in figure 3.2 and their parameters during testing are given in table 3.2.

Environmental influences on fatigue were studied by instituting alternating "wet" and "dry" phases. The wet phases started every 12 minutes and consisted of fatigue in humid air with condensation, and fatigue during immersion in distilled water. These phases were terminated when a dew point hygrometer sensed condensation on the surfaces of the coupons or specimens exposed to humid air. Thus in one case the wet phase corresponded to a continuous increase in humidity until condensation occurred, while in the other there was immediate and continuous wetting.

The dry phase was fatigue in low humidity air. In fact this was a drying phase, whereby it is unlikely that a relatively complicated specimen like the 1½ dogbone would dry out completely after immersion in water.

The conditions for fatigue in wet and dry air were established in the following way. Both chambers were open ended and filtered laboratory air was pumped through. This air was heated in the environmental chambers with or without water injection:

- water injection resulted in wet phase testing with humid air that caused condensation on coupons and specimens and maintained their temperatures
- straightforward heating resulted in low humidity air that provided a reference environment for unnotched coupons, see table 3.2, and also dried and maintained the temperatures of coupons and specimens during dry phase testing.

3.3 Results

The complete set of fatigue life and primary fatigue origin data for the SAAB contribution to FACT is given in table 3.3. The way in which the test programme was set up and the results had consequences for the statistical methods used to analyse the data. This will be discussed in section 3.3.1.

The fatigue life results are presented and statistically analysed in section 3.3.2. This is followed by statistical analysis of the primary fatigue origin data in section 3.3.3.

3.3.1 Statistical methods for analysing the data

A survey of the statistical methods for analysing the SAAB data is given in figure 3.3. Owing to the limited number and unequal sample sizes of the data it had to be assumed that they at least approximated to random samples from log-normally distributed populations with equal variance. Unequal sample sizes also meant that modified versions of the least significant difference test and Duncan's new multiple range test had to be used for "fine tuning" the analysis of variance results. More details of the statistical methods are given in Appendix II.

3.3.2 Fatigue life data

The SAAB fatigue life data are shown in figure 3.4. The 1½ dogbone specimen data are compared with CFCTP core programme data in figure 3.5. From these figures the following trends are observed:

(1) Unnotched coupons:

- wetting by repeated condensation or alternate immersion in distilled water reduced the fatigue lives
- the fatigue lives of as machined and chromic acid anodised specimens were similar.

(2) 1½ dogbones:

- the SAAB fatigue testing in air with repeated condensation or alternating immersion in distilled water was as severe as the CFCTP fatigue testing in salt spray.

The two trends for unnotched coupons were confirmed by two-way analysis of variance (table 3.4) and "fine tuning" using the least significant difference test (table 3.5) and Duncan's new multiple range test (table 3.6).

The SAAB 1½ dogbone data were analysed using one-way analysis of variance (table 3.4) and Duncan's new multiple range test (table 3.7). The analysis showed that there were no significant differences in fatigue lives, i.e. the four fatigue testing schedules were equivalent in severity. These data were also compared with CFCTP data using one-way analysis of variance (table 3.4) and the least significant difference test (table 3.8). This statistical comparison confirmed the forementioned trend, namely the surprising result that fatigue testing in air with repeated condensation or alternate immersion in distilled water was as severe as fatigue testing continuously in salt spray.

3.3.3 Primary fatigue origin data

The primary fatigue origin data for the SAAB 1½ dogbone tests were analysed using Fisher's exact test, table 3.9. Changing the environment (fatigue testing schedule) had no significant effects on the locations of primary fatigue origins.

3.4 Discussion

The results for both the unnotched coupons and 1½ dogbone specimens showed that repeated condensation or alternate immersion in distilled water reduced the fatigue lives. On the other hand, pre-exposure either outdoors for 8 months (unnotched coupons) or for 72 hours in acidified aqueous NaCl (1½ dogbones) had no significant effect.

As mentioned in section 3.3.2, comparison of SAAB and CFCTP 1½ dogbone fatigue life data gave the surprising result that fatigue testing in air with repeated condensation or alternate immersion in distilled water was as severe as fatigue testing continuously in salt spray. A contributing factor is the likelihood that the "dry" phases during the SAAB tests may not have been sufficient to dry out the specimens, especially for fatigue in air with alternating immersion.

Albeit, this result is still remarkable: in fact it is positive. The SAAB fatigue testing schedules are relevant to the flight-by-flight transpiration of aircraft structures, whereby alternate wetting by condensation and drying take place (reference 4). The humid air with repeated condensation is difficult to control in a laboratory test. Salt spray testing is also complicated and rather unpleasant to use in the proximity of expensive laboratory equipment. However, the repeated immersion test is easy to control. The similar effect on fatigue lives of all three environments means that the repeated immersion test is an attractive and convenient alternative for the more complicated testing procedures.

3.5 Conclusions

(1) Repeated condensation or alternate immersion in distilled water reduced the fatigue lives of unnotched coupons and 1½ dogbone specimens.

(2) Pre-exposure outdoors (unnotched coupons) or in acidified salt spray (1½ dogbones) had no significant effect on fatigue lives.

(3) For each fatigue testing schedule (environment) the lives of unnotched coupons in the as machined or chromic acid anodised conditions were similar.

(4) Comparison of the SAAB and CFCTP 1½ dogbone fatigue life data showed that fatigue testing in air with repeated condensation or alternate immersion in distilled water was as severe as fatigue testing continuously in salt spray.

(5) Changing the environment (fatigue testing schedule) had no significant effects on the locations of primary fatigue origins in the SAAB 1½ dogbone specimens.

3.6 References

1. L.E. Jarfall, "Comparison of corrosion fatigue in gaseous and liquid environments", SAAB-SCANIA Progress Report FKHU-80.21 (April 1980) plus Enclosures A-D (March 1981). The final report (in Swedish) was Aeronautical Research Institute of Sweden Technical Note FFA TN 1982-10, 1982, and was written by Å. Magnusson.

2. L.E. Jarfall and Å. Magnusson, "Fatigue testing of bolted joints in humid air and alternating immersion", Aeronautical Reseach Institute of Sweden Technical Note FFA TN 1982-34, 1982.

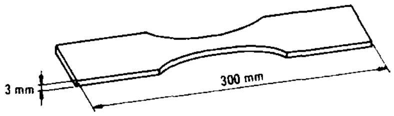
3. R.J.H. Wanhill and J.J. De Luccia, "An AGARD-coordinated corrosion fatigue cooperative testing programme", AGARD Report No. 695, February 1982.

4. W.E. Anderson, "Fatigue of aircraft structures", International Metallurgical Reviews, Vol. 17, pp. 240 - 263 (1972).

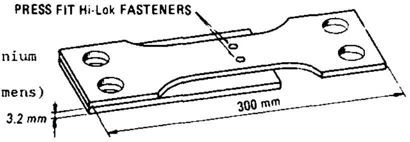
TABLE 3.1: OVERVIEW OF THE SAAB TEST PROGRAMME FOR FACT

MATERIALS AND SPECIMENS

- 3 mm thick 7075-T6 clad aluminium alloy sheet



  3.2 mm thick 7075-T76 aluminium alloy sheet
  (CFCTP core programme specimens)



PROTECTION SYSTEMS

- 7075-T6 (batches I and II): none and chromic acid anodising

  7075-T76: chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat

PROTECTION SYSTEM DAMAGE

- 7075-T76: two stress cycles at low temperature to crack paint and primer around the fastener heads

FATIGUE LOADING

- Constant amplitude, $S_{min}/S_{max} = 0.1$

FATIGUE ENVIRONMENTS

- Low humidity air; air with repeated condensation; alternating immersion in distilled water

STATIC PRE-EXPOSURE

- 7075-T6 clad (batch I): 8 months outdoors near Stockholm (light industry area)

  7075-T76: 72 hours in 5 % aqueous NaCl + SO_2 at 315 K

TEST PROGRAMME

SCHEDULES	UNNOTCHED COUPONS $S_{max} = 150$ MPa CYCLE FREQUENCY 1.4 Hz		1½ DOGBONES $S_{max} = 144$ MPa CYCLE FREQUENCY 0.5 Hz
	7075-T6 (BATCH II)	7075-T6 (BATCH I)	
fatigue in low humidity air	●		
pre-exposure + fatigue in low humidity air		●	
fatigue in air with repeated condensation	●		●
pre-exposure + fatigue in air with repeated condensation		●	●
fatigue with alternating immersion in distilled water	●		●
pre-exposure + fatigue with alternating immersion in distilled water		●	●

STATISTICAL ANALYSIS

- Fatigue lives and primary fatigue origins

TABLE 3.2: ENVIRONMENTAL CHAMBER PARAMETERS FOR THE SAAB CONTRIBUTION TO FACT

TYPE OF TEST	SPECIMEN ENVIRONMENT	PARAMETERS	UNNOTCHED COUPONS		1½ DOGBONE SPECIMENS	
REFERENCE	low humidity air	airflow air temperature near specimen relative humidity near specimen specimen temperature	100 ml/s 300 - 311 K 10 - 30 % 299 ± 0.5 K			
			REPEATED CONDENSATION	ALTERNATING IMMERSION	REPEATED CONDENSATION	ALTERNATING IMMERSION
ENVIRONMENTAL INFLUENCE	"wet": ● humid air with condensation ● distilled water	duration airflow water injection in air stream in evaporator water temperature specimen temperature	~ 150 s 100 ml/s 0.005 ml/s 299 ± 0.5 K	~ 150 s 100 ml/s 299 ± 0.5 K 299 ± 0.5 K	~ 150 s 150 ml/s 0.067 ml/s 303 ± 1 K	~ 150 s 150 ml/s 303 ± 1 K 303 ± 1 K
	"wet" and "dry"	air temperature near specimen	302 – 309 K	302 – 305 K	305 – 309 K	304 – 311 K
	"dry": ● drying by exposure to low humidity air	duration airflow relative humidity near specimen specimen temperature	570 s 100 ml/s 15 – 40 % 299 ± 0.5 K	570 s 100 ml/s 15 – 40 % 299 ± 0.5 K	570 s 150 ml/s ≤ 30 % 303 ± 1 K	570 s 150 ml/s ≤ 30 % 303 ± 1 K

TABLE 3.3: FATIGUE LIFE AND PRIMARY FATIGUE ORIGIN DATA FOR THE SAAB CONTRIBUTION TO FACT

TYPE OF SPECIMEN	CHARACTERISTIC STRESS LEVEL	MATERIALS AND CORROSION PROTECTION SYSTEMS		FATIGUE LIFE TO FAILURE (CYCLES AND LOG MEAN VALUES)/LOCATIONS OF PRIMARY ORIGINS OF FATIGUE *					
				fatigue in low humidity air	pre-exposure + fatigue in low humidity air	fatigue in air with repeated condensation	pre-exposure + fatigue in air with repeated condensation	fatigue with alternating immersion in distilled water	pre-exposure + fatigue with alternating immersion in distilled water
unnotched coupon	S_{max} = 150 MPa	7075-T6 clad (batch II)	as machined	505,000 486,000 436,000 454,000 469,000		383,000 317,000 358,000 284,000 333,000		296,000 215,000 258,000 191,000 237,000	
			chromic acid anodised	456,000 349,000 373,000 347,000 379,000		308,000 177,000 308,000 295,000 265,000		235,000 293,000 265,000 254,000 261,000	
		7075-T6 clad (batch I)	as machined		340,000 425,000 366,000 378,000 389,000 379,000		277,000 199,000 362,000 321,000 269,000		267,000 218,000 235,000 243,000 240,000
			chromic acid anodised		408,000 301,000 681,000 414,000 371,000 419,000		298,000 249,000 336,000 308,000 296,000		294,000 239,000 198,000 302,000 255,000
CFCTP core programme 1¼ dogbone	S_{max} = 144 MPa	7075-T76 with U.S. Navy protection system				153,000 R 112,000 E 91,400 F 57,300 R 97,300	201,000 C 32,800 F 46,300 F 67,300	62,900 S 56,800 F 55,400 R 105,000 F 67,500	51,900 R 93,700 E 34,000 E 101,000 Q,R 63,900

* Key to locations of fatigue origins in 1¼ dogbone specimens

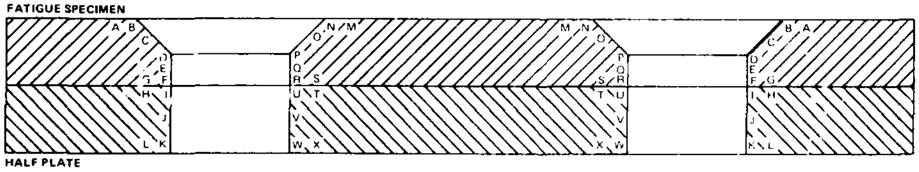


TABLE 3.4: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE)

TYPE OF SPECIMEN AND SOURCE	CHARACTERISTIC STRESS LEVEL	SOURCE OF VARIATION	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES F_o > F DISTRIBUTION VALUE
unnotched coupon	S_{max} = [illegible] MPa	● MAIN EFFECTS environment* anodizing	[illegible] [illegible]	[illegible] [illegible]	yes [illegible]
		● 2-WAY INTERACTIONS environment × anodizing	[illegible]	[illegible]	[illegible]
1 in dogbone (SAAB)	S_{max} = [illegible] MPa	● MAIN EFFECT environment*	[illegible]	[illegible]	[illegible]
1 in dogbone (SAAB and [illegible])	S_{max} = [illegible] MPa	● MAIN EFFECT environment*	[illegible]	[illegible]	yes

TABLE 3.5: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF ENVIRONMENT ON FATIGUE LIFE OF UNNOTCHED COUPONS

FATIGUE TESTING SCHEDULE	fatigue in low humidity air	pre-exposure + fatigue in low humidity air	fatigue in air with repeated condensation	pre-exposure + fatigue in air with repeated condensation	fatigue with alternating immersion in distilled water	pre-exposure + fatigue with alternating immersion in distilled water
LOG MEAN FATIGUE LIFE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SAMPLE SIZE n	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

$t_{0.025,18}$ = [illegible] $MS_{residual}$ = [illegible]

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	[illegible]	SIGNIFICANT DIFFERENCE [illegible]
fatigue in low humidity air/pre exposure + fatigue in low humidity air	[illegible]	[illegible]
fatigue in low humidity air/fatigue in air with repeated condensation*	[illegible]	yes
fatigue in low humidity air/pre exposure + fatigue in air with repeated condensation*	[illegible]	yes
fatigue in low humidity air/fatigue with alternating immersion in distilled water*	[illegible]	yes
fatigue in low humidity air/pre exposure + fatigue with alternating immersion in distilled water*	[illegible]	yes
pre-exposure + fatigue in low humidity air/fatigue in air with repeated condensation	[illegible]	yes
pre-exposure + fatigue in low humidity air/pre-exposure + fatigue in air with repeated condensation	[illegible]	yes
pre-exposure + fatigue in low humidity air/fatigue with alternating immersion in distilled water	[illegible]	[illegible]
pre-exposure + fatigue in low humidity air/pre-exposure + fatigue with alternating immersion in distilled water	[illegible]	[illegible]
fatigue in air with repeated condensation/pre exposure + fatigue in air with repeated condensation*	[illegible]	[illegible]
fatigue in air with repeated condensation/fatigue with alternating immersion in distilled water*	[illegible]	[illegible]
fatigue in air with repeated condensation/pre exposure + fatigue with alternating immersion in distilled water*	[illegible]	yes
pre exposure + fatigue in air with repeated condensation/fatigue with alternating immersion in distilled water*	[illegible]	[illegible]
pre exposure + fatigue in air with repeated condensation/pre-exposure + fatigue with alternating immersion in distilled water*	[illegible]	[illegible]
fatigue with alternating immersion in distilled water/pre-exposure + fatigue with alternating immersion in distilled water*	[illegible]	[illegible]

*Owing to equal sample size these comparisons can also be made using the unmodified least significant difference test. The same result is obtained.

TABLE 3.6: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % *CONFIDENCE) FOR UNNOTCHED COUPONS*

FATIGUE TESTING SCHEDULE	fatigue in low humidity air		pre-exposure + fatigue in low humidity air		fatigue in air with repeated condensation		pre-exposure + fatigue in air with repeated condensation		fatigue with alternating immersion in distilled water		pre-exposure + fatigue with alternating immersion in distilled water	
CORROSION PROTECTION SYSTEM	as machined	chromic acid anodised	as machined	chromic acid anodised	as machined	chromic acid anodised	as machined	chromic acid anodised	as machined	chromic acid anodised	as machined	chromic acid anodised
LOG MEAN FATIGUE LIFE	5.672	5.578	5.578	5.622	5.523	5.424	5.430	5.471	5.374	5.417	5.380	5.406
SAMPLE SIZE n	4	4	5	5	4	4	4	4	4	4	4	4

COMPARISONS OF DATA FOR TEST PARAMETER	TEST PARAMETER	p	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_i n_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i - \bar{x}_j)\sqrt{\frac{2n_i n_j}{n_i+n_j}} > SSR$
fatigue in low humidity air/pre-exposure + *fatigue in low humidity air*	as machined	2	0.198	0.220	no
	chromic acid anodised	2	0.093	0.220	no
fatigue in low humidity air/fatigue in air with repeated condensation*	as machined	3	0.298	0.231	yes
	chromic acid anodised	3	0.308	0.231	yes
fatigue in low humidity air/pre-exposure + fatigue in air with repeated condensation*	as machined	4	0.484	0.239	yes
	chromic acid anodised	2	0.214	0.220	no
fatigue in low humidity air/fatigue with alternating immersion in distilled water*	as machined	6	0.596	0.248	yes
	chromic acid anodised	4	0.322	0.239	yes
fatigue in low humidity air/pre-exposure + fatigue with alternating immersion in distilled water*	as machined	5	0.584	0.244	yes
	chromic acid anodised	5	0.344	0.244	yes
pre-exposure + fatigue in low humidity air/fatigue in air with repeated condensation	as machined	2	0.116	0.220	no
	chromic acid anodised	4	0.417	0.239	yes
pre-exposure + fatigue in low humidity air/pre-exposure + fatigue in air with repeated condensation	as machined	3	0.312	0.231	yes
	chromic acid anodised	3	0.318	0.231	yes
pre-exposure + fatigue in low humidity air/fatigue with alternating immersion in distilled water	as machined	5	0.430	0.244	yes
	chromic acid anodised	5	0.432	0.244	yes
pre-exposure + fatigue in low humidity air/pre-exposure + fatigue with alternating immersion in distilled water	as machined	4	0.417	0.239	yes
	chromic acid anodised	6	0.455	0.248	yes
fatigue in air with repeated condensation/pre-exposure + fatigue in air with repeated condensation*	as machined	2	0.186	0.220	no
	chromic acid anodised	2	0.094	0.220	no
fatigue in air with repeated condensation/fatigue with alternating immersion in distilled water*	as machined	4	0.298	0.239	yes
	chromic acid anodised	2	0.014	0.220	no
fatigue in air with repeated condensation/pre-exposure + fatigue with alternating immersion in distilled water*	as machined	3	0.286	0.231	yes
	chromic acid anodised	3	0.036	0.231	no
pre-exposure + fatigue in air with repeated condensation/fatigue with alternating immersion in distilled water*	as machined	3	0.112	0.231	no
	chromic acid anodised	3	0.108	0.231	no
pre-exposure + fatigue in air with repeated condensation/pre-exposure + fatigue with alternating immersion in distilled water*	as machined	2	0.100	0.220	no
	chromic acid anodised	4	0.130	0.239	no
fatigue with alternating immersion in distilled water/pre-exposure + fatigue with alternating immersion in distilled water*	as machined	2	0.012	0.220	no
	chromic acid anodised	2	0.022	0.220	no

*Owing to equal sample size these comparisons can also be made using the unmodified version of Duncan's test. The same result is obtained.

COMPARISONS OF DATA PER TEST PARAMETER	TEST PARAMETER	p	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SSR	SIGNIFICANT DIFFERENCE DIFFERENCE > SSR
as machined/chromic acid anodised	fatigue in low humidity air	2	0.094	0.111	no
	pre-exposure + fatigue in low humidity air	2	0.044	0.100	no
	fatigue in air with repeated condensation	2	0.099	0.111	no
	pre-exposure + fatigue in air with repeated condensation	2	0.041	0.111	no
	fatigue with alternating immersion in distilled water	2	0.043	0.111	no
	pre-exposure + fatigue with alternating immersion in distilled water	2	0.026	0.111	no

TABLE 3.7: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR SAAB 1½ DOGBONES

FATIGUE TESTING SCHEDULE	fatigue in air with repeated condensation	pre-exposure + fatigue in air with repeated condensation	fatigue with alternating immersion in distilled water	pre-exposure + fatigue with alternating immersion in distilled water
LOG MEAN FATIGUE LIFE	4.988	4.828	4.829	4.806
SAMPLE SIZE n	4	3	4	4

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULE	p	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_in_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i - \bar{x}_j) \sqrt{\frac{2n_in_j}{n_i+n_j}} > SSR$
fatigue in air with repeated condensation/pre-exposure + fatigue in air with repeated condensation	3	0.296	0.788	no
fatigue in air with repeated condensation/fatigue with alternating immersion in distilled water*	2	0.318	0.753	no
fatigue in air with repeated condensation/pre exposure + fatigue with alternating immersion in /distilled water*	4	0.364	0.809	no
pre-exposure + fatigue in air with repeated condensation/fatigue with alternating immersion in /distilled water	2	0.002	0.753	no
pre-exposure + fatigue in air with repeated condensation/pre-exposure + fatigue with alternating /immersion in distilled water	2	0.041	0.753	no
fatigue with alternating immersion in distilled water/pre-exposure + fatigue with alternating /immersion in distilled water*	3	0.046	0.788	no

*Owing to equal sample size these comparisons can also be made using the unmodified version of Duncan's test. The same result is obtained

TABLE 3.8: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF ENVIRONMENT ON FATIGUE LIFE OF SAAB AND CFCTP 1½ DOGBONES

FATIGUE TESTING SCHEDULE	CFCTP				SAAB			
	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	fatigue in air with repeated condensation	pre-exposure + fatigue in air with repeated condensation	fatigue with alternating immersion in distilled water	pre-exposure + fatigue with alternating immersion in distilled water
LOG MEAN FATIGUE LIFE	5.125	5.072	4.962	4.819	4.988	4.828	4.829	4.806
SAMPLE SIZE n	35	28	36	35	4	3	4	4

$t_{0.025,141} = 1.98$ $MS_{residual} = 0.045$

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	t	SIGNIFICANT DIFFERENCE $(t > t_{0.025,141})$
fatigue in air/fatigue in air with repeated condensation	1.22	no
fatigue in air/pre-exposure + fatigue in air with repeated condensation	2.33	yes
fatigue in air/fatigue with alternating immersion in distilled water	2.64	yes
fatigue in air/pre-exposure + fatigue with alternating immersion in distilled water	2.85	yes
pre-exposure + fatigue in air/fatigue in air with repeated condensation	0.24	no
pre-exposure + fatigue in air/pre-exposure + fatigue in air with repeated condensation	1.89	no
pre-exposure + fatigue in air/fatigue with alternating immersion in distilled water	2.14	yes
pre-exposure + fatigue in air/pre-exposure + fatigue with alternating immersion in distilled water	2.35	yes
fatigue in salt spray/fatigue in air with repeated condensation	0.23	no
fatigue in salt spray/pre-exposure + fatigue in air with repeated condensation	1.05	no
fatigue in salt spray/fatigue with alternating immersion in distilled water	1.19	no
fatigue in salt spray/pre-exposure + fatigue with alternating immersion in distilled water	1.40	no
pre-exposure + fatigue in salt spray/fatigue in air with repeated condensation	1.51	no
pre-exposure + fatigue in salt spray/pre-exposure + fatigue in air with repeated condensation	0.07	no
pre-exposure + fatigue in salt spray/fatigue with alternating immersion in distilled water	0.09	no
pre-exposure + fatigue in salt spray/pre-exposure + fatigue with alternating immersion in distilled water	0.12	no
fatigue in air with repeated condensation/pre-exposure + fatigue in air with repeated condensation	0.94	no
fatigue in air with repeated condensation/fatigue with alternating immersion in distilled water*	1.06	no
fatigue in air with repeated condensation/pre-exposure + fatigue with alternating immersion in distilled water*	1.21	no
pre-exposure + fatigue in air with repeated condensation/fatigue with alternating immersion in distilled water	0.01	no
pre-exposure + fatigue in air with repeated condensation/pre-exposure + fatigue with alternating immersion in distilled water	0.14	no
fatigue with alternating immersion in distilled water/pre-exposure + fatigue with alternating immersion in distilled water*	0.15	no

*Owing to equal sample size these comparisons can also be made using the unmodified least significant difference test. The same result is obtained

TABLE 3.9: FISHER'S EXACT TEST FOR ANALYSING THE SAAB 1½ DOGBONE PRIMARY FATIGUE ORIGIN DATA (95 % CONFIDENCE)

- CONSTRUCTION OF INITIAL *CONTINGENCY TABLE*

PRIMARY FATIGUE ORIGINS VERSUS ENVIRONMENT

ROWS, r (LOCATIONS OF PRIMARY FATIGUE ORIGINS)	COLUMNS, c (FATIGUE TESTING SCHEDULES)				ROW TOTALS, R
	fatigue in air with repeated condensation	pre-exposure + fatigue in air with repeated condensation	fatigue with alternating immersion in distilled water	pre-exposure + fatigue with alternating immersion in distilled water	
E/Q	1	0	0	3	4
F/R	3	2	3	2	10
G/S	0	0	1	0	1
C/O	0	1	0	0	1
COLUMN TOTALS, C	4	3	4	5	16 = N

- MODIFICATION OF THE CONTINGENCY TABLE (SEE TEXT)

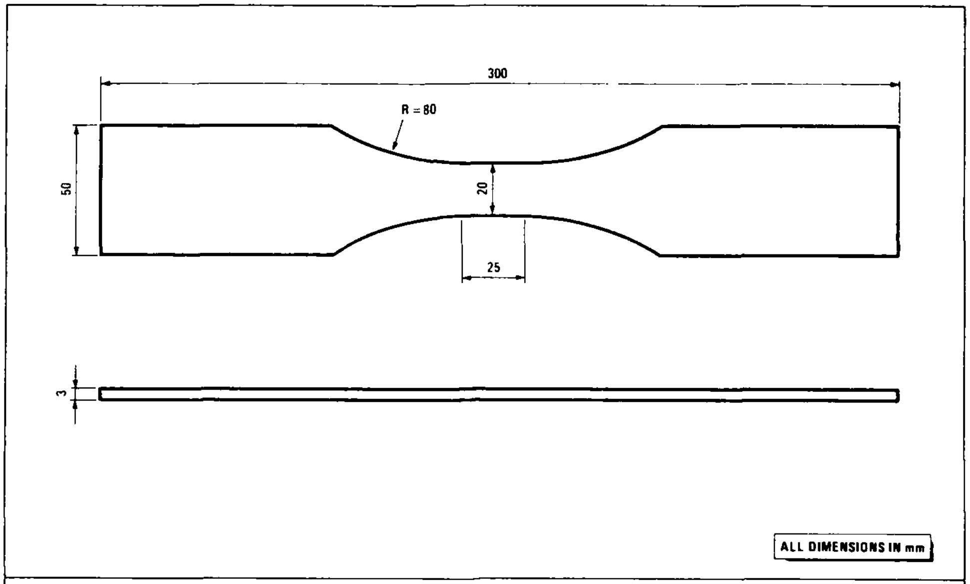
PRIMARY FATIGUE ORIGINS VERSUS ENVIRONMENT

ROWS, r (LOCATIONS OF PRIMARY FATIGUE ORIGINS)	COLUMNS, c (COMBINATIONS OF FATIGUE TESTING SCHEDULES)		ROW TOTALS, R
	pre-exposure and/or fatigue in air with repeated condensation	pre-exposure and/or fatigue with alternating immersion in distilled water	
E/Q or C/O	2	3	5
F/R or G/S	5	6	11
COLUMN TOTALS, C	7	9	16 = N

- CALCULATION OF P AND COMPARISON WITH $\alpha = 5$ %

$$P = \frac{5! \times 11! \times 7! \times 9!}{16! \times 2! \times 3! \times 5! \times 6!} = 0.6346$$

SINCE P = 0.6346 IS GREATER THAN $\alpha = 0.05$ IT MAY BE CONCLUDED WITH 95 % CONFIDENCE THAT THERE IS NO SIGNIFICANT ASSOCIATION BETWEEN PRIMARY FATIGUE ORIGINS AND ENVIRONMENTS (FATIGUE TESTING SCHEDULES).



NOTES

(1) MILL FINISH RETAINED ON SIDE SURFACES.

(2) TOLERANCE INDICATIONS NOT INCLUDED.

Fig. 3.1 Unnotched specimen configuration for the SAAB programme

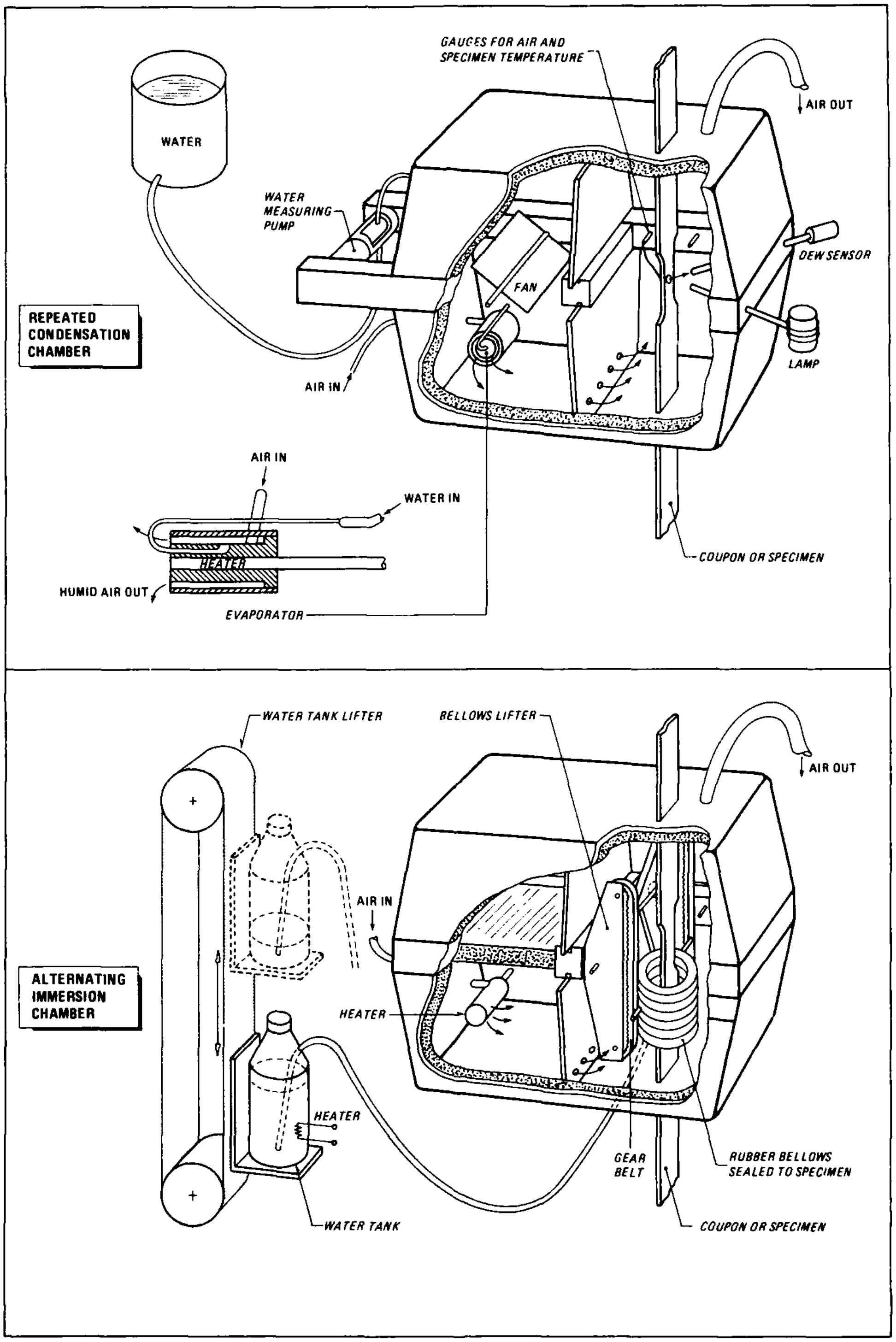


Fig. 3.2 The FFA environmental chambers used in the SAAB contribution to the FACT programme

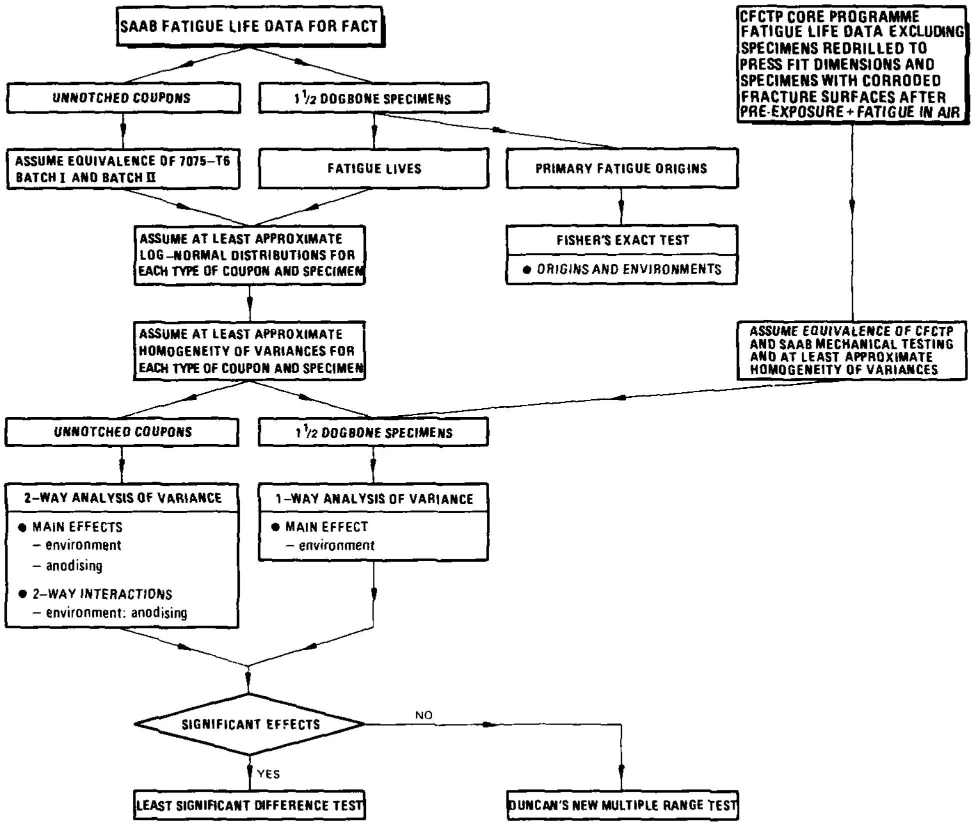


Fig. 3.3 Survey of statistical methods for analysing the SAAB fatigue life data for FACT

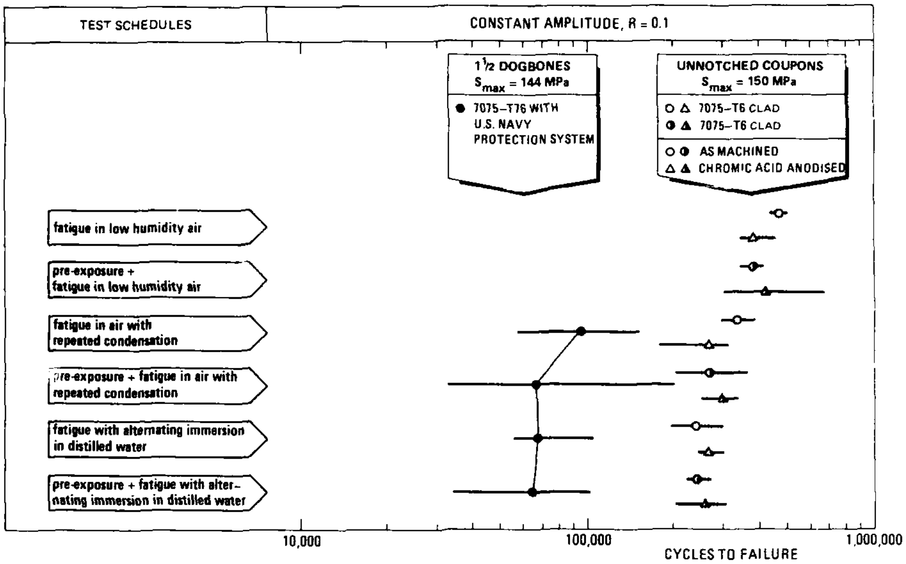


Fig. 3.4 SAAB fatigue life data contribution to the FACT programme

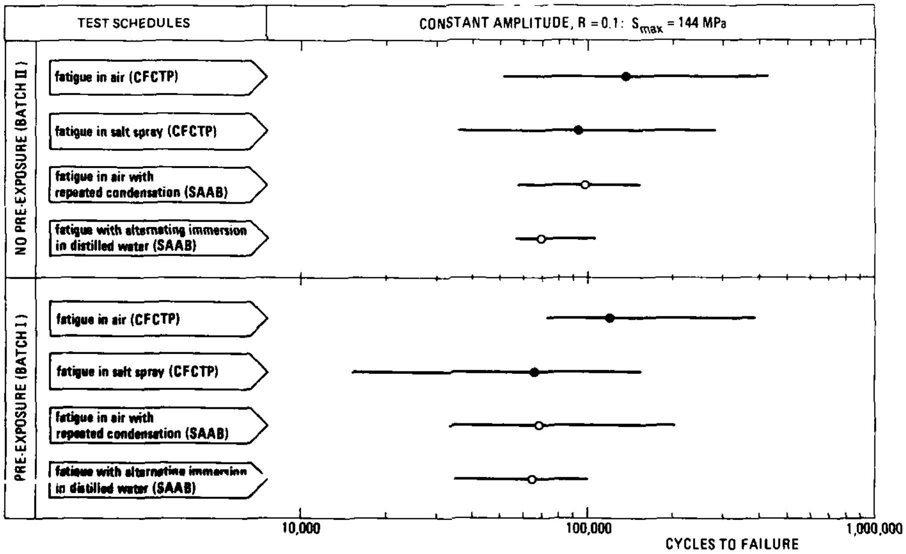


Fig. 3.5 Comparison of SAAB FACT contribution and CFCTP core programme data. The CFCTP core programme data are for all specimens except those redrilled to press fit dimensions and those with corroded fracture surfaces after pre-exposure + fatigue in air, see tables 2 and 9 in Part II of this report

4. THE NADC CONTRIBUTION TO THE FACT PROGRAMME

J.J. De Luccia, Naval Air Development Centre NADC, Aeronautical Materials Laboratory, Warminster, Pennsylvania, USA

4.1 Introduction

The NADC contribution to FACT examined the effect of fastener fit (interference versus press fit) and the use of a flexible, elastomeric primer instead of the standard non-flexible primer selected for the CFCTP core programme. The advantage of using flexible paint systems to improve the corrosion protection of aircraft has been known for many years. However, there appear to be no data comparing flexible and non-flexible paint systems with respect to fatigue and corrosion fatigue of aircraft structural joints.

4.2 The Test Programme

An overview of the test programme is given in table 4.1. All specimens were 1½ dogbones from the same material as the CFCTP core programme specimens but drilled to interference fit dimensions, as discussed in detail in reference (1). Cadmium plated steel Hi-Lok fasteners were used. The diameter of the holes for the fasteners was 6.248 ± 0.0127 mm, see figure 1.1 of the introduction to this part of the report.

4.2.1 Protection systems and specimen assembly

Half the specimens had the same U.S. Navy paint scheme as in the CFCTP core programme, see reference (1) and Part II of this report. The remaining specimens were painted and assembled in the same way except that a flexible, elastomeric primer "Koroflex" was used instead of the standard primer. Koroflex is a strontium chromate inhibited polyurethane primer that retains flexibility even at low temperatures (209 K).

4.2.2 Mechanical testing conditions (static prestressing and fatigue)

All stresses were defined in terms of loads on the total cross-section of the fatigue specimen dogbone at the location of the centreline between the fasteners, i.e. the fastener holes were included in the cross-sectional area. Before environmental exposure and fatigue testing the specimens were prestressed at 209 ± 10 K by applying two load cycles up to a stress of 215 MPa. The procedure for this is discussed in reference (1). The purpose of this low temperature prestressing was to ensure that intact non-flexible paint and primer layers would crack around the Hi-Lok fasteners holes, thereby simulating service damage that enables corrosion and corrosion fatigue to occur.

The fatigue load history was constant amplitude sinusoidal loading with a stress ratio $R = S_{min}/S_{max}$ of 0.1 and a maximum stress of 210 MPa. Detailed procedures for fatigue testing are given in reference (1).

4.2.3 Environmental conditions (pre-exposure, fatigue and corrosion fatigue)

Specimens scheduled for static exposure to an aggressive environment before fatigue testing were sealed at the faying surface side edges and Hi-Lok collars to prevent corrosion except in the fastener head areas. The procedure for static pre-exposure is described in detail in reference (1). The specimens were immersed for 72 hours in 5 % aqueous NaCl acidified by a predetermined amount of SO_2 gas and maintained at 315 ± 2 K. The specimen cleaning procedure after pre-exposure followed the amendment in section 4.4 of Part 2 of reference (1).

For fatigue testing all specimens were electrically insulated from the loading grips and bolts by polymeric liners and bushings. Specimens to be fatigued in salt spray were also sealed at the faying surface side edges and Hi-Lok collars. The fatigue environments were laboratory air and 5 % aqueous NaCl salt spray acidified with H_2SO_4 to pH 4, both at a nominal temperature of 295 K. The salt spray tests were done in a specially constructed cabinet, fully described in reference (1). The cyclic loading frequencies were as follows:

- fatigue in air, 2 Hz
- fatigue in salt spray, 0.5 Hz.

4.3 Results

The complete set of fatigue life and primary fatigue origin data for the NADC contribution to FACT is given in table 4.2. The way in which the test programme was set up had consequences for the statistical methods used to analyse the data. This will be discussed in section 4.3.1.

The fatigue life results are presented and statistically analysed in section 4.3.2. This is followed by presentation and statistical analysis of the primary fatigue origin data in section 4.3.3.

4.3.1 Statistical methods for analysing the data

A survey of the statistical methods for analysing the NADC data is given in figure 4.1. Owing to the limited number of data it had to be assumed that they at least approximated to random samples from log-normally distributed populations. Also, comparison of the data with CFCTP core programme data meant that equal variances had to be assumed and that for some "fine tuning" of analysis of variance results modified versions of the least significant difference test and Duncan's new multiple range test had to be used. More details of the statistical methods are given in Appendix II.

4.3.2 Fatigue life data

The fatigue life data are shown in figure 4.2. The data indicate the following trends:

(1) For specimens with interference fit Hi-Loks the use of Koroflex instead of a standard U.S. Navy primer appears to have been beneficial in all three environments.

(2) The use of interference fit Hi-Loks instead of press fit Hi-Loks did not improve fatigue life. (Interference fit fasteners are usually considered to have a beneficial effect on fatigue life.)

(3) The salt spray environment was particularly detrimental to fatigue life.

As will be discussed, statistical analysis confirmed trend (2) and showed trends (1) and (3) to be partly true.

The Box test was used to check for homogeneity of variances of the NADC data, see table 4.3. The variances were not all equal. However, analysis of variance is a very robust statistical technique, such that approximate compliance with the criterion of homogeneity of variances is sufficient for continuing the statistical treatment of the fatigue life data.

Analysis of variance was carried out separately for the complete set of NADC data and a combination of NADC and CFCTP core programme data for specimens using the standard U.S. Navy primer. The results are summarised in table 4.4. The main effects of environment, primer and fastener fit were found to be significant. Since there were only two types of primer and fastener fit, it is obvious that the significant differences were between the standard and Koroflex primers and the press and interference fit Hi-Loks. Thus it was not necessary to "fine tune" these results using the least significant difference test. However, this test was used to investigate the effect of environment (fatigue testing schedule). The results are given in table 4.5. Significant differences in fatigue lives were found mainly as a consequence of fatigue in salt spray.

According to the analysis of variance the other potential sources of variation (environment : primer and environment : fastener fit interactions) were not significant. These were further investigated using Duncan's new multiple range test. The results are listed in tables 4.6 and 4.7, and show the following:

- for specimens with interference fit Hi-Loks the use of Koroflex instead of the standard primer was significantly beneficial only for pre-exposure + fatigue in salt spray
- use of interference fit Hi-Loks instead of press fit Hi-Loks was either detrimental or had no significant effect on fatigue life
- the salt spray environment was particularly detrimental to fatigue life for specimens using the standard primer but not for specimens using Koroflex.

4.3.3 Primary fatigue origin data

The χ^2 test of independence, Yates' corrected χ^2 test and Fisher's exact test were used to analyse the primary fatigue origin data for the NADC contribution to FACT and the relevant CFCTP core programme specimens. The results are given in table 4.8. Neither environment (fatigue testing schedule), type of primer nor fastener fit had significant effects on the locations of fatigue origins for the test conditions selected.

4.4 Discussion

The present test results show that use of the flexible, elastomeric primer "Koroflex" was significantly beneficial to the fatigue life of 1½ dogbone specimens assembled with interference fit Hi-Loks and fatigued in salt spray. Overall the use of Koroflex appears to have been beneficial as compared to the use of a standard, non-flexible U.S. Navy primer.

Use of interference fit Hi-Loks instead of press fit Hi-Loks did not improve fatigue life. The reason is that under load the 1½ dogbone specimen exhibits secondary bending that increases when the clearance between fasteners and holes is reduced, see references (2, 3) and Appendix 1. This characteristic behaviour tends to nullify the usually beneficial effect on fatigue life of using interference fit fasteners.

Changing from fatigue in air, with or without pre-exposure, to pre-exposure + fatigue in salt spray resulted in significantly shorter fatigue lives for specimens using the standard primer, irrespective of fastener fit. The use of Koroflex resulted in the detrimental effect of salt spray becoming statistically insignificant.

4.5 Conclusions

(1) Use of the flexible, elastomeric primer "Koroflex" instead of a standard, non-flexible U.S. Navy primer was beneficial to fatigue life, notably in a salt spray environment.

(2) Use of interference fit Hi-Loks instead of press fit Hi-Loks did not improve the fatigue life of 1½ dogbone specimens.

(3) Changing from fatigue in air, with or without pre-exposure, to pre-exposure + fatigue in salt spray resulted in significantly shorter fatigue lives for specimens using the standard U.S. Navy primer. However, the use of Koroflex resulted in statistically equivalent fatigue lives.

(4) Neither environment (fatigue testing schedule), type of primer nor fastener fit had significant effects on the locations of primary origins of fatigue.

4.6 References

1. R.J.H. Wanhill and J.J. De Luccia, "An AGARD-coordinated corrosion fatigue cooperative testing programme", AGARD Report No. 695, February 1982.

2. H.H. van der Linden, "Fatigue rated fastener systems", AGARD Report No. 721, November 1985.

3. H.H. van der Linden, L. Lazzeri and A. Lanciotti, "Fatigue rated fastener systems in 1½ dogbone specimens", NLR Technical Report TR 86082 U, August 1986.

TABLE 4.1: OVERVIEW OF THE NADC TEST PROGRAMME FOR FACT

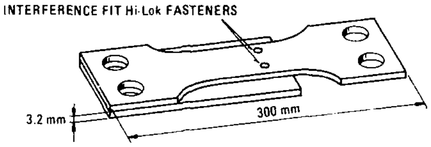
<table>
<tr><td>MATERIAL</td><td>●</td><td>3.2 mm thick 7075-T76 aluminium alloy sheet (CFCTP core programme material)</td></tr>
<tr><td>SPECIMEN</td><td>●</td><td>
</td></tr>
<tr><td>PROTECTION SYSTEMS</td><td>●</td><td>Chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat;
Chromate conversion + Koroflex elastomeric inhibited polyurethane primer + aliphatic polyurethane topcoat</td></tr>
<tr><td>PROTECTION SYSTEM DAMAGE</td><td>●</td><td>Two stress cycles at low temperature to crack non-flexible paint and primer around the fastener heads</td></tr>
<tr><td>FATIGUE LOADING</td><td>●</td><td>Constant amplitude, $S_{min}/S_{max} = 0.1$, $S_{max} = 210$ MPa</td></tr>
<tr><td>FATIGUE ENVIRONMENTS</td><td>●</td><td>Laboratory air; 5 % aqueous NaCl salt spray with pH 4</td></tr>
<tr><td>STATIC PRE-EXPOSURE</td><td>●</td><td>72 hours in 5 % aqueous NaCl + SO_2 at 315 K</td></tr>
<tr><td>TEST PROGRAMME</td><td>●</td><td>
<table>
<tr><th>SCHEDULES</th><th>STANDARD PRIMER</th><th>KOROFLEX PRIMER</th></tr>
<tr><td>fatigue in air</td><td>●</td><td>●</td></tr>
<tr><td>pre-exposure + fatigue in air</td><td>●</td><td>●</td></tr>
<tr><td>pre-exposure + fatigue in salt spray</td><td>●</td><td>●</td></tr>
</table>
</td></tr>
<tr><td>STATISTICAL ANALYSIS</td><td>●</td><td>Fatigue lives and primary fatigue origins</td></tr>
</table>

TABLE 4.2: FATIGUE LIFE AND PRIMARY FATIGUE ORIGIN DATA FOR THE NADC CONTRIBUTION TO FACT

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	PRIMER TYPE	FATIGUE LIFE TO FAILURE (CYCLES AND LOG MEAN VALUES) AND LOCATIONS OF PRIMARY ORIGINS OF FATIGUE*		
			fatigue in air	pre-exposure + fatigue in air	pre-exposure + fatigue in salt spray
constant amplitude R = 0.1	S_{max} = 210 MPa	STANDARD U.S. NAVY (NON-FLEXIBLE)	7,833 R 15,326 E 15,127 F 19,129 Q 13,652	9,128 Q 19,207 F 12,723 E 14,739 F 13,465	6,094 E 9,774 R 7,732 D 5,183 R 6,990
		KOROFLEX (FLEXIBLE)	20,109 E 20,804 E,F 20,474 E 22,824 Q 21,027	9,812 E 17,137 D 20,987 Q 29,197 G 17,911	12,446 E 15,490 E,R 14,208 E 15,951 E 14,458

* KEY TO LOCATIONS OF FATIGUE ORIGINS

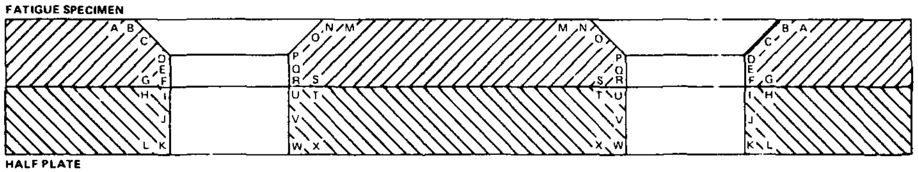


TABLE 4.3: BOX TEST FOR HOMOGENEITY OF VARIANCES OF NADC CONTRIBUTION TO FACT (95 % CONFIDENCE)

FATIGUE TESTING SCHEDULE	SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - x)^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
fatigue in air	1 STANDARD 2 KOROFLEX	4 4	0.084 0.002	3 3	0.333 0.333	0.028 0.001	− 1.552 − 3.224	− 4.655 − 9.671
	k = 2							
	SUM	–	–	–	0.666	–	–	− 14.322
	POOLED	–	0.086	6	0.167	0.014	− 1.8[illegible]	− 11.062
	DIFFERENCE	–	–	–	$D_1 = 0.499$	–	–	$D_2 = 3.260$

$K = 2.3026\ D_2 = 7.506$ $\quad L = \frac{D_1}{3(k-1)} = 0.166$ $\quad \nu_1 = k - 1 = 1$ $\quad \nu_2 = \frac{k+1}{L^2} = 109$

$D = \frac{\nu_2}{1 - L + (2/\nu_2)} - K = 120.376$ $\quad F_o = \frac{K/\nu_1}{D/\nu_2} = 6.79$[illegible] WITH 1 AND 109 DEGREES OF FREEDOM

FOR $\alpha = 5$ % AND 1 AND 109 DEGREES OF FREEDOM F = 3.94. SINCE 6.79[illegible] > 3.94 THE POPULATION VARIANCES ARE NOT EQUAL

FATIGUE TESTING SCHEDULE	SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - x)^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
pre-exposure + fatigue in air	1 STANDARD 2 KOROFLEX	4 4	0.054 0.118	3 3	0.333 0.333	0.018 0.039	− 1.7[illegible] − 1.40[illegible]	− 5.22[illegible] − 4.21[illegible]
	k = 2							
	SUM	–	–	–	0.666	–	–	− [illegible].439
	POOLED	–	0.172	6	0.167	0.029	− 1.5[illegible]3	− [illegible].2[illegible]6
	DIFFERENCE	–	–	–	$D_1 = 0.499$	–	–	$D_2 = 0.183$

$K = 2.3026\ D_2 = 0.421$ $\quad L = \frac{D_1}{3(k-1)} = 0.166$ $\quad \nu_1 = k - 1 = 1$ $\quad \nu_2 = \frac{k+1}{L^2} = 109$

$D = \frac{\nu_2}{1 - L + (2/\nu_2)} - K = 127.461$ $\quad F_o = \frac{K/\nu_1}{D/\nu_2} = 0.360$ WITH 1 AND 109 DEGREES OF FREEDOM

FOR $\alpha = 5$ % AND 1 AND 109 DEGREES OF FREEDOM F = 3.94 SINCE 0.360 < 3.94 THE POPULATION VARIANCES ARE EQUAL

FATIGUE TESTING SCHEDULE	SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - x)^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
pre-exposure + fatigue in salt spray	1 STANDARD 2 KOROFLEX	4 4	0.043 0.007	3 3	0.333 0.333	0.014 0.002	− 1.8[illegible] − 2.63[illegible]	− 5.[illegible] − 7.842
	k = 2							
	SUM	–	–	–	0.666	–		− 13.41[illegible]
	POOLED	–	0.050	6	0.167	0.008	− 2.0[illegible]9	− 12.4[illegible]5
	DIFFERENCE	–		–	$D_1 = 0.499$	–	–	$D_2 = $ [illegible].93[illegible]

$K = 2.3026\ D_2 = 2.158$ $\quad L = \frac{D_1}{3(k-1)} = 0.166$ $\quad \nu_1 = k - 1 = 1$ $\quad \nu_2 = \frac{k+1}{L^2} = 109$

$D = \frac{\nu_2}{1 - L + (2/\nu_2)} - K = 125.724$ $\quad F_o = \frac{K/\nu_1}{D/\nu_2} = 1.871$ WITH 1 AND 109 DEGREES OF FREEDOM

FOR $\alpha = 5$ % AND 1 AND 109 DEGREES OF FREEDOM F = 3.94. SINCE 1.871 < 3.94 THE POPULATION VARIANCES ARE EQUAL

TABLE 4.4: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE)

[illegible]	[illegible]	[illegible]
[illegible]	● [illegible] ● [illegible]	[illegible]
[illegible]	● ●	[illegible]

[illegible]

TABLE 4.6: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR THE NADC FACT DATA

FATIGUE TESTING SCHEDULE	fatigue in air		pre-exposure + fatigue in air		pre exposure + fatigue in salt spray	
PRIMER	standard	Koroflex	standard	Koroflex	standard	Koroflex
LOG MEAN FATIGUE LIFE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SAMPLE SIZE n	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TEST PARAMETER	P	COMPARISONS OF DATA PER TEST PARAMETER	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SSR	SIGNIFICANT DIFFERENCE (DIFFERENCE > SSR)
fatigue in air	2	standard U.S. Navy primer/Koroflex	0.188	0.143	no
pre-exposure + fatigue in air	2		0.124	0.193	no
pre-exposure + fatigue in salt spray	2		0.316	0.143	yes
standard U.S. Navy primer	3	fatigue in air/pre-exposure + fatigue in salt spray	0.242	0.203	yes
	2	fatigue in air/pre-exposure + fatigue in air	0.066	0.143	no
	2	pre exposure + fatigue in air/pre exposure + fatigue in salt spray	0.265	0.143	yes
Koroflex	3	fatigue in air/pre exposure + fatigue in salt spray	0.163	0.203	no
	2	fatigue in air/pre exposure + fatigue in air	[illegible]	0.193	no
	2	pre exposure + fatigue in air/pre exposure + fatigue in salt spray	0.093	0.143	no

TABLE 4.7: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR THE NADC FACT DATA (STANDARD U.S. NAVY PRIMER) AND CFCTP* DATA (S_{max} = 210 MPa)

FATIGUE TESTING SCHEDULE	fatigue in air		pre exposure + fatigue in air		pre exposure + fatigue in salt spray	
FASTENER FIT	press	interference	press	interference	press	interference
LOG MEAN FATIGUE LIFE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SAMPLE SIZE n	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TEST PARAMETER	P	COMPARISONS OF DATA PER TEST PARAMETER	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES [illegible]	SSR	SIGNIFICANT DIFFERENCE [illegible]
fatigue in air	[illegible]	press fit [illegible] interference fit [illegible]	[illegible]	[illegible]	[illegible]
pre exposure + fatigue in air	[illegible]		[illegible]	[illegible]	[illegible]
pre exposure + fatigue in salt spray	[illegible]		[illegible]	[illegible]	[illegible]
press fit holes	3	fatigue in air/pre exposure + fatigue in salt spray**	[illegible]	[illegible]	[illegible]
	[illegible]	fatigue in air/pre exposure + fatigue in air	[illegible]	[illegible]	[illegible]
	[illegible]	pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]

TEST PARAMETER	P	COMPARISONS OF DATA PER TEST PARAMETER	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SSR	SIGNIFICANT DIFFERENCE [illegible]
interference fit holes	3	fatigue in air/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]
	[illegible]	fatigue in air/pre exposure + fatigue in air	[illegible]	[illegible]	[illegible]
	2	pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]

*[illegible]

**[illegible]

TABLE 4.8[illegible]: SUMMARY OF χ^2 TEST, YATES' CORRECTED χ^2 TEST AND FISHER'S EXACT TEST RESULTS FOR THE PRIMARY FATIGUE ORIGIN DATA (95 % CONFIDENCE)

DATA SOURCE	SOURCE OF ASSOCIATION	$\chi^2_{0.05;(r-1)(c-1)}$	χ^2_o OR χ^2_c	SIGNIFICANT ASSOCIATION (χ^2_o OR $\chi^2_c > \chi^2_{0.05;(r-1)(c-1)}$)
NADC FACT DATA	ENVIRONMENT (FATIGUE TESTING SCHEDULE)	$\chi^2_{0.05;2} = 5.99$	$\chi^2_o = 0.04$	no
	PRIMER (U.S. NAVY STANDARD VERSUS KOROFLEX)	$\chi^2_{0.05;1} = 3.84$	$\chi^2_c = 1.24$	no
NADC FACT DATA (STANDARD U.S. NAVY PRIMER) AND CFTTF* DATA (S_{max} = 210 MPa)	FASTENER FIT (PRESS FIT VERSUS INTERFERENCE FIT)	$\chi^2_{0.05;1} = 3.84$	$\chi^2_c = 0.52$	no

*Excluding specimens redrilled to press fit dimensions and specimens with corroded fracture surfaces after pre-exposure + fatigue in air.

		α	P	SIGNIFICANT ASSOCIATION ($P < \alpha = 0.05$)
NADC FACT DATA	PRIMER (U.S. NAVY STANDARD VERSUS KOROFLEX)	$\alpha = 0.05$	0.1076	no

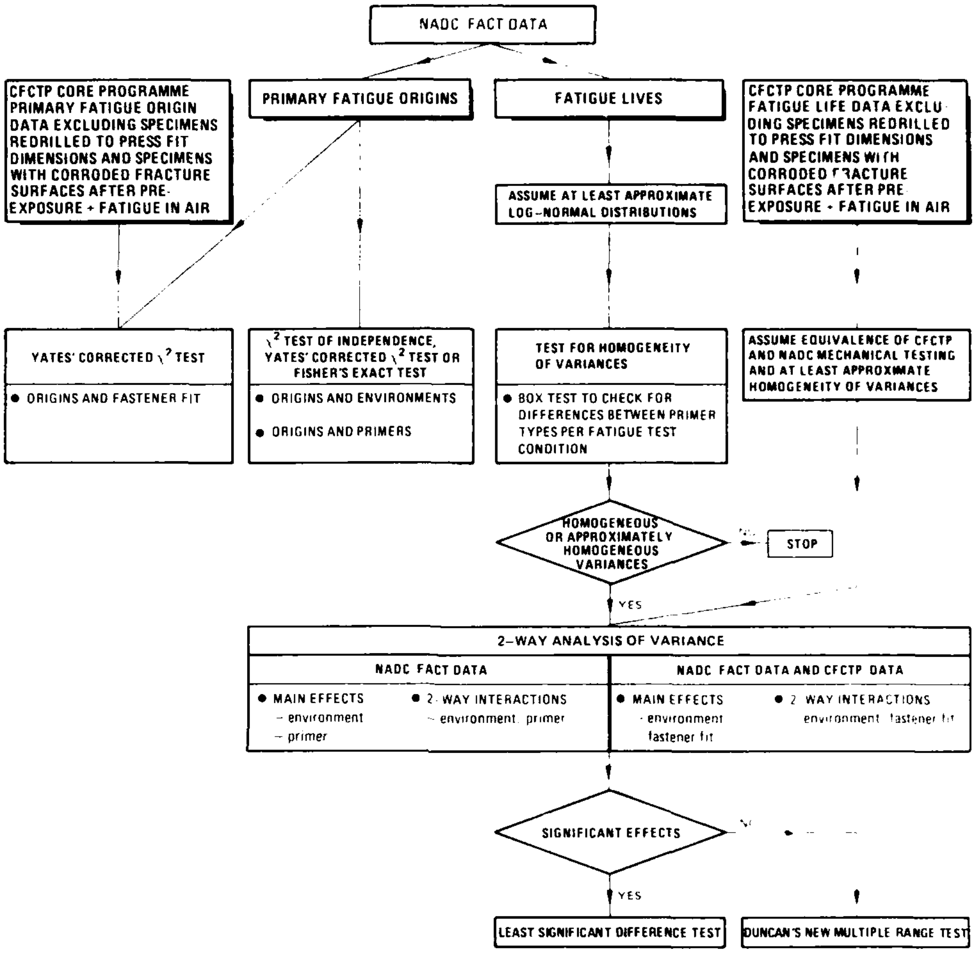


Fig. 4.1 Survey of statistical methods for analysing the NADC data for FACT

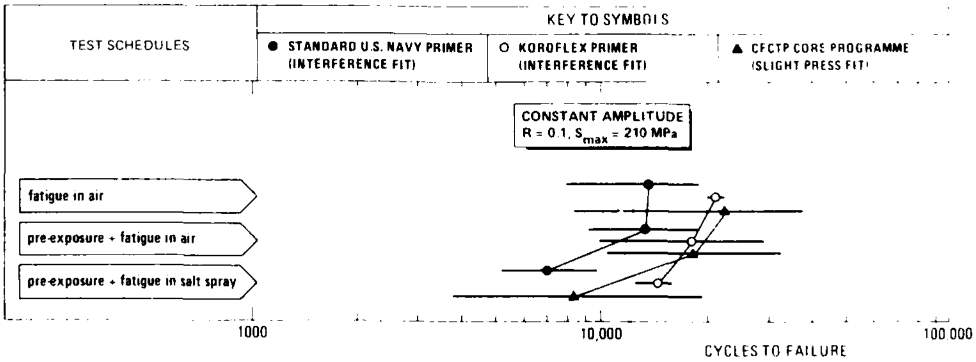


Fig. 4.2 NADC fatigue life data contribution to the FACT programme and CFCTP core programme fatigue life data. The CFCTP core programme data exclude specimens redrilled to press fit dimensions and specimens with corroded fracture surfaces after pre-exposure + fatigue in air

5. THE AFWAL CONTRIBUTION TO THE FACT PROGRAMME

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5.1 Introduction

The AFWAL contribution to FACT concentrated on the effects of using another fastener system (SLEEVbolt) to replace the Hi-Lok system chosen for the CFCTP core programme. The SLEEVbolt fastener system is of particular interest because it can be used to repair a structure. The system incorporates a tapered pin in an internally tapered/externally straight shanked sleeve.

In addition the effects of installing press fit Hi-Loks with or without polysulphide sealant in the fastener holes were investigated.

5.2 The Test Programme

An overview of the test programme is given in table 5.1. All specimens were 1½ dogbones from the same batch as the CFCTP core programme specimens and with the same U.S. Navy paint scheme, as discussed in detail in reference (1) and Part II of this report. However, some of these specimens were altered by removing the press fit Hi-Loks and either reinstalling them with sealant or replacing them by SLEEVbolts.

5.2.1 Fastener systems

The specimens were supplied to the AFWAL containing press-fit Hi-Loks dry installed in chromate conversion coated fastener holes. For some of these specimens the Hi-Loks were removed and either re-installed "wet", i.e. coated with sealant, or replaced by SLEEVbolts. Figure 5.1 illustrates the installation of both types of fastener system: installation details are given in references (1 - 4).

The sealant used in reassembling specimens with Hi-Loks was a polysulphide with added chromates for corrosion inhibition and conforming to MIL-S-81733 B. Most of the sealant was squeezed out during Hi-Lok installation but some remained around the fastener head to seal off the countersink area.

To reassemble specimens with SLEEVbolts the fastener holes were redrilled from 6.306 mm to 7.763 mm nominal diameter. The holes were left in the as-machined condition. The SLEEVbolt combination selected for installation was an aluminium coated steel bolt with an aluminium sleeve. The fasteners were pressed into place before installation of the Hi-Lok collars. Installation resulted in a typical interference of 0.064 mm.

5.2.2 Mechanical testing conditions (static prestressing and fatigue)

All stresses were defined in terms of loads on the total cross-section of the fatigue specimen dogbone at the location of the centreline between the fasteners, i.e. the fastener holes were included in the cross-sectional area. This meant that the net section stresses for the specimens with SLEEVbolts were approximately 8 % higher than those for the specimens containing Hi-Loks.

Before environmental exposure and fatigue testing the specimens with Hi-Loks were prestressed at 209 ± 10 K by applying two load cycles up to either the maximum stress occurring in the subsequent fatigue test or 215 MPa, whichever was the greater. The procedure for this is discussed in reference (1). The purpose of this low temperature prestressing was to ensure that any intact paint, primer and sealant layers were brittle and would crack around the Hi-Lok fastener holes, thereby simulating service damage that enables corrosion and corrosion fatigue to occur.

The specimens containing SLEEVbolts were not prestressed at low temperature. This was considered unnecessary because the specimens had not been repainted after reassembly.

The characteristic fatigue stress levels for the test programme have been indicated already in table 5.1. These stress levels were obtained from the pilot tests described in section 1.4 of this part of the report. The fatigue load histories were constant amplitude sinusoidal loading with a stress ratio $R = S_{min}/S_{max}$ of 0.1 and the manoeuvre spectrum FALSTAFF (references 5, 6). A short description of this spectrum is given in section 1.3 of this part of the report.

5.2.3 Environmental conditions (pre-exposure, fatigue and corrosion fatigue)

Specimens scheduled for static exposure to an aggressive environment before fatigue testing were sealed at the faying surface side edges and Hi-Lok collars to prevent corrosion except in the fastener head areas. The procedure for static pre-exposure is described in detail in reference (1). The specimens were immersed for 72 hours in 5 % aqueous NaCl acidified by a predetermined amount of SO_2 gas and maintained at 315 ± 2 K. The cleaning procedure after pre-exposure followed the unamended procedure in section 7.4 of Part 1 of reference (1).

For fatigue testing all specimens were electrically insulated from the loading grips and bolts by polymeric liners and bushings. Specimens to be fatigued in salt spray were also sealed at the faying surface side edges and Hi-Lok collars. The fatigue environments were laboratory air and 5 % aqueous NaCl salt spray acidified with H_2SO_4 to pH 4, both at a nominal temperature of 295 K. The salt spray tests were done in a specially constructed cabinet, fully described in reference (1).

The nominal cycle frequencies for each combination of fatigue load history and environment were as follows:

FATIGUE LOAD HISTORY	NOMINAL CYCLE FREQUENCY	
	fatigue in air	fatigue in salt spray
constant amplitude, R = 0.1	2 Hz	0.5 Hz
FALSTAFF	7 Hz	2 Hz

5.3 Results

The complete set of fatigue life and primary fatigue origin data for the AFWAL contribution to FACT is given in table 5.2. The way in which the test programme was set up and the results had consequences for the statistical methods used to analyse the data. This will be discussed in section 5.3.1.

The fatigue life results are presented and statistically analysed in section 5.3.2. This is followed by presentation and statistical analysis of the primary fatigue origin data in section 5.3.3.

5.3.1 Statistical methods for analysing the data

A survey of the statistical methods for analysing the AFWAL data is given in figure 5.2. Owing to the limited number and unequal sample sizes of the fatigue life data it had to be assumed that they at least approximated to random samples from log-normally distributed populations with equal variance. Unequal sample sizes also meant that modified versions of the least significant difference test and Duncan's new multiple range test would have to be used for "fine tuning" the analysis of variance results. More details of the statistical methods are given in Appendix II.

5.3.2 Fatigue life data

The fatigue life data are shown in figure 5.3. These data indicate that pre-exposure + fatigue in salt spray resulted in shorter lives than fatigue in air. This was confirmed by two-way analysis of variance, the results of which are summarised in table 5.3. Since there were only two test schedules representing the effect of environment (fatigue in air, pre-exposure + fatigue in salt spray) it is obvious that the significant difference is between them. Thus it was not necessary to "fine tune" this result using the least significant difference test.

According to the analysis of variance the other potential sources of variation (fastener system, environment : fastener system interactions) were not significant. These were further investigated using Duncan's new multiple range test. The results are given in table 5.4. For both constant amplitude and FALSTAFF loading and for a given test schedule (environmental condition) there were no significant differences in fatigue lives owing to different fastener installations.

5.3.3 Primary fatigue origin data

Yates' corrected χ^2 test and Fisher's exact test were used to analyse the primary fatigue origin data listed in table 5.2. Owing to the limited number of data it was not possible to analyse separately for each combination of fatigue load history, environment and fastener system. Instead various "lumped" combinations were examined including combining data for constant amplitude and FALSTAFF loading. This is felt to be justified since other results (see the NLR and LRTH contribution to FACT) show that the dependence of primary fatigue origin locations on stress level is similar for constant amplitude and FALSTAFF loading, such that the same trends are obtained for a constant amplitude S_{max} of 144 MPa and a FALSTAFF S_{max} of 238 MPa. The results of the tests are summarised in table 5.5. Both environment (fatigue testing schedule) and fastener system had significant effects on the locations of primary fatigue origins, as follows:

(1) Changing from fatigue in air to pre-exposure + fatigue in salt spray promoted failure initiation in the bores (E/Q) and countersink areas (B/N, C, D) of the fastener holes, especially for specimens with slight press fit Hi-Loks installed dry as per cFCTP core programme.

(2) Use of SLEEVbolts promoted failure initiation in the countersink areas (C, D) of the fastener holes. This effect is especially noticeable for specimens fatigued in air, see table 5.2.

5.4 Discussion

Use of the 1½ dogbone specimen for this test programme is a fairly severe test of the efficacy of the SLEEVbolt fastener system. Under load the 1½ dogbone specimen exhibits secondary bending that increases when the clearance between fasteners and holes is reduced, see references (7, 8) and Appendix I. This characteristic behaviour tends to nullify the usually beneficial effect on fatigue life of using interference fit fasteners.

On the other hand, the equivalent fatigue lives of specimens containing Hi-Loks and SLEEVbolts demonstrates the usefulness of SLEEVbolts for repairing a structure.

Changing from fatigue in air to pre-exposure + fatigue in salt spray resulted in significantly shorter fatigue lives. Wet installation of press fit Hi-Loks using inhibited polysulphide sealant made no difference.

5.5 Conclusions

(1) The usefulness of SLEEVbolts for repairing aircraft structures has been demonstrated.

(2) Wet installation of press fit Hi-Loks using inhibited polysulphide sealant was not beneficial to corrosion fatigue resistance.

(3) Changing from fatigue in air to pre-exposure + fatigue in salt spray promoted failure initiation in the bores and countersink areas of fastener holes and reduced the number of failures commencing at faying surfaces.

(4) Use of SLEEVbolts instead of press fit Hi-Loks promoted failure initiation in the bare countersink areas of fastener holes.

5.6 References

1. R.J.H. Wanhill and J.J. De Luccia, "An AGARD-coordinated corrosion fatigue cooperative testing programme", AGARD Report No. 695, February 1982.

2. N.R. Ontko, "Evaluation report: supplemental data in support of the NATO-AGARD coordinated corrosion fatigue cooperative testing programme (CFCTP)", AFWAL Report AFWAL/MLS 82 - 48, June 1982.

3. "Hi-Lok and Hi-Lok/Hi-Tigue fasteners installation instructions", Hi-Shear Corporation, 2600 Skypark Drive, Torrance, California, USA.

4. "SLEEVbolt interference fastening system", SLEEVbolt Systems Committee, 1700 West 132nd Street, Gardena, California, USA.

5. "Description of a Fighter Aircraft Loading STAndard For Fatigue evaluation", Combined Report of the F + W, LBF, NLR and IABG, March 1976.

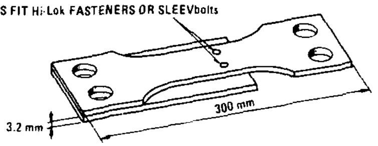
6. J.B. de Jonge, "Additional information about FALSTAFF", NLR Technical Report TR 79056 U, June 1979.

7. H.H. van der Linden, "Fatigue rated fastener systems", AGARD Report No. 721, November 1985.

8. H.H. van der Linden, L. Lazzeri and A. Lanciotti, "Fatigue rated fastener systems in 1½ dogbone specimens", NLR Technical Report TR 86082 U, August 1986.

TABLE 5.1: OVERVIEW OF THE AFWAL TEST PROGRAMME FOR FACT

MATERIAL
- 3.2 mm thick 7075-T76 aluminium alloy sheet (CFCTP core programme material)

SPECIMEN
- 

PROTECTION SYSTEMS
- SLEEVbolt specimens: chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat

  Hi-Lok specimens: chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat and with or without inhibited polysulphide sealant in the fastener holes

PROTECTION SYSTEM DAMAGE
- Hi-Lok specimens: two stress cycles at low temperature to crack paint and primer around the fastener heads

FATIGUE LOADING
- constant amplitude, $S_{min}/S_{max} = 0.1$, $S_{max} = 144$ MPa; FALSTAFF, $S_{max} = 238$ MPa

FATIGUE ENVIRONMENTS
- laboratory air; 5 % aqueous NaCl salt spray with pH 4

STATIC PRE-EXPOSURE
- 72 hours in 5 % aqueous NaCl + SO_2 at 315 K

TEST PROGRAMME
-

SCHEDULES	FATIGUE LOAD HISTORY	CFCTP CORE PROGRAMME SPECIMENS		
		AS RECEIVED	Hi-Loks REINSTALLED WITH SEALANT	Hi-Loks REPLACED BY SLEEVbolts
fatigue in air	constant amplitude, cycle frequency 2 Hz	✱		●
	FALSTAFF, cycle frequency 7 Hz	●		●
pre-exposure + fatigue in salt spray	constant amplitude, cycle frequency 0.5 Hz	✱	●	●
	FALSTAFF, cycle frequency 2 Hz	●	●	●

✱Previously tested in the CFCTP core programme

STATISTICAL ANALYSIS
- fatigue lives and primary fatigue origins

TABLE 5.2: FATIGUE LIFE AND PRIMARY FATIGUE ORIGIN DATA FOR THE AIWAL CONTRIBUTION TO FACT

FASTENER SYSTEMS	FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	FATIGUE LIFE TO FAILURE (CYCLES OR FLIGHTS, AND LOG MEAN VALUES) AND LOCATIONS OF PRIMARY ORIGINS OF FATIGUE*	
			fatigue in air	pre-exposure + fatigue in salt spray
slight press fit Hi-Loks installed dry as per CFCTP core programme	constant amplitude, R = 0.1	S_{max} = 144 MPa	152,700 G 244,600 G 104,200 G 293,800 F 183,888	139,690 E 79,830 F 73,840 C,D 67,940 R 96,484
	FALSTAFF	S_{max} = 238 MPa	22,572 G 16,772 G 25,529 G 19,972 S 20,961	8,080 B 14,231 N 11,280 B 10,906
slight press fit Hi-Loks reinstalled with sealant	constant amplitude, R = 0.1	S_{max} = 144 MPa		37,337 F 36,516 F 76,426 R 47,057
	FALSTAFF	S_{max} = 238 MPa		16,572 Q 10,880 F 13,428
SLEEVbolts (interference fit)	constant amplitude, R = 0.1	S_{max} = 144 MPa	441,410 C 266,360 F 706,070 C 174,320 C 346,837	39,410 D 107,150 D 30,650 Q 98,130 F 59,698
	FALSTAFF	S_{max} = 238 MPa	23,231 D,F 28,729 S 16,112 D 22,072	12,031 E 6,529 D,E 7,231 D,E 11,172 N 8,925

* KEY TO LOCATIONS OF FATIGUE ORIGINS

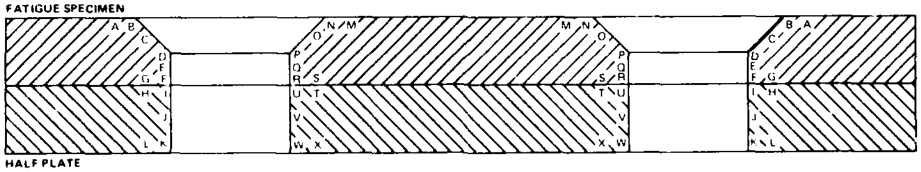


TABLE 5.3: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF VARIATION	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES (F_o > F DISTRIBUTION VALUE)
constant amplitude, R = 0.1	S_{max} = 144 MPa	● MAIN EFFECTS			
		- environment	4.60	24.29	yes
		- fastener system	3.74	0.89	no
		● 2-WAY INTERACTIONS			
		- environment · fastener system	4.60	3.88	no
FALSTAFF	S_{max} = 238 MPa	● MAIN EFFECTS			
		- environment	4.84	28.63	yes
		fastener system	3.98	1.24	no
		● 2-WAY INTERACTIONS			
		environment · fastener system	4.84	[illegible]	no

TABLE 5.4: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	constant amplitude, R = 0.1					FALSTAFF				
FATIGUE TESTING SCHEDULE	fatigue in air		pre-exposure + fatigue in salt spray			fatigue in air		pre-exposure + fatigue in salt spray		
FASTENER SYSTEM	dry Hi-Loks	SLEEVbolts	dry Hi-Loks	sealed Hi-Loks	SLEEVbolts	dry Hi-Loks	SLEEVbolts	dry Hi-Loks	sealed Hi-Loks	SLEEVbolts
LOG MEAN FATIGUE LIFE	5.265	5.349	4.957	4.673	[illegible]	5.121	[illegible]	[illegible]	[illegible]	[illegible]
SAMPLE SIZE n	4	[illegible]	[illegible]	3	[illegible]	[illegible]	3	[illegible]	[illegible]	[illegible]

FATIGUE LOAD HISTORY AND CHARACTERISTIC STRESS LEVEL	TEST PARAMETER	p	COMPARISONS OF DATA PER TEST PARAMETER	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES A	[illegible] R	SIGNIFICANT DIFFERENCE [illegible]
constant amplitude, R = 0.1 S_{max} = 144 MPa	fatigue in air	2	SLEEVbolts-dry Hi-Loks*	[illegible]	[illegible]	[illegible]
	pre-exposure + fatigue in salt spray	3	dry Hi-Loks-sealed Hi-Loks	[illegible]	[illegible]	[illegible]
		2	dry Hi-Loks-SLEEVbolts*	[illegible]	[illegible]	[illegible]
		2	SLEEVbolts-sealed Hi-Loks	[illegible]	[illegible]	[illegible]
	SLEEVbolts	2	fatigue in air-pre-exposure + fatigue in salt spray	[illegible]	[illegible]	yes
	dry Hi-Loks	2		[illegible]	[illegible]	no
FALSTAFF, S_{max} = 238 MPa	fatigue in air	2	SLEEVbolts-dry Hi-Loks	[illegible]	[illegible]	no
	pre-exposure + fatigue in salt spray	3	sealed Hi-Loks-SLEEVbolts	[illegible]	[illegible]	[illegible]
		2	sealed Hi-Loks-dry Hi-Loks	[illegible]	[illegible]	[illegible]
		2	dry Hi-Loks-SLEEVbolts	[illegible]	[illegible]	[illegible]
	SLEEVbolts	2	fatigue in air-pre-exposure + fatigue in salt spray	[illegible]	[illegible]	yes
	dry Hi-Loks	2		[illegible]	0.367	yes

*Owing to equal sample size these comparisons can also be made using the unmodified version of Duncan's test. The same result is obtained.

TABLE 5.5: SUMMARY OF YATES' CORRECTED χ^2 TEST AND FISHER'S EXACT TEST RESULTS FOR THE PRIMARY FATIGUE ORIGIN DATA (95 % CONFIDENCE)

SOURCE OF ASSOCIATION	FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	CRITICAL VALUE OF $\chi^2_{0.05;1}$ OR α	χ^2_c OR P	SIGNIFICANT ASSOCIATION ($\chi^2_c > \chi^2_{0.05;1}$) OR ($P < \alpha = 0.05$)
ENVIRONMENT (FATIGUE TESTING SCHEDULE)	constant amplitude, R = 0.1	S_{max} = 144 MPa	$\chi^2_{0.05;1} = 3.84$	$\chi^2_c = 4.14$	yes
	FALSTAFF	S_{max} = 238 MPa			
ENVIRONMENT (FATIGUE TESTING SCHEDULE) PER FATIGUE LOAD HISTORY	constant amplitude, R = 0.1	S_{max} = 144 MPa	$\alpha = 0.05$	P = 0.465	no
	FALSTAFF	S_{max} = 238 MPa	$\alpha = 0.05$	P = 0.006	yes
FASTENER SYSTEM (SLEEVbolts VERSUS DRY Hi-Loks)	constant amplitude, R = 0.1	S_{max} = 144 MPa	$\chi^2_{0.05;1} = 3.84$	$\chi^2_c = 4.13$	yes
	FALSTAFF	S_{max} = 238 MPa			
FASTENER SYSTEM (SLEEVbolts VERSUS DRY Hi-Loks) PER FATIGUE LOAD HISTORY	constant amplitude, R = 0.1	S_{max} = 144 MPa	$\alpha = 0.05$	P = 0.109	no
	FALSTAFF	S_{max} = 238 MPa	$\alpha = 0.05$	P = 0.145	no

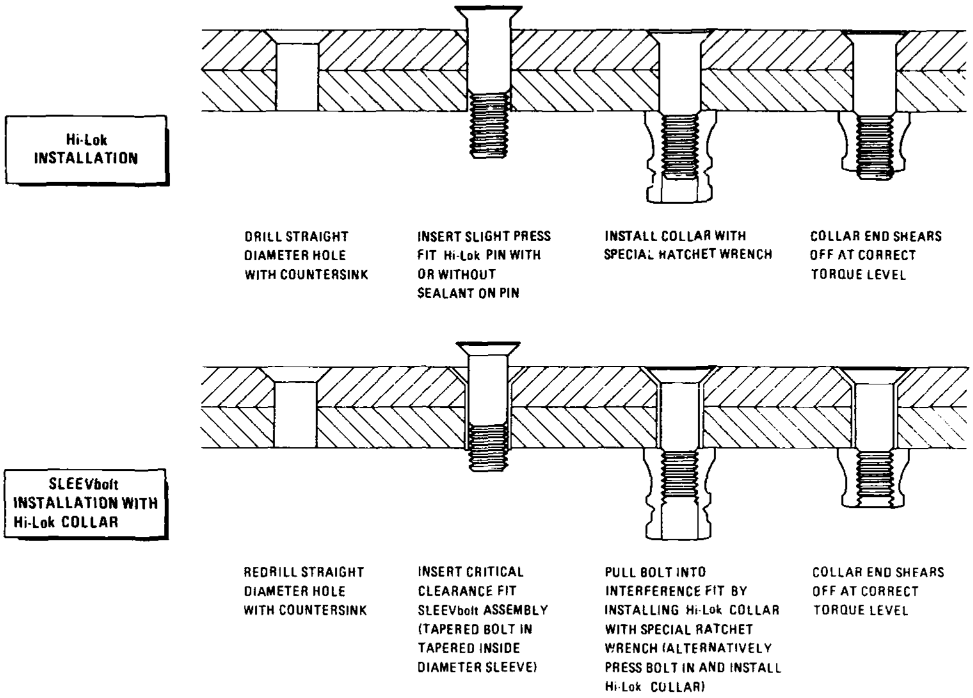


Fig. 5.1 Fastener systems used in the AFWAL contribution to FACT

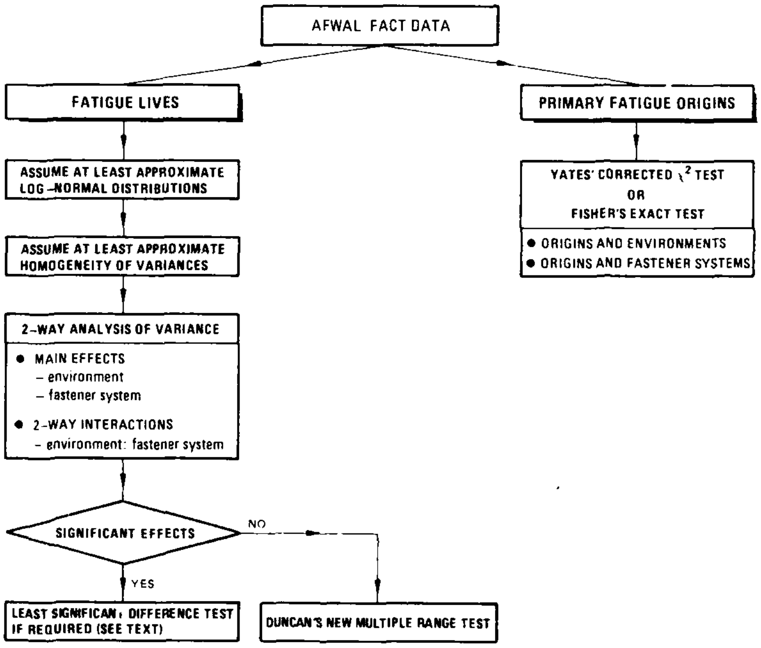


Fig. 5.2 Survey of statistical methods for analysing the AFWAL data for FACT

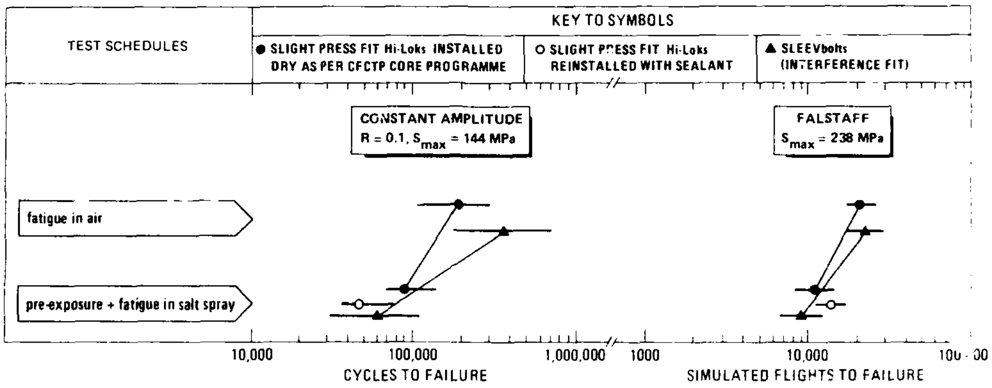


Fig. 5.3 AFWAL fatigue life data contribution to the FACT programme

6. THE NDRE CONTRIBUTION TO THE FACT PROGRAMME

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6.1 Introduction

The NDRE contribution to FACT compared the fatigue and corrosion fatigue properties of 7075 aluminium alloy sheet in the T76 and RRA (retrogression and reage) conditions. As is well known, the T76 condition provides improved resistance to stress corrosion compared to the T6 temper but is accompanied by a strength reduction of 5 - 10 %. The RRA treatment was developed to avoid this strength loss (reference 1).

In the first instance 7075-T6 sheet was supplied to the NDRE from a common batch purchased by the NLR and also supplied to the IABG and RAE, see table 1.1 of the introduction to this part of the report. This sheet material was subsequently converted to the T76 and RRA conditions by the A/S Raufoss Ammunisjonsfabrikker.

Conversion to the T76 condition is achieved simply by overageing 7075-T6 for several hours (typically about 10 hours) at 463 ± 3 K. The RRA treatment is a more complex two-step process. 7075-T6 is first "retrogressed" at a temperature between 473 - 533 K for a short time (1 - 2 minutes at most). This is usually accomplished in a silicone oil bath in view of the short times involved. The material is then water quenched and reaged at 393 K for between 16 - 48 hours.

In the present work the RRA treatment consisted of retrogression in a salt bath at 513 K for 35 s, followed by reageing at 393 K for 24 hours.

6.2 The Test Programme

An overview of the test programme is given in table 6.1. All specimens were of the 1½ dogbone configuration discussed in detail in reference (2) and recommended for the FACT programme. Cadmium plated steel Hi-Lok fasteners were used. The diameter of the holes for the fasteners was 6.306 ± 0.044 mm, which corresponds to a slight press fit, see figure 1.1 of the introduction to this part of the report.

After conversion of the sheet material to the T76 and RRA conditions the specimens were manufactured, painted and assembled by the U.S. Naval Air Development Centre NADC. The specimens had the same U.S. Navy paint scheme as in the CFCTP core programme, see reference (2) and Part II of this report.

6.2.1 Material properties

Engineering property data of the 7075 sheet as supplied in the T6 temper and after conversion to the T76 and RRA conditions are compared with data for the 7075-T76 sheet used in the CFCTP core programme as follows:

MATERIALS	0.2 % YIELD STRESS (MPa)	UTS (MPa)	ELONGATION %
7075-T6	547	582	11.2
7075-T76 (conversion)	485	537	17
7075-T6RRA (conversion)	562	582	16
7075-T76 (CFCTP core programme)	479 (max) 455 (min)	550 (max) 541 (min)	11.0

6.2.2 Mechanical testing conditions (static prestressing and fatigue)

All stresses were defined in terms of loads on the total cross-section of the fatigue specimen dogbone at the location of the centreline between the fasteners, i.e. the fastener holes were included in the cross-sectional area.

Before environmental exposure and fatigue testing all specimens were prestressed at 209 ± 10 K by applying two load cycles up to either the maximum stress occurring in the subsequent fatigue test or 215 MPa, whichever was the greater. The procedure for this is discussed in reference (2). The purpose of this low temperature prestressing was to ensure that the paint and primer layers were brittle and would crack around the Hi-Lok fastener holes, thereby simulating service damage that enables corrosion and corrosion fatigue to occur.

The characteristic fatigue stress levels for the test programme have been indicated already in table 6.1. These stress levels were obtained from the pilot tests described in section 1.4 of this part of the report. Detailed procedures for fatigue testing are given in reference (2). The fatigue load histories were constant amplitude sinusoidal loading with a stress ratio $R = S_{min}/S_{max}$ of 0.1 and the manoeuvre spectrum FALSTAFF (references 3, 4). A short description of FALSTAFF is given in section 1.3 of this part of the report.

6.2.3 Environmental conditions (pre-exposure, fatigue and corrosion fatigue)

Specimens scheduled for static exposure to an aggressive environment before fatigue testing were sealed at the faying surface side edges and Hi-Lok collars to prevent corrosion except in the fastener head areas. The procedure for static pre-exposure is described in detail in reference (2). The specimens were immersed for 72 hours in 5 % aqueous NaCl acidified by a predetermined amount of SO_2 gas and maintained at 315 ± 2 K. The specimen cleaning procedure after pre-exposure followed the amendment in section 4.4 of Part 2 of reference (2).

For fatigue testing all specimens were electrically insulated from the loading grips and bolts by polymeric liners and bushings. Specimens to be fatigued in salt spray were also sealed at the faying surface side edges and Hi-Lok collars. The fatigue environments were laboratory air and 5 % aqueous NaCl salt spray acidified with H_2SO_4 to pH 4, both at a nominal temperature of 295 K. The salt spray tests were done in a specially constructed cabinet, fully described in reference (2).

The nominal cycle frequencies for each combination of fatigue load history and environment were as follows:

FATIGUE LOAD HISTORY	NOMINAL CYCLE FREQUENCY	
	fatigue in air	fatigue in salt spray
constant amplitude, R = 0.1	2 Hz	0.5 Hz
FALSTAFF	15 Hz	2 Hz

6.3 Results

The complete set of fatigue life and primary fatigue origin data for the NDRE contribution to FACT is given in table 6.2. The way in which the test programme was set up and the results had consequences for the statistical methods used to analyse the data. This will be discussed in section 6.3.1.

The fatigue life results are presented and statistically analysed in section 6.3.2. This is followed by presentation and statistical analysis of the primary fatigue origin data in section 6.3.3.

6.3.1 Statistical methods for analysing the data

A survey of the statistical methods for analysing the NDRE data is given in figure 6.1. Owing to the limited number of data it had to be assumed that they at least approximated to random samples from log-normally distributed populations. Also, unequal sample sizes for the FALSTAFF data and comparison of the constant amplitude data with CFCTP core programme data meant that equal variances had to be assumed for analysis of variance, and that for some "fine tuning" of analysis of variance results modified versions of the least significant difference test and Duncan's new multiple range test had to be used. More details of the statistical methods are given in Appendix II.

6.3.2 Fatigue life data

The fatigue life data are shown in figure 6.2. In a general way these data indicate that stress level (FALSTAFF), environment and material had significant effects on fatigue lives. As will be shown, this was confirmed by statistical analysis.

The Box test was used to check homogeneity of variances of the NDRE constant amplitude data. The variances were found to be equal, see table 6.3. Analysis of variance was carried out separately for the constant amplitude and FALSTAFF data. The results are summarised in table 6.4. The main effects of stress level, environment and material were found to be significant. Because there were only two stress levels for the FALSTAFF tests and only two test schedules representing the effect of environment (fatigue in air, pre-exposure + fatigue in salt spray) it is obvious that the significant differences were between each stress level and each environment. For the FALSTAFF tests it is also evident that the significant effect of material is due to 7075-T6RRA specimens having longer average fatigue lives than 7075-T76 (conversion) specimens.

For the constant amplitude tests there were three material conditions. The least significant difference test was therefore used to "fine tune" the significant material effect indicated by analysis of variance. The results are given in table 6.5 and show that also for constant amplitude loading the 7075-T6RRA specimens had significantly longer average fatigue lives than 7075-T76 specimens.

The other potential sources of variation (2-way and 3-way interactions) were not found to be significant by analysis of variance. These were further investigated using Duncan's new multiple range test. Table 6.6 lists the results, which may be described as follows:

(1) The effect of stress level (FALSTAFF) was significant for each environment and material.

(2) The effect of environment depended on load history, stress level and material. Changing from fatigue in air to pre-exposure + fatigue in salt spray was especially significant in reducing the fatigue lives of 7075-T6RRA specimens tested under constant amplitude loading and FALSTAFF with S_{max} = 289 MPa.

(3) Although 7075-T6RRA specimens generally had significantly longer average fatigue lives than 7075-T76 specimens, this was not true for all combinations of load history, stress level and environment. Changing from fatigue in air to pre-exposure + fatigue in salt spray tended to reduce the differences between materials.

6.3.3 Primary fatigue origin data

Yates' corrected χ^2 test and Fisher's exact test were used to analyse the primary fatigue origin data listed in table 6.2. The results are summarised in table 6.7. Only one significant effect was found, namely the influence of environment (fatigue testing schedule) on the locations of primary fatigue origins in specimens tested with FALSTAFF. Specifically, changing from fatigue in air to pre-exposure + fatigue in salt spray promoted failure initiation in the bores (E/Q) and countersink areas (A/M, B/N) of the fastener holes, especially for $S_{max} = 238$ MPa.

6.4 Discussion

This test programme has shown that the retrogression and reageing (RRA) treatment for 7075 aluminium alloy sheet has two important advantages compared to the conventional T76 overageing treatment. The static yield and ultimate strengths of 7075-T6RRA are significantly higher, by about 15 % and 8 % respectively, and are equivalent to 7075-T6 values. This confirms the work of Cina (reference 1). Secondly, when assembled into specimens representing realistic structural joints the fatigue and corrosion fatigue resistances of 7075-T6RRA are generally better than those of 7075-T76.

6.5 Conclusions

(1) Retrogression and reageing (RRA) enabled 7075 aluminium alloy sheet to retain T6 strength levels combined with generally better fatigue and corrosion fatigue properties than 7075-T76.

(2) The effects of stress level and environment on fatigue lives were significant. Changing from fatigue in air to pre-exposure + fatigue in salt spray tended to reduce the differences between 7075-T6RRA and 7075-T76.

(3) From the tests with FALSTAFF it was found that changing from fatigue in air to pre-exposure + fatigue in salt spray promoted failure initiation in the bores and countersink areas of fastener holes and reduced the number of failures commencing at faying surfaces.

6.6 References

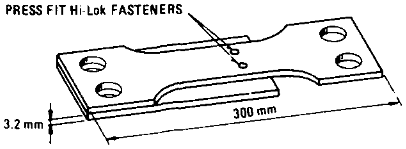
1. B.M. Cina, "Reducing the susceptibility of alloys, particularly aluminium alloys, to stress corrosion cracking", U.S. Patent 3,856,584, December 24 (1974).

2. R.J.H. Wanhill and J.J. De Luccia, "An AGARD-coordinated corrosion fatigue cooperative testing programme", AGARD Report No. 695, February 1982.

3. "Description of a Fighter Aircraft Loading STAndard For Fatigue evaluation", Combined Report of the F + W, LBF, NLR and IABG, March 1976.

4. J.B. de Jonge, "Additional information about FALSTAFF", NLR Technical Report TR 79056 U, June 1979.

TABLE 6.1: OVERVIEW OF THE NDRE TEST PROGRAMME FOR FACT

MATERIAL	• 3.2 mm thick 7075-T76 aluminium alloy sheet converted to the T76 and RRA conditions
SPECIMEN	• 
PROTECTION SYSTEM	• chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat
PROTECTION SYSTEM DAMAGE	• two stress cycles at low temperature to crack paint and primer around the fastener heads
FATIGUE LOADING	• constant amplitude, $S_{min}/S_{max} = 0.1$; FALSTAFF
FATIGUE ENVIRONMENTS	• laboratory air; 5 % aqueous NaCl salt spray with pH 4
STATIC PRE-EXPOSURE	• 72 hours in 5 % aqueous NaCl + SO_2 at 315 K

TEST PROGRAMME •

SCHEDULES	FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	MATERIAL CONDITIONS	
			7075-T76	7075-T6RRA
fatigue in air	constant amplitude	$S_{max} = 144$ MPa	●	●
	FALSTAFF	$S_{max} = 289$ MPa	●	●
		$S_{max} = 238$ MPa	●	●
pre-exposure + fatigue in salt spray	constant amplitude	$S_{max} = 144$ MPa	●	●
	FALSTAFF	$S_{max} = 289$ MPa	●	●
		$S_{max} = 238$ MPa	●	●

STATISTICAL ANALYSIS • fatigue lives and primary fatigue origins

TABLE 6.2: FATIGUE LIFE AND PRIMARY FATIGUE ORIGIN DATA FOR THE NDRE CONTRIBUTION TO FACT

MATERIAL CONDITIONS	FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	FATIGUE LIFE TO FAILURE (CYCLES OR FLIGHTS, AND LOG MEAN VALUES) AND LOCATIONS OF PRIMARY ORIGINS OF FATIGUE*	
			fatigue in air	pre-exposure + fatigue in salt spray
7075-T76	constant amplitude, R = 0.1	S_{max} = 144 MPa	104,910 S 65,660 E 100,820 S 88,557	53,250 Q 44,930 E 56,580 D 51,346
	FALSTAFF	S_{max} = 289 MPa	3,131 E 3,578 E 1,731 E,Q 1,601 E 2,360	1,833 E,R 1,230 N 1,631 Q 1,544
		S_{max} = 238 MPa	6,594 S 12,733 S 13,332 G 12,597 G 10,897	7,604 E 6,943 Q 11,623 N 8,498
7075-T6RRA	constant amplitude, R = 0.1	S_{max} = 144 MPa	399,420 O 557,470 C 130,410 G 307,365	90,250 B 92,700 C 103,730 A 95,384
	FALSTAFF	S_{max} = 289 MPa	4,132 Q 10,256 S 7,996 G 4,001 E 6,068	2,633 Q 6,432 b 1,973 Q 3,221
		S_{max} = 238 MPa	18,396 G 11,396 G 8,233 G 15,375 G 12,763	12,103 B 15,973 M 13,939 Q 13,916

* KEY TO LOCATIONS OF FATIGUE ORIGINS

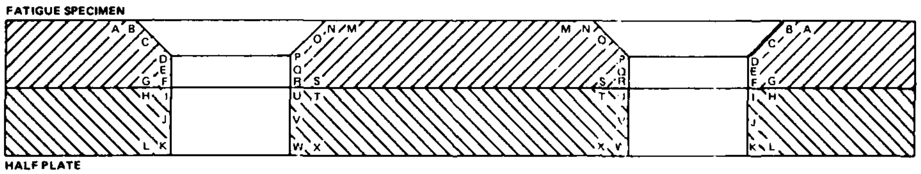


TABLE 6.3: BOX TEST FOR HOMOGENEITY OF VARIANCES OF NDRE CONSTANT AMPLITUDE DATA (95 % CONFIDENCE)

FATIGUE TESTING SCHEDULE	SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - x)^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
fatigue in air	1 7075-T76 2 7075-T6RRA	3 3	0.025 0.218	2 2	0.500 0.500	0.013 0.109	− 1.895 − 0.962	− 3.790 − 1.923
	k = 2							
	SUM	–	–	–	1.000	–	–	− 5.713
	POOLED	–	0.243	4	0.250	0.061	− 1.216	− 4.866
	DIFFERENCE	–	–	–	$D_1 = 0.750$	–	–	$D_2 = 0.847$

$K = 2.3026\ D_2 = 1.950$ $L = \frac{D_1}{3(k-1)} = 0.250$ $\nu_1 = k - 1 = 1$ $\nu_2 = \frac{k+1}{L^2} = 48$

$D = \frac{\nu_2}{1 - L + (2/\nu_2)} - K = 58.682$ $F_o = \frac{K/\nu_1}{D/\nu_2} = 1.595$ WITH 1 AND 48 DEGREES OF FREEDOM.

FOR $\alpha = 5$ % AND 1 AND 48 DEGREES OF FREEDOM $F = 4.04$. SINCE $1.595 < 4.04$ THE POPULATION VARIANCES ARE EQUAL.

FATIGUE TESTING SCHEDULE	SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - x)^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
pre-exposure + fatigue in salt spray	1 7075-T76 2 7075-T6RRA	3 3	0.005 0.002	2 2	0.500 0.500	0.003 0.001	− 2.570 − 2.988	− 5.139 − 5.975
	k = 2							
	SUM	–	–	–	1.000	–	–	− 11.114
	POOLED	–	0.007	4	0.250	0.002	− 2.757	− 11.028
	DIFFERENCE	–	–	–	$D_1 = 0.750$	–	–	$D_2 = 0.086$

$K = 2.3026\ D_2 = 0.198$ $L = \frac{D_1}{3(k-1)} = 0.250$ $\nu_1 = k - 1 = 1$ $\nu_2 = \frac{k+1}{L^2} = 48$

$D = \frac{\nu_2}{1 - L + (2/\nu_2)} - K = 60.434$ $F_o = \frac{K/\nu_1}{D/\nu_2} = 0.157$ WITH 1 AND 48 DEGREES OF FREEDOM.

FOR $\alpha = 5$ % AND 1 AND 48 DEGREES OF FREEDOM $F = 4.04$. SINCE $0.157 < 4.04$ THE POPULATION VARIANCES ARE EQUAL.

TABLE 6.4: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF VARIATION	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES (F_o > F DISTRIBUTION VALUE)
constant amplitude, R = 0.1	S_{max} = 144 MPa	● MAIN EFFECTS - environment - material	 3.97 3.12	 44.20 5.70	 yes yes
		● 2-WAY INTERACTIONS - environment : material	3.12	0.72	no
FALSTAFF	S_{max} = 289 MPa AND S_{max} = 238 MPa	● MAIN EFFECTS - stress - environment - material	 4.35 4.35 4.35	 84.71 4.38 16.05	 yes yes yes
		● 2-WAY INTERACTIONS - stress : environment - stress : material - environment : material	 4.35 4.35 4.35	 2.36 3.67 0.05	 no no no
		● 3-WAY INTERACTIONS - stress : environment : material	4.35	0.87	no

TABLE 6.5: *LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF MATERIAL ON CONSTANT AMPLITUDE FATIGUE LIFE*

<table>
<tr><td>MATERIAL</td><td colspan="2">7075-T76 (conversion)</td><td>7075-T6RRA</td><td>7075-T76 (CFCTP)</td></tr>
<tr><td>LOG MEAN FATIGUE LIFE</td><td colspan="2">4.829</td><td>5.234</td><td>4.972</td></tr>
<tr><td>SAMPLE SIZE n</td><td colspan="2">6</td><td>6</td><td>70</td></tr>
<tr><td colspan="3">$t_{0.025;76}$ = 1.99</td><td colspan="2">$MS_{residual}$ = 0.046</td></tr>
<tr><td>COMPARISONS OF MATERIALS</td><td>t</td><td colspan="3">SIGNIFICANT DIFFERENCE ($t > t_{0.025;76}$)</td></tr>
<tr><td>7075-T6RRA/7075-T76 (conversion)*
7075-T6RRA/7075-T76 (CFCTP)
7075-T76 (conversion)/7075-T76 (CFCTP)</td><td>3.27
2.87
1.57</td><td colspan="3">yes
yes
no</td></tr>
</table>

*Owing to equal sample size this comparison can also be made using the unmodified least significant difference test. The same result is obtained.

TABLE 6.6: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	constant amplitude R = [illegible]														FALSTAFF							
CHARACTERISTIC STRESS LEVEL	S_{max} = [illegible] MPa						S_{max} = [illegible] MPa				S_{max} = 238 MPa				S_{max} = [illegible] MPa				S_{max} = 238 MPa			
FATIGUE TESTING SCHEDULE AND/OR MATERIAL	fatigue in air		pre exposure + fatigue in salt spray				fatigue in air	pre exposure + fatigue in salt spray	7075 T76 conversion	T6RRA	fatigue in air	pre exposure + fatigue in salt spray	7075 T76 conversion	7075 T6RRA	fatigue in air		pre exposure + fatigue in salt spray		fatigue in air		pre exposure + fatigue in salt spray	
	7075 T76 (conversion)	7075 T6RRA	7075 T76 CRP TP	7075 T76 conversion	7075 T6RRA	7075 T76 CRP TP									7075 T76 conversion	7075 T6RRA	7075-T76 (conversion)	7075 T6RRA	7075 T76 conversion	7075 T6RRA	7075-T76 (conversion)	7075 T6RRA
LOG MEAN FATIGUE LIFE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.03[illegible]	4.106	3.929	4.166
SAMPLE SIZE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4	4	3	[illegible]

FATIGUE LOAD HISTORY AND CHARACTERISTIC STRESS LEVEL	COMPARISONS OF DATA PER TEST PARAMETER	TEST PARAMETER	p	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_i n_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $\bar{x}_i - \bar{x}_j \cdot \sqrt{\frac{2n_i n_j}{n_i+n_j}} > SSR$
constant amplitude R = [illegible] S_{max} = [illegible] MPa	fatigue in air/pre exposure + fatigue in salt spray*	7075 T76 (conversion)	2	[illegible]	0.605	no
		7075 T6RRA	2	[illegible]	0.605	yes
		7075 T76 CRP TP	[illegible]	[illegible]	0.605	yes
	[illegible] T6RRA [illegible] T76 [illegible] conversion*	fatigue in air	[illegible]	[illegible]	[illegible]	yes
	[illegible] T6RRA [illegible] T76 [illegible]		[illegible]	[illegible]	[illegible]	yes
	[illegible] T76 conversion [illegible] T76 CRP TP		[illegible]	[illegible]	[illegible]	no
	T6RRA [illegible] T76 (conversion)*	pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	no
	T6RRA [illegible] T76 CRP TP		2	[illegible]	0.605	no
	[illegible] T76 CRP TP		[illegible]	[illegible]	[illegible]	no
FALSTAFF S_{max} = [illegible] MPa AND S_{max} = 238 MPa	S_{max} = [illegible] MPa / S_{max} = 238 MPa*	fatigue in air	[illegible]	[illegible]	[illegible]	yes
		pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	yes
		[illegible] T76 conversion	[illegible]	[illegible]	[illegible]	yes
		[illegible] T6RRA	[illegible]	[illegible]	[illegible]	[illegible]
FALSTAFF S_{max} = [illegible] MPa	fatigue in air/pre exposure + fatigue in salt spray	[illegible] T76 conversion	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible] T6RRA	[illegible]	[illegible]	[illegible]	yes
	T6RRA [illegible] T76 [illegible]*	fatigue in air	[illegible]	[illegible]	[illegible]	yes
		pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
FALSTAFF S_{max} = [illegible] MPa	fatigue in air/pre exposure + fatigue in salt spray	[illegible] T76 conversion	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible] T6RRA	[illegible]	[illegible]	[illegible]	[illegible]
	T6RRA [illegible] T76 [illegible]*	fatigue in air	[illegible]	[illegible]	[illegible]	[illegible]
		pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	no

* [illegible] these comparisons [illegible] using the unmodified version of Duncan's test. The same result is obtained

TABLE 6.7: SUMMARY OF YATES' CORRECTED χ^2 TEST AND FISHER'S EXACT TEST RESULTS FOR THE PRIMARY FATIGUE ORIGIN DATA (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF ASSOCIATION	CRITICAL VALUE OF $\chi^2_{0.05,1}$ OR α	χ^2_c OR P	SIGNIFICANT ASSOCIATION ($\chi^2_c > \chi^2_{0.05;1}$) OR ($P < \alpha = 0.05$)
FALSTAFF	$S_{max} = 289$ MPa AND $S_{max} = 238$ MPa	STRESS LEVEL	$\chi^2_{0.05;1} = 3.84$	$\chi^2_c = 3.23$	no
		ENVIRONMENT (FATIGUE TESTING SCHEDULE)	$\chi^2_{0.05;1} = 3.84$	$\chi^2_c = 6.24$	yes
		MATERIAL: 7075-T6RRA VERSUS 7075-T76 (conversion)	$\chi^2_{0.05;1} = 3.84$	$\chi^2_c = 0.08$	no
constant amplitude, R = 0.1	$S_{max} = 144$ MPa	ENVIRONMENT (FATIGUE TESTING SCHEDULE)	$\alpha = 0.05$	P = 0.091	no
		MATERIAL: 7075-T6RRA VERSUS 7075-T76 (conversion)	$\alpha = 0.05$	P = 0.500	no

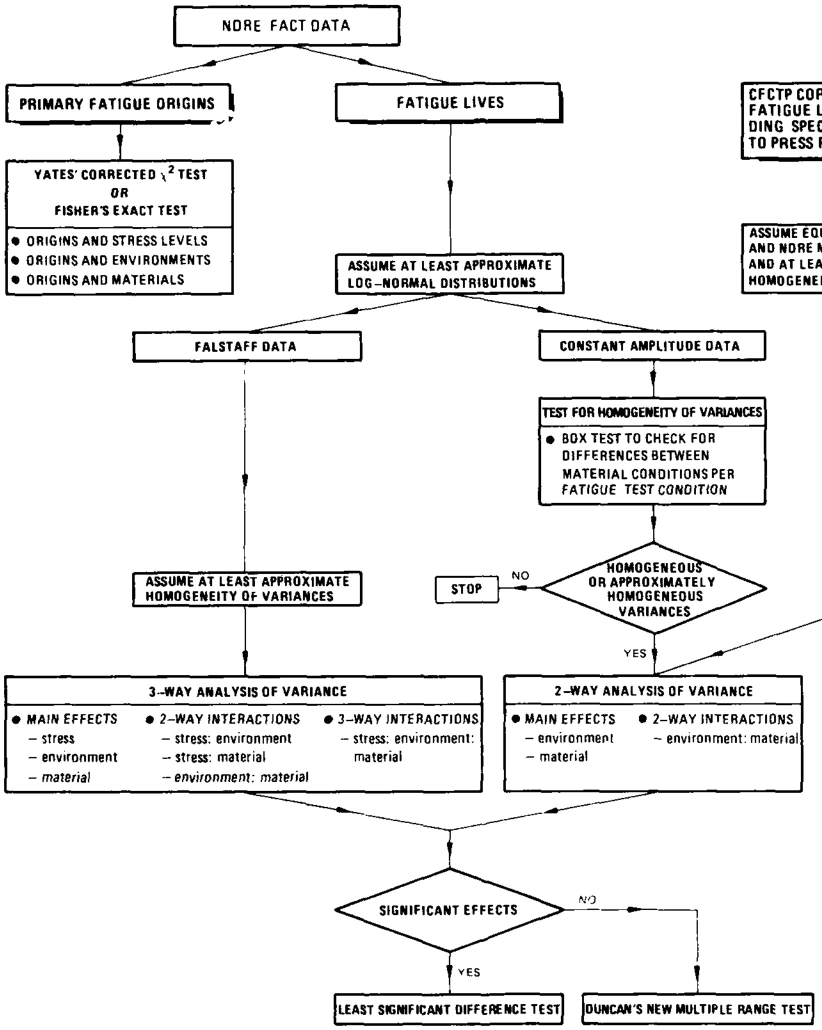


Fig. 6.1 Survey of statistical methods for analysing the NDRE data for FACT

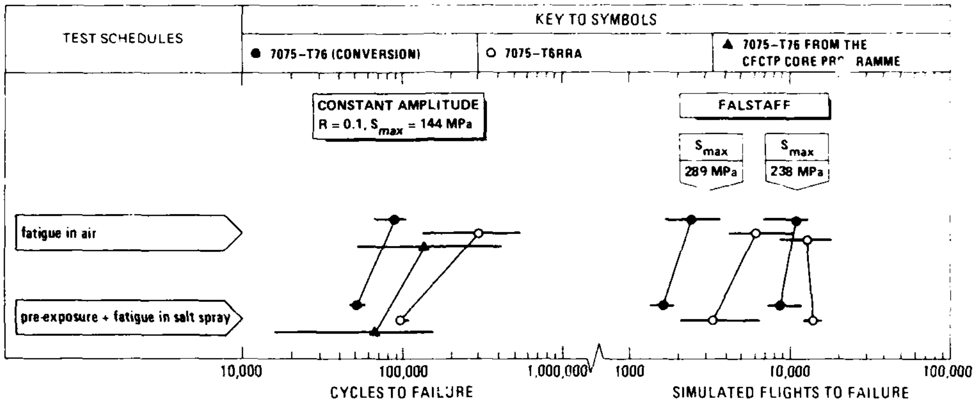


Fig. 6.2 NDRE fatigue life data contribution to the FACT programme and CFCTP core programme fatigue life data. The CFCTP core programme data exclude specimens redrilled to press fit dimensions

7. THE NLR AND LRTH CONTRIBUTION TO THE FACT PROGRAMME

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7.1 Introduction

The Structures and Materials Division of the NLR and the Department of Aerospace Engineering LRTH of Delft University of Technology were joint participants in the FACT supplemental programme. Most of the work was carried out with the support of the Scientific Research Division of the Directorate of Materiel, Royal Netherlands Air Force, and the Netherlands Agency for Aerospace Programs NIVR.

The primary objective of the NLR and LRTH contribution to FACT was to compare the resistance to corrosion fatigue of aircraft corrosion protection systems and aluminium alloy materials in use in the Netherlands. In addition the effectiveness of AMLGUARD, a water displacing corrosion preventive compound (reference 1), was examined.

To try and place the results in a broader context it was arranged that two of the aluminium alloys, 7075-T6 and 7475-T761 clad, came from the same batches of material tested by the NDRE, IABG and RAE, see table 1.1 of the introduction to this part of the report.

7.2 The Test Programme

An overview of the test programme as it finally evolved is given in table 7.1. The partial filling-in of the test matrix was the consequence of limited numbers of specimens and updating of priorities with respect to choice of fatigue testing schedules.

7.2.1 *Materials and specimen configuration*

The aluminium alloys used for monolithic specimens were 3.2 mm thick sheets of 2024-T3 Alclad, 7075-T6 and 7475-T761 clad. The 2024-T3/aramid fibre laminates were 3.2 mm thick and built up from 0.6 mm thick 2024-T3 sheets interleaved and adhesively bonded with single aramid 143 fabric layers and then plastically strained 0.[illegible] %. Additional details of the fabrication of these laminates, hereinafter referred to as ARALL (Aramid Reinforced ALuminium Laminate) are given in reference (2).

Engineering property data, based on total cross sectional area, were as follows:

MATERIALS	0.2 % YIELD STRESS (MPa)	UTS (MPa)	ELONGATION (%)
2024-T3 Alclad	350	474	16.5
7075-T6	547	582	11.2
7475-T761 clad	422	498	12.6
ARALL	470	600	1.8

Note the low elongation to failure for ARALL. In a *fatigue-sensitive material this would be* disastrous, but ARALL is highly resistant to fatigue (reference 2) as will also become clear in this *contribution to the* FACT programme.

All specimens were of the 1½ dogbone configuration discussed in detail in reference (3) and recommended for the FACT programme. Cadmium plated steel Hi-Lok fasteners were used. The diameter of the holes for the fasteners was 6.306 ± 0.044 mm, which corresponds to a slight press fit, see figure 1.1 of the introduction to this part of the report.

7.2.2 *Protection systems and specimen assembly*

Corrosion protection systems were applied by Fokker Aircraft Factories according to standard process specifications for the F-28, NF-5 and F-16 aircraft. Simplified processing schedules are shown in figure 7.1, which also includes Hi-Lok installation and assembly of the specimens. These processing schedules resulted in the Hi-Lok fastener holes being devoid of *protective coatings, i.e. bare aluminium alloy* directly contacted the cadmium plated fastener shanks and heads. This is a "worst case" situation which, however, is entirely feasible.

7.2.3 Mechanical testing conditions (static prestressing and fatigue)

All stresses were defined in terms of loads on the total cross-section (but excluding cladding layers if present) of the fatigue specimen dogbone *at the location of the centreline between the fasteners, i.e.* the fastener holes were included in the cross-sectional area.

Before environmental exposure and fatigue testing all specimens were prestressed at 209 ± 10 K by applying two load cycles up to either the maximum stress occurring in the subsequent fatigue test or 215 MPa, whichever was the greater. The procedure for this is discussed in reference (3). The purpose of this low temperature prestressing was to ensure that the paint and primer layers were brittle and would crack around the Hi-Lok fastener holes, thereby simulating *service damage that enables* corrosion and corrosion fatigue to occur.

The characteristic fatigue stress levels for the test programme have been indicated already in table 7.1. These stress levels were obtained from the pilot tests described in section 1.4 of this part of the report. Detailed procedures for fatigue testing are given in reference (3). All tests were done using a 900 kN load frame fitted to a WOLPERT-AMSLER/MTS electrohydraulic machine. The closed loop system was controlled by an NLR-developed device, *MIDAS II (Magnetic tape Input Digital-to-Analogue Signal).*

Information on flight simulation load sequences was stored on magnetic tapes and read by a KENNEDY 9000 recorder.

The fatigue load histories were constant amplitude sinusoidal loading with a stress ratio $R = S_{min}/S_{max}$ of 0.1, the manoeuvre spectrum FALSTAFF (references 4, 5) and the gust spectrum MINITWIST (references 6, 7). The peak loads of both spectra were untruncated. Short descriptions of these spectra are given in section 1.3 of this part of the report.

7.2.4 Environmental conditions (pre-exposure, fatigue and corrosion fatigue)

Specimens scheduled for static exposure to an aggressive environment before fatigue testing were sealed at the faying surface side edges and Hi-Lok collars to prevent corrosion except possibly in the fastener head areas. Some of the specimens were then completely spray coated with AMLGUARD 24 hours before exposure, see the test matrix in table 7.1. The procedure for static pre-exposure is described in detail in reference (3). The specimens were immersed for 72 hours in 5 % aqueous NaCl acidified by a predetermined amount of [illegible]$_2$ gas and maintained at 315 ± 2 K. The specimen cleaning procedure after pre-exposure followed the amendment in section 4.4 of Part 2 of reference (3).

For fatigue testing all specimens were electrically insulated from the loading grips and bolts by polymeric liners and bushings. Specimens *to be fatigued in salt spray were also sealed at the faying* surface side edges and Hi-Lok collars. The fatigue environments were laboratory air and 5 % aqueous NaCl salt spray acidified with H_2SO_4 to pH 4, both at a nominal temperature of 295 K. The salt spray tests were done in a specially constructed cabinet, fully described in reference (3).

The nominal cycle frequencies for each combination of fatigue load history and environment were as follows:

FATIGUE LOAD HISTORY	NOMINAL CYCLE FREQUENCY	
	fatigue in air	fatigue in salt spray
constant amplitude, R = 0.1	2 Hz	0.5 Hz
MINITWIST	15 Hz	5 Hz
FALSTAFF	15 Hz	2 Hz

7.3 Results

The complete set of fatigue life and primary fatigue origin data for the NLR and LRTH contribution to FACT is given in table 7.2. The way in which the test programme was set up and the results had consequences for the statistical methods used to analyse the data. This will be discussed in section 7.3.1.

The fatigue life results are presented and statistically analysed in sections 7.3.2 - 7.3.4. This is followed by presentation and statistical analysis of the primary fatigue origin data in section 7.3.5. Correlations between fatigue lives and primary fatigue origins are discussed in section 7.3.6.

7.3.1 Statistical methods for analysing the data

A survey of the statistical methods for analysing the NLR and LRTH data is given in figure 7.2. Owing to *the limited number of data it had to be assumed that they at least approximated to random samples from* log-normally distributed populations. Also, unequal sample sizes for the MINITWIST data and comparison of the constant amplitude data with CFCTP core programme data meant that equal variances had to be assumed for analysis of variance, and that for some "fine tuning" of analysis of variance results modified versions of the least significant difference test and Duncan's new multiple range test had to be used. More details of the statistical methods are given in Appendix II.

7.3.2 Constant amplitude fatigue life data

The constant amplitude fatigue life data are shown in figure 7.3. The data indicate the following trends:

(1) 7075-T6 specimens had significantly shorter fatigue lives than other specimens.

(2) The fatigue lives of 2024-T3 specimens and 7475-T761 specimens without interfay sealant were equivalent to those of CFCTP specimens, as indicated by the shaded bar in figure 7.3.

(3) An interfay sealant was beneficial to the fatigue lives of 7475-T761 specimens.

(4) Coating with AMLGUARD to prevent corrosion during pre-exposure or fatigue in salt spray had little or no beneficial effect on the fatigue lives of 2024-T3 and 7075-T6 specimens.

(5) Changing the fatigue environment from air to salt spray was more detrimental to fatigue life than pre-exposure.

As will be discussed, statistical analysis confirmed trends (1), (3), (4) and (5) and showed trend (2) to be partly true.

Analysis of variance was carried out separately for the NLR constant amplitude data and a combination of NLR and CFCTP core programme data. The results are summarised in table 7.3. The main effects of environment and material were found to be significant in both cases. The environment : material interactions were found to be significant only when the NLR data were analysed separately.

The analysis of variance results were "fine tuned" using the least significant difference test or Duncan's new multiple range test, as appropriate. The results of these tests are listed in tables 7.4 - 7.7, and show the following:

- 7075-T6 specimens had significantly shorter fatigue lives than other specimens, in agreement with (1) above
- for fatigue in air, with or without pre-exposure, the fatigue lives of 2024-T3 specimens and 7475-T761 specimens without interfay sealant were equivalent to those of CFCTP specimens
- for pre-exposure + fatigue in salt spray the fatigue lives of 2024-T3 and CFCTP specimens were equivalent and significantly shorter than those of 7475-T761 specimens without interfay sealant
- 7475-T761 specimens with interfay sealant had significantly longer fatigue lives than other specimens: this confirms the beneficial effect of sealant
- coating with AMLGUARD before pre-exposure had no significant effect on the lives of 2024-T3 and 7075-T6 specimens fatigued in air and salt spray
- an indication that pre-exposure significantly affected fatigue life was found only for 7075-T6 specimens (table 7.5)
- changing the fatigue environment from air to salt spray significantly shortened the lives of 2024-T3, 7075-T6 and CFCTP specimens
- 7475-T761 specimens with and without interfay sealant were insensitive to pre-exposure and changing the fatigue environment from air to salt spray.

7.3.3 Gust spectrum (MINITWIST) fatigue life data

The MINITWIST fatigue life data are shown in figure 7.4. The data indicate the following:

(1) ARALL specimens were greatly superior to monolithic 2024-T3 specimens (fatigue lives more than 10X longer at the same stress level).

(2) Stress level had a significant effect for 2024-T3 specimens.

(3) Coating with AMLGUARD to prevent corrosion during pre-exposure or fatigue in salt spray had little or no beneficial effect on the fatigue lives of 2024-T3 specimens.

(4) Fatigue in salt spray was more detrimental to fatigue life than pre-exposure.

Owing to the evident superiority of ARALL it was considered unnecessary to check (*1*) *statistically*. However, statistical analysis was used to check and confirm (2) - (4).

The results of two-way analysis of variance are summarised in table 7.3. The effects of stress and environment and their interactions were found to be significant. Because there were only two stress levels it is obvious that the significant difference is between them. Thus it was not necessary to "fine tune" this result using the least significant difference test.

The stress : environment interactions were further investigated using the least significant difference test. The results are given in table 7.8, and show that

- the effect of stress level was significant for all environments (fatigue testing schedules)
- coating with AMLGUARD before pre-exposure had no significant beneficial effect on the lives of 2024-T3 specimens fatigued in air and salt spray
- environmental effects were more significant at the lower stress level (S_{mf} = 89 MPa) and were mainly due to changing *the fatigue environment from air to salt spray.*

7.3.4 Manoeuvre spectrum (FALSTAFF) fatigue life data

The FALSTAFF fatigue life data are shown in figure 7.5. The following trends can be observed:

(1) Stress level had a significant effect.

(2) At the higher stress level (S_{max} = 289 MPa) the 7075-T6 specimens had significantly shorter fatigue lives than 7475-T761 specimens with interfay sealant. However, the ranges in fatigue lives of 7075-T6 specimens and 7475-T761 specimens without interfay sealant tended to overlap.

(3) At the lower stress level (S_{max} = 238 MPa) the 7075-T6 specimens had significantly shorter fatigue lives than both types of 7475-T761 specimens.

(4) An interfay sealant was beneficial to the fatigue lives of 7475-T761 specimens only at the higher stress level.

(5) Coating with AMLGUARD to prevent corrosion during pre-exposure or fatigue in salt spray had little or no beneficial effect on the fatigue lives of 7075-T6 specimens.

(6) 7075-T6 specimens were more sensitive to environmental effects than 7475-T761 specimens. At the lower stress level (S_{max} = 238 MPa) 7475-T761 specimens were completely insensitive to environmental effects, as shown by the shaded bar in figure 7.5.

(7) When environmental effects were present, notably for 7075-T6 specimens, the change from fatigue in air to fatigue in salt spray was more detrimental to fatigue life than pre-exposure.

As will be discussed, statistical analysis confirmed all these trends, with minor refinements.

The Box test was used to check for homogeneity of variances of the FALSTAFF fatigue life data. The variances were found to be equal, see tables 7.9 and 7.10. The results of three-way analysis of variance are summarised in table 7.3. The effects of stress, environment and material and most of their interactions were found to be significant. Because there were only two stress levels it is obvious that the significant difference is between them. Thus it was not necessary to "fine tune" this result using the least significant difference test.

The remaining analysis of variance results were "fine tuned" using the least significant difference test or Duncan's new multiple range test, as appropriate. The results of these tests are given in tables 7.11 - 7.13, and show the following:

- the effect of stress level was significant for all environments (fatigue testing schedules)
- at the higher stress level (S_{max} = 289 MPa) the 7075-T6 specimens had significantly shorter fatigue lives than 7475-T761 specimens with interfay sealant; but the fatigue lives of 7075-T6 specimens and 7475-T761 specimens without interfay sealant were equivalent for two of the three fatigue testing schedules (fatigue in air, pre-exposure + fatigue in salt spray)
- at the lower stress level (S_{max} = 238 MPa) the 7075-T6 specimens had significantly shorter fatigue lives than both types of 7475-T761 specimens, whose lives were equivalent
- an interfay sealant was significantly beneficial to the fatigue lives of 7475-T761 specimens only at the higher stress level
- coating with AMLGUARD before pre-exposure had no significant effect on the lives of 7075-T6 specimens fatigued in air and salt spray
- at the higher stress level 7075-T6 specimens and 7475-T761 specimens without interfay sealant showed equivalent sensitivity to environmental effects; 7475-T761 specimens with interfay sealant were insensitive to changing the fatigue testing schedule
- at the lower stress level 7075-T6 specimens were significantly sensitive to environmental effects but 7475-T761 specimens were completely insensitive
- significant environmental effects were due to changing the fatigue environment from air to salt spray: pre-exposure had no significant effect by itself.

7.3.5 Primary fatigue origin data

The χ^2 test of independence and Yates' corrected χ^2 test were used to analyse the primary fatigue origin data listed in table 7.2. Owing to the limited number of data it was not possible to analyse separately for each combination of types of primary fatigue origin, stress level, environment and material. Instead various "lumped" combinations were examined. The results of the tests are summarised in table 7.14 and qualitatively compared in figures 7.6 - 7.8. Stress level, environment and material usually had significant effects on the locations of primary fatigue origins. In more detail:

(1) Under constant amplitude fatigue a change from fatigue in air to pre-exposure + fatigue in salt spray promoted failure initiation at the bore/faying surface corners (F/R) of the fastener holes and reduced the number of faying surface (G/S) failures. The effect of changing the material and protection system was also significant: 7475-T761 specimens with or without interfay sealant had no failure initiations at bore/faying surface corners (F/R) and had many more faying surface (G/S) failures as compared to 2024-T3 and 7075-T6 specimens.

(2) For MINITWIST fatigue of monolithic 2024-T3 specimens the effect of a higher stress level was to promote failure initiation in the bores (E/Q) of the fastener holes and reduce the number of bore/faying surface corner (F/R) and faying surface (G/S) failures. However, changing the fatigue environment from air to salt spray did not have a significant effect on the locations of primary fatigue origins.

(3) For FALSTAFF fatigue the effect of a higher stress level and changing the fatigue environment from air to salt spray was to promote failure initiation at the bore/faying surface corners (F/R) of the fastener holes and reduce the number of faying surface (G/S) failures. The effect of changing the material and protection system was also significant: 7475-T761 specimens had more faying surface (G/S) failures than 7075-T6 specimens.

7.3.6 Fatigue lives and primary fatigue origins

Some unusual locations for primary fatigue origins were observed for 7475-T761 specimens with interfay sealant, see table 7.2. This was especially true for constant amplitude fatigue. The specimens had very long fatigue lives both in air and salt spray. For fatigue in air all the specimens failed at faying surface locations remote from the fastener holes. For fatigue in salt spray three out of four specimens failed near the top of the countersink area (B/N) as a consequence of paint cracking and corrosion attack of the underlying metal during the fatigue tests.

In view of these results it seems reasonable to conclude that for constant amplitude loading the use of interfay sealant prevented fatigue crack initiation at the more usual locations, i.e. bore/faying surface corners (F/R) and faying surfaces (G/S) close to the fastener holes. This resulted in prolongation of the fatigue lives until failures became possible at the other initiation sites.

It is unfortunate that under FALSTAFF loading, which is more realistic than constant amplitude loading, similar changes in primary fatigue origin locations (presumably owing to the use of interfay sealant) did not result in significantly longer fatigue lives.

These contrasting results illustrate the complexity of environmental fatigue in aircraft structural joints and the necessity for realistic testing.

7.4 Discussion

As mentioned in the introduction (section 7.1) the primary objective of the NLR and LRTH contribution to FACT was to compare the resistance to corrosion fatigue of aircraft corrosion protection systems and aluminium alloy materials in use in the Netherlands. The results of this test programme have shown that there were significant differences in environmental fatigue performance of 1½ dogbone specimens made from different materials and with different protection systems. An overview of the results is given in figure 7.9. This will be helpful in the following discussion.

7.4.1 Fatigue lives at higher stress levels

For MINITWIST loading the fatigue performance of ARALL (2024-T3/aramid fibre laminates) was much superior to that of monolithic 2024-T3 Alclad. This is most encouraging for the use of ARALL in advanced aircraft structures. Subsequent testing of a full-scale wing panel has confirmed this (reference 8).

For FALSTAFF loading the fatigue resistance of 7475-T761 clad specimens with interfay was superior to that of 7075-T6 specimens and 7475-T761 clad specimens without interfay. Thus the interfay sealant was beneficial to fatigue lives.

Use of the water displacing corrosion preventive compound AMLGUARD, which was applied before pre-exposure and fatigue testing, proved to be ineffective in prolonging fatigue life. However, this does not invalidate the use of AMLGUARD or similar compounds for inhibiting corrosion.

Pre-exposure was not detrimental to fatigue life. Changing the fatigue environment from air to salt spray was detrimental for 2024-T3 Alclad, ARALL, 7075-T6 and 7475-T761 clad specimens without interfay, but not for 7475-T761 clad specimens with interfay. Thus the 7475-T761 clad specimens in combination with the F-16 paint system and interfay sealant were more resistant to environmental effects. This is an important result, since it means that corrosion-related fatigue problems for F-16 aircraft based in the Netherlands should be less severe than those for the previous generation of aircraft.

7.4.2 Fatigue lives at lower stress levels

At lower stress levels the fatigue resistances of 7075-T76, 2024-T3 Alclad and 7475-T761 clad specimens were equivalent. 7075-T6 was consistently inferior, thus differences in susceptibility to corrosion (pre-exposure) and corrosion fatigue were not primarily responsible. Possible reasons for the inferiority of 7075-T6 are a lower resistance to fatigue crack initiation, with or without fretting, and greater susceptibility of the relatively thick sulphuric acid anodisation layer to cracking as compared to the chromic acid anodisation layers on other specimens (see figure 7.1). However, it has been shown that anodisation layers are beneficial to the fatigue resistance of aircraft structural joints because they provide wear resistant coatings that delay the onset of fretting (reference 9).

With regard to corrosion protection systems, an interfay sealant was beneficial for 7475-T761 clad specimens tested under constant amplitude loading, but not under FALSTAFF loading. The reason for this is unclear, especially because the interfay sealant was beneficial at the higher FALSTAFF stress level, see the previous section and figure 7.9. As at higher stress levels, AMLGUARD was not effective in prolonging fatigue life.

Except for 7075-T6 specimens, pre-exposure was not detrimental to fatigue life. Changing the fatigue environment from air to salt spray was detrimental for 7075-T76, 2024-T3 Alclad and 7075-T6 specimens, but not for 7475-T761 clad specimens with or without interfay. This confirms that 7475-T761 clad specimens in combination with the F-16 corrosion protection system were more resistant to environmental fatigue effects.

7.4.3 Primary fatigue origins

An overview of the main influences on locations of primary fatigue origins in the 1½ dogbone specimens is given in figure 7.10. These influences may be summarised as follows:

(1) Higher stress levels, pre-exposure and/or changing the fatigue environment from air to salt spray promoted fatigue crack initiation in the bores and at bore/faying surface corners of the fastener holes. This means that the number of failures at the faying surfaces decreased.

(2) Lower stress levels and the absence of corrosion or corrosion fatigue favoured fatigue crack initiation at the faying surfaces close to the fastener holes. This means that there were fewer failures in the bores and at bore/faying surface corners of the fastener holes.

7.5 Conclusions

(1) Significant differences in environmental fatigue performance were found for 1½ dogbone specimens made from different materials and with different corrosion protection systems.

(2) Under gust spectrum (MINITWIST) loading the fatigue performance of ARALL (2024-T3/aramid fibre laminates) was much superior to that of monolithic 2024-T3 Alclad.

(3) Under constant amplitude and manoeuvre spectrum (FALSTAFF) loading the fatigue performance of 7475-T761 clad specimens was equivalent to, or better than that of 7075-T76, 2024-T3 Alclad and 7075-T6 specimens.

(4) An interfay sealant was beneficial to the fatigue lives of 7475-T761 clad specimens tested under constant amplitude loading at a lower stress level and FALSTAFF at a higher stress level, but not for FALSTAFF at a lower stress level.

(5) The water displacing corrosion preventive compound AMLGUARD was not beneficial to fatigue lives.

(6) Environmental effects were mainly due to changing the fatigue environment from air to salt spray: pre-exposure had no significant effect except for 7075-T6 specimens fatigued in air under constant amplitude loading.

(7) It may be concluded that AMLGUARD's ineffectiveness in prolonging fatigue life can be associated with the lack of effect of pre-exposure on fatigue lives. It should be noted that AMLGUARD was developed specifically for combatting corrosion under static conditions, which it does very effectively. The present results therefore show that extension of corrosion protection to fatigue conditions will probably require a dynamic inhibitor system capable of being delivered to growing cracks.

(8) 7475-T761 clad specimens in combination with the F-16 corrosion protection system were more resistant to environmental fatigue effects than other combinations of materials and corrosion protection systems.

(9) Higher stress levels, pre-exposure and/or changing the fatigue environment from air to salt spray promoted fatigue crack initiation in the bores and at bore/faying surface corners of the fastener holes and reduced the number of failures at the faying surfaces.

(10) Lower stress levels and the absence of corrosion or corrosion fatigue favoured fatigue crack initiation at the faying surfaces. Thus there were fewer failures in the bores and at bore/faying surface corners of the fastener holes.

7.6 References

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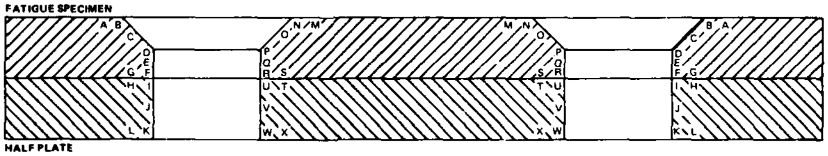
TABLE 7.1: OVERVIEW OF THE NLR AND LRTH TEST PROGRAMME FOR FACT. ALL SPECIMENS WERE OF THE 1½ DOGBONE CONFIGURATION

MATERIALS AND CORROSION PROTECTION SYSTEMS		FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	FATIGUE TESTING SCHEDULE					
				fatigue in air	pre-exposure + fatigue in air	AMLGUARD coat + pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	AMLGUARD coat + pre-exposure + fatigue in salt spray
2024-T3 Alclad, with Fokker F-28 protection system		constant amplitude, R = 0.1	S_{max} = 144 MPa	●	●	●		●	●
		MINITWIST	S_{mf} = 101 MPa	●	●	●	●	●	●
			S_{mf} = 89 MPa	●	●	●	●	●	●
2024-T3/aramid fibre laminates with Fokker F-28 protection system		MINITWIST	S_{mf} = 101 MPa	●	●		●	●	
7075-T6 with Royal Netherlands Air Force NF-5 protection system		constant amplitude, R = 0.1	S_{max} = 144 MPa	●	●	●		●	●
		FALSTAFF	S_{max} = 289 MPa	●	●	●		●	●
			S_{max} = 238 MPa	●	●	●		●	●
7475-T761 clad, with Royal Netherlands Air Force F-16 protection system	without interfay sealant	constant amplitude, R = 0.1	S_{max} = 144 MPa	●	●			●	
		FALSTAFF	S_{max} = 289 MPa	●	●			●	
			S_{max} = 238 MPa	●	●			●	
	with interfay sealant	constant amplitude, R = 0.1	S_{max} = 144 MPa	●				●	
		FALSTAFF	S_{max} = 289 MPa	●				●	
			S_{max} = 238 MPa	●				●	

TABLE 7.2: FATIGUE LIFE AND PRIMARY FATIGUE ORIGIN DATA FOR THE NLR AND LRTH CONTRIBUTION TO FACT

MATERIALS AND CORROSION PROTECTION SYSTEMS		FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	FATIGUE LIFE TO FAILURE (CYCLES OR FLIGHTS, AND LOG MEAN VALUES)/LOCATIONS OF PRIMARY FATIGUE ORIGINS*					
				fatigue in air	pre-exposure + fatigue in air	AMLGUARD coat + pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	AMLGUARD coat + pre-exposure + fatigue in salt spray
2024-T3 Alclad, with F-28 protection system		constant amplitude, R = 0.1	S_{max} = 144 MPa	221,285 S 138,735 G 175,214	101,039 R 217,132 S 258,474 E 76,274 F,R 144,212	98,577 Q 74,000 E 120,956 G 150,745 G 107,391		98,648 F 73,395 F 66,795 E 61,261 F 73,777	73,948 R 118,667 S 74,585 E 84,745 F 86,299
		MINITWIST	S_{mf} = 101 MPa	9,656 E 9,656 E 7,533 Q 8,889	6,687 Q 6,855 E 6,856 E 11,721 Q 7,791	11,672 Q 6,859 E 5,656 E 14,856 Q 9,056	5,656 E 5,656 E 5,656 E 5,656 E 5,656	5,656 E 5,656 F 5,656 E 5,656 R 5,656	6,856 Q,F 9,656 E 5,656 E 6,682 E 7,072
			S_{mf} = 89 MPa	34,856 G 38,856 G 35,840 G 36,478	33,656 F 14,856 R 38,850 R 58,856 R 32,699	19,537 F,G 40,470 G 48,105 G 27,320 G 31,928	17,656 F 37,656 E 30,415 E,Q 26,856 E 27,146	15,068 R 25,378 R 13,656 F 26,936 G 19,366	14,856 F 8,106 F,E 15,709 R 10,856 F 11,971
ARALL with F-28 protection system		MINITWIST	S_{mf} = 101 MPa	> 250,000 – > 250,000 – > 250,000	> 250,000 – > 250,000 – > 250,000		134,371 – 226,682 – 174,526	97,510 – 168,501 – 128,181	
7075-T6 with NF-5 protection system		constant amplitude, R = 0.1	S_{max} = 144 MPa	38,701 S 48,746 G,S 39,428 G 38,165 S 41,047	31,142 R 31,135 S 28,017 R 15,459 R 25,457	42,495 R 29,674 G 37,980 S 36,724 G 36,417		14,308 F 15,385 F 20,896 R 16,631	20,767 G 16,749 R 15,115 R 12,115 F 15,766
		FALSTAFF	S_{max} = 289 MPa	4,372 S 3,972 S 6,231 G 6,231 G 5,096	3,372 R 3,572 R 5,572 F 3,172 R 3,820	6,972 G 4,031 G 5,231 G 5,031 G 5,215		2,831 R,G 1,680 F 3,172 R 2,831 R 2,556	2,824 F 2,680 R 2,372 R 2,172 R 2,499
			S_{max} = 238 MPa	9,771 G 10,572 G 9,373 S 8,960 G 9,651	9,572 F 10,529 G 9,831 N 6,031 N 8,792	8,824 S 9,631 S 8,329 G 10,031 G 9,179		6,759 R 4,559 F 6,031 F 5,999 F 5,778	6,172 F 3,911 F 6,431 F 4,031 F 5,002
7475-T761 clad, with F-16 protection system	without interfay sealant	constant amplitude, R = 0.1	S_{max} = 144 MPa	193,301 G 141 963 G 147,262 G 152,266 G 157,498	125,117 G 168,741 G 271,473 G 108,130 G 157,780			141,941 G 134,268 G 188,244 G 262,870 B,S 175,241	
		FALSTAFF	S_{max} = 289 MPa	7,972 R 4,624 F 8,631 E,G 6,827 F 6,828	11,529 G 10,231 S 4,372 F 10,972 G 8,673			2,824 F 3,511 F 1,924 E,F 3,972 Q,R 2,950	
			S_{max} = 238 MPa	17,480 G,S 17,480 S 16,972 G 21,231 S 18,216	16,372 G 15,314 G 24,372 G 15,538 S 17,554			16,501 G 17,392 G 20,796 G 18,480 G 18,752	
	interfay with sealant	constant amplitude, R = 0.1	S_{max} = 144 MPa	442,310 S ♦ 577,252 G ♦ 373,934 G ♦ 411,851 S ♦ 445,303				236,720 B § 292,367 B § 407,376 B § 336,846 G ♦ 312,174	
		FALSTAFF	S_{max} = 289 MPa	7,431 S 7,372 R 12,700 G 12,972 G,S 9,747				5,424 F 10,996 G 4,172 R 12,424 G ♦ 7,457	
			S_{max} = 238 MPa	19,086 G 21,525 G 17,772 G 21,780 G 19,969				17,831 G ♦ 14,025 G ♦ 17,559 S 21,232 ■ 17,474	

* KEY TO LOCATIONS OF FATIGUE ORIGINS



– Fracture surfaces not available.

♦ These failures were remote from the fastener holes and close to the cross-section at which the half plate ended

§ These failures were just below the fastener holes and originated from paint cracking during the fatigue tests, i.e. they were not initiated by corrosion pits from pre-exposure.

■ This failure occurred at a corner just beyond where the half plate ended

TABLE 7.3: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE)

	FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF VARIATION	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES (F_o > F DISTRIBUTION VALUE)
NLR FACT DATA	constant amplitude, R = 0.1	S_{max} = 144 MPa	● MAIN EFFECTS			
			- environment	2.59	8.76	yes
			- material	2.83	171.96	yes
			● 2-WAY INTERACTIONS			
			- environment : material	2.24	3.19	yes
FACT AND CFCTP DATA	constant amplitude, R = 0.1	S_{max} = 144 MPa	● MAIN EFFECTS			
			- environment	3.07	28.82	yes
			- material	2.44	49.60	yes
			● 2-WAY INTERACTIONS			
			- environment : material	2.08	1.42	no
2024-T3 Alclad	MINITWIST	S_{mf} = 101 MPa AND S_{mf} = 89 MPa	● MAIN EFFECTS			
			- stress	4.13	170.69	yes
			- environment	2.49	5.65	yes
			● 2-WAY INTERACTIONS			
			- stress : environment	2.49	2.65	yes
	FALSTAFF	S_{max} = 289 MPa AND S_{max} = 238 MPa	● MAIN EFFECTS			
			- stress	4.00	226.79	yes
			- environment	2.53	16.18	yes
			- material	3.15	65.47	yes
			● 2-WAY INTERACTIONS			
			- stress : environment	2.53	2.90	yes
			- stress : material	3.15	5.59	yes
			- environment : material	2.76	2.13	no
			● 3-WAY INTERACTIONS			
			- stress : environment : material	2.76	3.96	yes

TABLE 7.4: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECTS OF ENVIRONMENT AND MATERIAL ON CONSTANT AMPLITUDE FATIGUE LIFE OF NLR FACT SPECIMENS

FATIGUE TESTING SCHEDULE OR MATERIAL AND PROTECTION SYSTEM	fatigue in air	pre-exposure + fatigue in air	AMLGUARD coat + pre-exposure + fatigue in air	pre-exposure + fatigue in salt spray	AMLGUARD coat + pre-exposure + fatigue in salt spray	2024-T3 Alclad with F-28 protection system	7075-T6 with NF-5 protection system	7075-T761 clad with F-16 protection system	7475-T761 clad with F-16 protection system and sealant
LOG MEAN FATIGUE LIFE	5.166	4.921	4.796	5.006	4.567	5.026	4.409	5.213	5.572
SAMPLE SIZE n	14	12	8	15	8	18	19	12	8
$t_{0.025;42} = 2.02$						$MS_{residual} = 0.016$			

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;42}$)
fatigue in air/pre-exposure + fatigue in air	4.92	yes
fatigue in air/AMLGUARD coat + pre-exposure + fatigue in air	6.60	yes
fatigue in air/pre-exposure + fatigue in salt spray	3.40	yes
fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray	10.69	yes
pre-exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in air	2.17	yes
pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	1.74	no
pre-exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray	6.13	yes
AMLGUARD coat + pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	3.79	yes
AMLGUARD coat + pre-exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray*	3.62	yes
pre-exposure + fatigue in salt spray/AMLGUARD coat + pre-exposure + fatigue in salt spray	7.93	yes

*Owing to equal sample size this comparison can also be made using the unmodified least significant difference test. The same result is obtained.

COMPARISONS OF MATERIALS	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;42}$)
2024-T3 Alclad + F-28 / 7075-T6 + NF-5	14.83	yes
2024-T3 Alclad + F-28 / 7475-T761 clad + F-16	3.97	yes
2024-T3 Alclad + F-28 / 7475-T761 clad + F-16 + sealant	10.16	yes
7075-T6 + NF-5 / 7475-T761 clad + F-16	17.24	yes
7075-T6 + NF-5 / 7475-T761 clad + F-16 + sealant	21.82	yes
7475-T761 clad + F-16 / 7475-T761 clad + F-16 + sealant	6.22	yes

TABLE 7.5: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR ENVIRONMENT: MATERIAL INTERACTIONS DURING CONSTANT AMPLITUDE FATIGUE OF NLR FACT SPECIMENS

FATIGUE TESTING SCHEDULE	fatigue in air				pre-exposure + fatigue in air			AMLGUARD coat + pre-exposure + fatigue in air		pre-exposure + fatigue in salt spray				AMLGUARD coat + pre-exposure + fatigue in salt spray	
MATERIAL AND PROTECTION SYSTEM	2024-T3 + F-28	7075-T6 + NF-5	7475-T761 + F-16	7475-T761 + F-16 + sealant	2024-T3 + F-28	7075-T6 + NF-5	7475-T761 + F 16	2024-T3 + F-28	7075-T6 + NF-5	2024-T3 + F-28	7075-T6 + NF-5	7475-T761 + F-16	7475-T761 + F 16 + sealant	2024-T3 + F-28	7075-T6 + NF 5
LOG MEAN FATIGUE LIFE	5.244	4.613	5.197	5.649	5.159	4.406	5.198	5.031	4.561	4.868	4.221	5.244	5.494	4.936	4.198
SAMPLE SIZE n	2	4	4	4	4	4	4	4	4	4	3	4	4	4	4

$t_{0.025,42} = 2.02$ $MS_{residual} = 0.016$

TEST PARAMETER	COMPARISONS OF DATA PER TEST PARAMETER	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025,42}$)
2024-T3 Alclad with *F 28 protection system*	fatigue in air/pre-exposure + fatigue in air	0.78	no
	fatigue in air/AMLGUARD coat + pre exposure + fatigue in air	1.94	no
	fatigue in air/pre-exposure + fatigue in salt spray	3.43	yes
	fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray	2.81	yes
	pre-exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in air*	1.43	no
	*pre exposure + fatigue in air/pre-exposure + fatigue in salt spray**	3.25	yes
	pre-exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray*	2.49	yes
	AMLGUARD coat + pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray*	1.82	no
	AMLGUARD coat + pre-exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray*	1.06	no
	pre-exposure + fatigue in salt spray/AMLGUARD coat + pre-exposure + fatigue in salt spray*	0.76	no
7075-T6 with NF 5 protection system	fatigue in air/pre-exposure + fatigue in air*	2.31	yes
	fatigue in air/AMLGUARD coat + pre-exposure + fatigue in air*	0.58	no
	fatigue in air/pre-exposure + fatigue in salt spray	4.06	yes
	fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray*	4.64	yes
	pre-exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in air*	1.73	no
	pre exposure + fatigue in air/pre-exposure + fatigue in salt spray	1.92	no
	pre-exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray*	2.33	yes
	AMLGUARD coat + pre-exposure + fatigue in air/pre exposure + fatigue in salt spray	3.52	yes
	AMLGUARD coat + pre-exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray*	4.06	yes
	pre-exposure + fatigue in salt spray/AMLGUARD coat + pre-exposure + fatigue in salt spray	0.24	no
7475-T761 clad with F-16 protection system	fatigue in air/pre-exposure + fatigue in air*	0.01	no
	fatigue in air/pre-exposure + fatigue in salt spray*	0.53	no
	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray*	0.51	no
7475-T761 clad with F-16 protection system and interfay sealant	fatigue in air/pre exposure + fatigue in salt spray*	1.73	no

fatigue in air	2024-T3 Alclad + F 28 / 7075-T6 + NF-5	5.76	yes
	2024-T3 Alclad + F 28 / 7475-T761 clad + F-16	0.43	no
	2024-T3 Alclad + F-28 / 7475-T761 clad + F 16 + sealant	3.70	yes
	7075-T6 + NF 5 / 7475-T761 clad + F-16*	6.53	yes
	7075-T6 + NF-5 / 7475-T761 clad + F 16 + sealant*	11.58	yes
	7475-T761 clad + F-16 / 7475-T761 clad + F-16 + sealant*	5.05	yes
pre exposure + fatigue in air	2024-T3 Alclad + F 28 / 7075-T6 + NF-5*	8.42	yes
	2024-T3 Alclad + F 28 / 7475-T761 clad + F 16*	0.44	no
	7075-T6 + NF 5 / 7475-T761 clad + F 16*	8.85	yes
AMLGUARD coat + pre-exposure + fatigue in air	2024-T3 Alclad + F-28 / 7075-T6 + NF-5*	5.25	yes
pre-exposure + fatigue in salt spray	2024-T3 Alclad + F 28 / 7075-T6 + NF-5	6.70	yes
	2024-T3 Alclad + F 28 / 7475-T761 clad + F-16*	4.20	yes
	2024-T3 Alclad + F-28 / 7475-T761 clad + F 16 + sealant*	2.08	yes
	7075-T6 + NF-5 / 7475-T761 clad + F 16	10.59	yes
	7075-T6 + NF 5 / 7475-T761 clad + F 16 + sealant	13.18	yes
	7475-T761 clad + F 16 / 7475-T761 clad + F 16 + sealant*	2.80	yes
AMLGUARD coat + pre-exposure + fatigue in salt spray	2024-T3 Alclad + F 28 / 7075-T6 + NF-5*	8.2	yes

Owing to equal sample size these comparisons can also be made using the unmodified least significant difference test. The same result is obtained

TABLE 7.6: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECTS OF ENVIRONMENT AND MATERIAL ON CONSTANT AMPLITUDE FATIGUE LIFE OF NLR FACT AND CFCTP SPECIMENS (OMITTING AMLGUARD COATED SPECIMENS)

FATIGUE TESTING SCHEDULE OR MATERIAL AND PROTECTION SYSTEM	fatigue in air	pre-exposure + fatigue in air	pre-exposure + fatigue in salt spray	7075-T76 with U.S. Navy protection system	2024-T3 Alclad with F-28 protection system	7075-T6 with NF-5 protection system	7475-T761 clad with F-16 protection system	7475-T761 clad with F-16 protection system and sealant
LOG MEAN FATIGUE LIFE	5.137	5.027	4.875	5.001	5.059	4.431	5.213	5.572
SAMPLE SIZE n	49	40	50	98	10	11	12	8
	$t_{0.025;125} = 1.98$					$MS_{residual} = 0.036$		

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;125}$)
fatigue in air/pre-exposure + fatigue in air	2.72	yes
fatigue in air/pre-exposure + fatigue in salt spray	6.87	yes
pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	3.78	yes

COMPARISONS OF MATERIALS	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;125}$)
7075-T76 + U.S. Navy / 2024-T3 Alclad + F-28	0.92	no
7075-T76 + U.S. Navy / 7075-T6 + NF-5	9.45	yes
7075-T76 + U.S. Navy / 7475-T761 clad + F-16	3.65	yes
7075-T76 + U.S. Navy / 7475-T761 clad + F-16 + sealant	8.18	yes
2024-T3 Alclad + F-28 / 7075-T6 + NF-5	7.58	yes
2024-T3 Alclad + F-28 / 7475-T761 clad + F-16	1.90	no
2024-T3 Alclad + F-28 / 7475-T761 clad + F-16 + sealant	5.70	yes
7075-T6 + NF-5 / 7475-T761 clad + F-16	9.87	yes
7075-T6 + NF-5 / 7475-T761 clad + F-16 + sealant	12.94	yes
7475-T761 clad + F-16 / 7475-T761 clad + F-16 + sealant	4.15	yes

TABLE 7.7: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR ENVIRONMENT : MATERIAL INTERACTIONS DURING CONSTANT AMPLITUDE FATIGUE OF NLR FACT AND CFCTP SPECIMENS (OMITTING AMLGUARD COATED SPECIMENS)

FATIGUE TESTING SCHEDULE	fatigue in air					pre-exposure + fatigue in air				pre-exposure + fatigue in salt spray				
MATERIAL AND PROTECTION SYSTEM	7075-T76 + U.S. Navy	2024-T3 + F-28	7075-T6 + NF-5	7475-T761 + F-16	7475-T761 + F-16 + *sealant*	7075-T76 + U.S. Navy	2024-T3 + F-28	7075-T6 + NF-5	7475-T761 + U.S. Navy	7075-T76 + U.S. Navy	2024-T3 + F-28	7075-T6 + NF-5	7475-T761 + F-16	7475-T761 + F-16 + sealant
LOG MEAN FATIGUE LIFE	5.125	5.244	4.613	5.197	5.649	5.072	5.159	4.406	5.198	4.819	4.868	4.221	5.244	5.494
SAMPLE SIZE n	35	2	4	4	4	28	4	4	4	35	4	3	4	4

TEST PARAMETER	COMPARISONS OF DATA PER TEST PARAMETER	p	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_in_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i - \bar{x}_j)\sqrt{\frac{2n_in_j}{n_i+n_j}} > SSR$
7075-T76 with U.S. Navy protection system (CFCTP core programme)	*fatigue in air/pre-exposure + fatigue in air*	2	0.296	0.532	no
	fatigue in air/pre-exposure + fatigue in salt spray*	3	1.810	0.560	yes
	pre exposure + fatigue in air/pre-exposure + fatigue in salt spray	2	1.411	0.532	yes
2024-T3 Alclad with F-28 protection system	fatigue in air/pre-exposure + fatigue in air	2	0.139	0.532	no
	fatigue in air/pre-exposure + fatigue in salt spray	3	0.614	0.560	yes
	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray*	2	0.582	0.532	yes
7075-T6 with NF-5 protection system	fatigue in air/pre-exposure + fatigue in air*	2	0.414	0.532	no
	fatigue in air/pre-exposure + fatigue in salt spray	3	0.726	0.560	yes
	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	2	0.343	0.532	no
7475-T761 clad with F-16 protection system	fatigue in air/pre-exposure + fatigue in air*	2	0.002	0.532	no
	fatigue in air/pre-exposure + fatigue in salt spray*	3	0.094	0.560	no
	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray*	2	0.092	0.532	no
7475-T761 clad with F-16 protection system and interfay sealant	fatigue in air/pre-exposure + fatigue in salt spray*	2	0.310	0.532	*no*

fatigue in air	7075-T76 + U.S. Navy / 2024-T3 Alclad + F-28	3	0.231	0.560	no
	7075-T76 + U.S. Navy / 7075-T6 + NF-5	2	1.372	0.532	yes
	7075-T76 + U.S. Navy / 7475-T761 clad + F-16	2	0.193	0.532	no
	7075-T76 + U.S. Navy / 7475-T761 clad + F-16 + sealant	4	1.404	0.579	yes
	2024-T3 Alclad + F-28 / 7075-T6 + NF-5	4	1.030	0.579	yes
	2024-T3 Alclad + F-28 / 7475-T761 clad + F-16	2	0.077	0.532	no
	2024-T3 Alclad + F-28 / 7475-T761 clad + F-16 + sealant	2	0.661	0.532	yes
	7075-T6 + NF-5 / 7475-T761 clad + F-16*	3	1.168	0.560	yes
	7075-T6 + NF-5 / 7475-T761 clad + F-16 + sealant*	5	2.072	0.592	yes
	7475-T761 clad + F-16 / 7475-T761 clad + F-16 + sealant*	3	0.904	0.560	yes
pre-exposure + fatigue in air	7075-T76 + U.S. Navy / 2024-T3 Alclad + F-28	2	0.230	0.532	no
	7075-T76 + U.S. Navy / 7075-T6 + NF-5	2	1.762	0.532	yes
	7075-T76 + U.S. Navy / 7475-T761 clad + F-16	3	0.333	0.560	no
	2024-T3 Alclad + F-28 / 7075-T6 + NF-5*	3	1.506	0.560	yes
	2024-T3 Alclad + F-28 / 7475-T761 clad + F-16*	2	0.078	0.532	no
	7075-T6 + NF-5 / 7475-T761 clad + F-16*	4	1.584	0.579	yes
pre-exposure + fatigue in salt spray	7075-T76 + U.S. Navy / 2024-T3 Alclad + F-28	2	0.131	0.532	no
	7075-T76 + U.S. Navy / 7075-T6 + NF-5	2	1.406	0.532	yes
	7075-T76 + U.S. Navy / 7475-T761 clad + F-16	3	1.139	0.560	yes
	7075-T76 + U.S. Navy / 7475-T761 clad + F-16 + sealant	4	1.809	0.579	yes
	2024-T3 Alclad + F-28 / 7075-T6 + NF-5	3	1.198	0.560	yes
	2024-T3 Alclad + F-28 / 7475-T761 clad + F-16*	2	0.752	0.532	yes
	2024-T3 Alclad + F-28 / 7475-T761 clad + F-16 + sealant*	3	1.252	0.560	yes
	7075-T6 + NF-5 / 7475-T761 clad + F-16	4	1.894	0.579	yes
	7075-T6 + NF-5 / 7475-T761 clad + F-16 + sealant	5	2.357	0.592	yes
	7475-T761 clad + F-16 / 7475-T761 clad + F-16 + sealant*	2	0.500	0.532	no

*Owing to equal sample size these comparisons can also be made using the unmodified version of Duncan's test. The same result is obtained

TABLE 7.8: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR STRESS : ENVIRONMENT INTERACTIONS DURING MINITWIST FATIGUE OF 2024-T3 ALCLAD WITH F-28 PROTECTION SYSTEM

FATIGUE TESTING SCHEDULE	fatigue in air		pre exposure + fatigue in air		AMLGUARD coat + pre exposure + fatigue in air		fatigue in salt spray		pre exposure + fatigue in salt spray		AMLGUARD coat + pre exposure + fatigue in salt spray	
CHARACTERISTIC STRESS LEVEL S_{mf} (MPa)	101	89	101	89	101	89	101	89	101	89	101	89
LOG MEAN FATIGUE LIFE	3.969	4.562	3.89[illegible]	4.515	3.95[illegible]	4.564	3.[illegible]3	4.43[illegible]	3.[illegible]3	4.28[illegible]	3.850	4.078
SAMPLE SIZE n	3	3	4	4	4	4	4	4	4	4	4	4
	$t_{0.025;34}$ = 2.03						$MS_{residual}$ = [illegible]					

COMPARISONS OF DATA FOR DIFFERENT STRESS LEVELS	FATIGUE TESTING SCHEDULE	t	SIGNIFICANT DIFFERENCE (t > $t_{0.025;34}$)
S_{mf} = 101 MPa / S_{mf} = 89 MPa*	fatigue in air	5.4[illegible]	yes
	pre-exposure + fatigue in air	6.3[illegible]	yes
	AMLGUARD coat + pre-exposure + fatigue in air	[illegible]	yes
	fatigue in salt spray	[illegible]	yes
	pre-exposure + fatigue in salt spray	[illegible].48	yes
	AMLGUARD coat + pre exposure + fatigue in salt spray	2.[illegible]	yes

CHARACTERISTIC STRESS LEVEL	COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	t	SIGNIFICANT DIFFERENCE (t > $t_{0.025;34}$)
S_{mf} = 101 MPa	fatigue in air/pre-exposure + fatigue in air	[illegible]	no
	fatigue in air/AMLGUARD coat + pre-exposure + fatigue in air	[illegible].08	no
	fatigue in air/fatigue in salt spray	[illegible]	no
	fatigue in air/pre-exposure + fatigue in salt spray	[illegible]	no
	fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	no
	pre-exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in air*	[illegible]	no
	pre exposure + fatigue in air/fatigue in salt spray*	[illegible]	no
	pre-exposure + fatigue in air/pre exposure + fatigue in salt spray*	[illegible]	[illegible]
	pre-exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	[illegible]
	AMLGUARD coat + pre-exposure + fatigue in air/fatigue in salt spray*	[illegible]	yes
	AMLGUARD coat + pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray*	[illegible]	yes
	AMLGUARD coat + pre-exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	no
	fatigue in salt spray/pre-exposure + fatigue in salt spray*	[illegible]	no
	fatigue in salt spray/AMLGUARD coat + pre-exposure + fatigue in salt spray*	[illegible]	no
	pre-exposure + fatigue in salt spray/AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	no
S_{mf} = 89 MPa	fatigue in air/pre exposure + fatigue in air	[illegible]	no
	fatigue in air/AMLGUARD coat + pre exposure + fatigue in air	[illegible]	no
	fatigue in air/fatigue in salt spray	[illegible]	no
	fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
	fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
	pre exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in air*	[illegible]	no
	pre-exposure + fatigue in air/fatigue in salt spray*	[illegible]	[illegible]
	pre-exposure + fatigue in air/pre exposure + fatigue in salt spray*	[illegible]	yes
	pre-exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	yes
	AMLGUARD coat + pre exposure + fatigue in air/fatigue in salt spray*	[illegible]	[illegible]
	AMLGUARD coat + pre exposure + fatigue in air/pre exposure + fatigue in salt spray*	[illegible]	yes
	AMLGUARD coat + pre-exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	[illegible]
	fatigue in salt spray/pre exposure + fatigue in salt spray*	[illegible]	[illegible]
	fatigue in salt spray/AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	[illegible]
	pre exposure + fatigue in salt spray/AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	[illegible]

* Owing to equal sample size these comparisons can also be made using the unmodified least significant difference test. The same result is obtained

TABLE 7.9: BOX TEST FOR HOMOGENEITY OF VARIANCES OF NLR FALSTAFF DATA FOR S_{max} = 289 MPa (95 % CONFIDENCE)

FATIGUE TESTING SCHEDULE	SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - \bar{x})^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
[illegible]	[illegible] T6 + NF [illegible]	4	[illegible]	3	0.333	0.010	− 1.980	[illegible]
	[illegible] T7[illegible] + [illegible]	4	[illegible]	3	0.333	[illegible]	− [illegible].838	[illegible]
	[illegible] T7[illegible] + [illegible]	4	[illegible]	3	0.333	[illegible]	[illegible]	[illegible]
	SUM				[illegible]			[illegible]
	POOLED		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	DIFFERENCE				[illegible]			[illegible]
	[illegible]							
	[illegible]							
	FOR [illegible] AND [illegible] AND [illegible] DEGREES OF FREEDOM F = [illegible] SINCE [illegible] THE POPULATION VARIANCES ARE EQUAL							
[illegible]	[illegible] T6 + NF	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible] T7[illegible] + [illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	SUM				[illegible]			[illegible]
	POOLED		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	DIFFERENCE				[illegible]			[illegible]
	[illegible]							
	[illegible] DEGREES OF FREEDOM							
	FOR n = [illegible] AND [illegible] AND [illegible] DEGREES OF FREEDOM F = [illegible] SINCE [illegible] THE POPULATION VARIANCES ARE EQUAL							
pre exposure + fatigue in salt spray	[illegible] T6 + NF	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible] T7[illegible] + [illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible] T7[illegible] + [illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	SUM				[illegible]			[illegible]
	POOLED		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	DIFFERENCE				[illegible]			[illegible]
	[illegible]							
	[illegible] WITH [illegible] AND [illegible] DEGREES OF FREEDOM							
	FOR n = 3 [illegible] AND 2 AND 183 DEGREES OF FREEDOM F = 3.06 SINCE 0.611 < 3.06 THE POPULATION VARIANCES ARE EQUAL							

TABLE 7.10: BOX TEST FOR HOMOGENEITY OF VARIANCES OF NLR FALSTAFF DATA FOR S_{max} = 238 MPa (95 % CONFIDENCE)

FATIGUE TESTING SCHEDULE	SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - \bar{x})^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	log s^2	ν log s^2
fatigue in air	1 7075-T6 + NF-5	4	0.003	3	0.333	0.001	−3.0[illegible]	9.092
	2 7475-T761 + F-16	4	0.006	3	0.333	0.002	−2.698	8.09[illegible]
	3 7475-T761 + F-16 + sealant	4	0.005	3	0.333	[illegible]	−2.[illegible]	[illegible]
	k = 3							
	SUM		–	–	1.000		–	[illegible]
	POOLED	–	0.014	9	0.111	0.002	−2.[illegible]	[illegible]
	DIFFERENCE	–	–	–	D_1 = 0.889			D_2 = [illegible]
	K = 2.3026 D_2 = 0.[illegible] $L = \frac{D_1}{3(k-1)}$ = 0.148 $\nu_1 = k - 1 = 2$ $\nu_2 = \frac{k+1}{L^2}$ = 183							
	$D = \frac{\nu_2}{1 - L + 2/\nu_2} - K$ = 211.[illegible] $F_0 = \frac{K\nu_2}{D\nu_1}$ = 0.139 WITH 2 AND 183 DEGREES OF FREEDOM							
	FOR α = 5 % AND 2 AND 183 DEGREES OF FREEDOM F = 3.06. SINCE 0.139 < 3.06 THE POPULATION VARIANCES ARE EQUAL							
pre exposure + fatigue in air	1 7075-T6 + NF-5	4	0.037	3	0.333	0.012	−1.9[illegible]	[illegible]
	2 7475-T761 + F-16	4	0.028	3	0.333	0.009	−2.0[illegible]	6.111
	k = 2							
	SUM	–	–	–	0.667	–	–	11.85[illegible]
	POOLED	–	0.065	6	0.167	0.011	−1.96[illegible]	11.[illegible]
	DIFFERENCE	–	–	–	D_1 = 0.500	–		D_2 = 0.[illegible]
	K = 2.3026 D_2 = 0.13[illegible] $L = \frac{D_1}{3(k-1)}$ = 0.166 $\nu_1 = k - 1 = 1$ $\nu_2 = \frac{k+1}{L^2}$ = 109							
	$D = \frac{\nu_2}{1 - L + 2/\nu_2} - K$ = 12[illegible] $F_0 = \frac{K\nu_2}{D\nu_1}$ = 0.116 WITH 1 AND 109 DEGREES OF FREEDOM							
	FOR α = 5 % AND 1 AND 109 DEGREES OF FREEDOM F = 3.94. SINCE 0.116 < 3.94 THE POPULATION VARIANCES ARE EQUAL							
pre exposure + fatigue in salt spray	1 7075-T6 + NF-5	4	0.016	3	0.333	0.00[illegible]	[illegible]	[illegible]
	2 7475-T76[illegible] + F-16	4	0.003	3	0.333	0.001	−[illegible]	8.[illegible]
	3 7475-T76[illegible] + F-16 + sealant	4	0.016	3	0.333	0.005	−2.[illegible]	6.[illegible]
	k = 3							
	SUM	–	–	–	1.000	–	–	[illegible]
	POOLED	–	[illegible]	9	0.111	[illegible]	[illegible]	[illegible]
	DIFFERENCE		–	–	D_1 = 0.889		–	D_2 = [illegible]
	K = [illegible] D_2 = [illegible] L = [illegible] ν_1 = k [illegible] $\nu_2 = \frac{k+1}{L^2}$ = [illegible]							
	D = [illegible] − K = [illegible] F_0 = [illegible] = 0.86[illegible] WITH 2 AND 183 DEGREES OF FREEDOM							
	FOR α = 5 % AND 2 AND 183 DEGREES OF FREEDOM F = 3.06. SINCE 0.86[illegible] < 3.06 THE POPULATION VARIANCES ARE EQUAL							

TABLE 7.11: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR STRESS : ENVIRONMENT AND STRESS : MATERIAL INTERACTIONS DURING FALSTAFF FATIGUE

CHARACTERISTIC STRESS LEVEL	S_{max} = 284 MPa								S_{max} = [illegible] MPa							
FATIGUE TESTING SCHEDULE OR MATERIAL AND PROTECTION SYSTEM	fatigue in air	pre exposure + fatigue in air	AMLGUARD coat + pre exposure + fatigue in salt spray	pre exposure + fatigue in salt spray	AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible] T6 + NF [illegible]	[illegible] T761 + F 16	[illegible] T761 + F 16 + sealant	fatigue in air	pre exposure + fatigue in salt	AMLGUARD coat + pre exposure + fatigue in salt spray	pre exposure + fatigue in salt spray	AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible] T6 + NF	[illegible] T761 + F 16	[illegible] T761 + F 16 + sealant
LOG MEAN FATIGUE LIFE	3.843	3.[illegible]	3.[illegible]	.583	3.338	3.5[illegible]	3.[illegible]	3.93[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SAMPLE SIZE n	12	8	4	12	6	2[illegible]	12	8	12	8	4	1[illegible]	4	[illegible]	1[illegible]	8

$t_{[illegible], 60}$ = 2.0[illegible]

$MS_{residual}$ = [illegible]

COMPARISONS OF DATA FOR DIFFERENT STRESS LEVELS	TEST PARAMETER	t	SIGNIFICANT DIFFERENCE [illegible]
S_{max} = 284 MPa S_{max} = 138 MPa*	fatigue in air	[illegible]	yes
	pre exposure + fatigue in air	[illegible]	yes
	AMLGUARD coat + pre exposure + fatigue in air	[illegible]	yes
	pre exposure + fatigue in salt spray	11.[illegible]	yes
	AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
	[illegible] T6 with NF [illegible] protection system	[illegible]	[illegible]
	[illegible] T761 clad with F 16 protection system	[illegible]	yes
	[illegible] T761 clad with F 16 protection system and [illegible] sealant	[illegible]	yes

CHARACTERISTIC STRESS LEVEL	COMPARISONS OF FATIGUE TESTING SCHEDULES OR MATERIALS AND PROTECTION SYSTEMS	t	SIGNIFICANT DIFFERENCE [illegible]
S_{max} = [illegible] MPa	fatigue in air pre exposure + fatigue in air	[illegible]	yes
	fatigue in air AMLGUARD coat + pre exposure + fatigue in air	[illegible]	[illegible]
	fatigue in air pre exposure + fatigue in salt spray*	[illegible]81	yes
	fatigue in air AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
	pre exposure + fatigue in air AMLGUARD coat + pre exposure + fatigue in air	[illegible]	[illegible]
	pre exposure + fatigue in air pre exposure + fatigue in salt spray	[illegible]	yes
	pre exposure + fatigue in air AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
	AMLGUARD coat + pre exposure + fatigue in air pre exposure + fatigue in salt spray	[illegible]	yes
	AMLGUARD coat + pre exposure + fatigue in air AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	yes
	pre exposure + fatigue in salt spray AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
	[illegible] T6 with NF [illegible] protection system [illegible] T761 clad with F 16 protection system	[illegible]	yes
	[illegible] T6 with NF [illegible] protection system [illegible] T761 clad with F 16 protection system and interfay sealant	[illegible]	yes
	[illegible] T761 clad with F 16 protection system [illegible] T761 clad with F 16 protection system and interfay sealant	[illegible]	yes
S_{max} = 138 MPa	fatigue in air pre exposure + fatigue in air	[illegible]	[illegible]
	fatigue in air AMLGUARD coat + pre exposure + fatigue in air	[illegible]	[illegible]
	fatigue in air pre exposure + fatigue in salt spray*	[illegible]	[illegible]
	fatigue in air AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	[illegible]
	pre exposure + fatigue in air AMLGUARD coat + pre exposure + fatigue in air	[illegible]	[illegible]
	pre exposure + fatigue in air pre exposure + fatigue in salt spray	[illegible]	[illegible]
	pre exposure + fatigue in air AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	[illegible]
	AMLGUARD coat + pre exposure + fatigue in air pre exposure + fatigue in salt spray	[illegible]	[illegible]
	AMLGUARD coat + pre exposure + fatigue in air AMLGUARD coat + pre exposure + fatigue in salt spray*	[illegible]	[illegible]
	pre exposure + fatigue in salt spray AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
	[illegible] T6 with NF [illegible] protection system [illegible] T761 clad with F 16 protection system	[illegible]	[illegible]
	[illegible] T6 with NF [illegible] protection system [illegible] T761 clad with F 16 protection system and interfay sealant	[illegible]	[illegible]
	[illegible] T761 clad with F 16 protection system [illegible] T761 clad with F 16 protection system and interfay sealant	[illegible]	[illegible]

*Owing to equal sample size these comparisons [illegible] the [illegible] least significant difference [illegible]

TABLE 7.12: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR ENVIRONMENT : MATERIAL INTERACTIONS DURING FALSTAFF FATIGUE

FATIGUE TESTING SCHEDULE	fatigue in air			pre-exposure + fatigue in air		AMLGUARD coat + pre exposure + fatigue in air	pre-exposure + fatigue in salt spray			AMLGUARD coat + pre exposure + fatigue in salt spray
MATERIAL AND PROTECTION SYSTEM	7075-T6 + NF-5	7475-T761 clad + F-16	7475-T761 clad + F-16 + sealant	7075-T6 + NF-5	7475-T761 clad + F-16	7075-T6 + NF-5	7075-T6 + NF-5	7475-T761 clad + F-16	7475-T761 clad + F-16 + sealant	7075-T6 + NF-5
LOG MEAN FATIGUE LIFE	3.846	4.047	4.145	3.763	4.091	3.840	3.585	3.871	4.057	3.548
SAMPLE SIZE n	8	8	8	8	8	8	8	8	8	8

TEST PARAMETER	COMPARISONS OF DATA PER TEST PARAMETER	P	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SSR	SIGNIFICANT DIFFERENCE (DIFFERENCE > SSR)
7075-T6 with NF-5 protection system	fatigue in air/pre-exposure + fatigue in air	3	0.083	0.116	no
	fatigue in air/AMLGUARD coat + pre-exposure + fatigue in air	2	0.006	0.110	no
	fatigue in air/pre exposure + fatigue in salt spray	4	0.261	0.120	yes
	fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray	5	0.298	0.125	yes
	pre exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in air	2	0.077	0.110	no
	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	2	0.178	0.110	yes
	pre-exposure + fatigue in air/AMLGUARD coat + pre-exposure + fatigue in salt spray	3	0.215	0.116	yes
	AMLGUARD coat + pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	3	0.255	0.116	yes
	AMLGUARD coat + pre-exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	4	0.292	0.120	yes
	pre exposure + fatigue in salt spray/AMLGUARD coat + pre-exposure + fatigue in salt spray	2	0.037	0.110	no
7475-T761 clad, with F-16 protection system	fatigue in air/pre exposure + fatigue in air	2	0.044	0.110	no
	fatigue in air/pre exposure + fatigue in salt spray	2	0.176	0.11	yes
	pre exposure + fatigue in air/pre exposure + fatigue in salt spray	3	0.220	0.116	yes
7475-T761 clad, with F-16 protection system and interfay sealant	fatigue in air/pre-exposure + fatigue in salt spray	2	0.088	0.110	no

fatigue in air	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	2	0.201	0.11	yes
	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	3	0.299	0.116	yes
	7475-T761 clad, with F-16 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	2	0.098	0.110	no
pre-exposure + fatigue in air	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	2	0.328	0.110	yes
pre-exposure + fatigue in salt spray	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	2	0.286	0.11	yes
	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	3	0.472	0.116	yes
	7475-T761 clad, with F-16 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	2	0.186	0.11	yes

TABLE 7.13: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR STRESS : ENVIRONMENT : MATERIAL INTERACTIONS DURING FALSTAFF FATIGUE

FATIGUE TESTING SCHEDULE	fatigue in air						pre exposure + fatigue in air				AMLGUARD coat + pre exposure + fatigue in air		pre exposure + fatigue in salt spray						AMLGUARD coat + pre exposure + fatigue in salt spray	
MATERIAL AND PROTECTION SYSTEM	7075-T6 + NF-5		7475-T761 clad + F-16		7475-T761 clad + F-16 + sealant		7075-T6 + NF-5		7475-T761 clad + F-16		7075-T6 + NF-5		7075-T6 + NF-5		7475-T761 clad + F-16		7475-T761 clad + F-16 + sealant		7075-T6 + NF-5	
CHARACTERISTIC STRESS LEVEL S_{max} (MPa)	289	238	289	238	289	238	289	238	289	238	289	238	289	238	289	238	289	238	289	238
LOG MEAN FATIGUE LIFE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.463	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.699
SAMPLE SIZE n	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

$LSD_{0.05}$ = 0.155

CHARACTERISTIC STRESS LEVEL	TEST PARAMETER	COMPARISONS OF DATA PER TEST PARAMETER	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SIGNIFICANT DIFFERENCE DIFFERENCE > [illegible]
S_{max} = 289 MPa	fatigue in air	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	[illegible]	no
		7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	[illegible]	yes
		7475-T761 clad, with F-16 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	[illegible]	no
	pre exposure + fatigue in air	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	[illegible]	yes
	pre exposure + fatigue in salt spray	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	[illegible]	no
		7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	[illegible]	yes
		7475-T761 clad, with F-16 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	[illegible]	yes
	7075-T6 with NF-5 protection system	fatigue in air/pre exposure + fatigue in air	[illegible]	no
		fatigue in air/AMLGUARD coat + pre exposure + fatigue in air	[illegible]	no
		fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
		fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
		pre exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in air	[illegible]	[illegible]
		pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
		pre exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
		AMLGUARD coat + pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
		AMLGUARD coat + pre exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
		pre exposure + fatigue in salt spray/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	no
	7475-T761 clad, with F-16 protection system	fatigue in air/pre exposure + fatigue in air	[illegible]	no
		fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
		pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
	7475-T761 clad, with F-16 protection system and interfay sealant	fatigue in air/pre exposure + fatigue in salt spray	[illegible]	no
S_{max} = 238 MPa	fatigue in air	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	[illegible]	yes
		7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	[illegible]	yes
		7475-T761 clad, with F-16 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	[illegible]	[illegible]
	pre exposure + fatigue in air	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	[illegible]	yes
	pre exposure + fatigue in salt spray	7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system	[illegible]	yes
		7075-T6 with NF-5 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	[illegible]	yes
		7475-T761 clad, with F-16 protection system/7475-T761 clad, with F-16 protection system and interfay sealant	[illegible]	no
	7075-T6 with NF-5 protection system	fatigue in air/pre exposure + fatigue in air	[illegible]	no
		fatigue in air/AMLGUARD coat + pre exposure + fatigue in air	[illegible]	no
		fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
		fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
		pre exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in air	[illegible]	no
		pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
		pre exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
		AMLGUARD coat + pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	yes
		AMLGUARD coat + pre exposure + fatigue in air/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	yes
		pre exposure + fatigue in salt spray/AMLGUARD coat + pre exposure + fatigue in salt spray	[illegible]	no
	7475-T761 clad, with F-16 protection system	fatigue in air/pre exposure + fatigue in air	[illegible]	no
		fatigue in air/pre exposure + fatigue in salt spray	[illegible]	no
		pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	no
	7475-T761 clad, with F-16 protection system and interfay sealant	fatigue in air/pre exposure + fatigue in salt spray	[illegible]	no

TABLE 7.14: SUMMARY OF χ^2 TEST AND YATES' CORRECTED χ^2 TEST FOR THE PRIMARY FATIGUE ORIGINS (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF ASSOCIATION	$\chi^2_{0.05;(r-1)(c-1)}$	χ^2_o OR χ^2_c	SIGNIFICANT ASSOCIATION (χ^2_o OR $\chi^2_c > \chi^2_{0.05;(r-1)(c-1)}$)
constant amplitude, R = 0.1	S_{max} = 144 MPa	ENVIRONMENT (FATIGUE TESTING SCHEDULE)	$\chi^2_{0.05;1} = 3.84$	6.47	yes
		MATERIAL AND PROTECTION SYSTEM	$\chi^2_{0.05;2} = 5.99$	14.09	yes
MINITWIST	S_{mf} = 101 MPa AND S_{mf} = 89 MPa	STRESS LEVEL	$\chi^2_{0.05;1} = 3.84$	20.65	yes
		ENVIRONMENT (FATIGUE TESTING SCHEDULE)	$\chi^2_{0.05;1} = 3.84$	0.07	no
FALSTAFF	S_{max} = 289 MPa AND S_{max} = 238 MPa	STRESS LEVEL	$\chi^2_{0.05;1} = 3.84$	6.79	yes
		ENVIRONMENT (FATIGUE TESTING SCHEDULE)	$\chi^2_{0.05;1} = 3.84$	16.43	yes
		MATERIAL AND PROTECTION SYSTEM	$\chi^2_{0.05;2} = 5.99$	6.79	yes

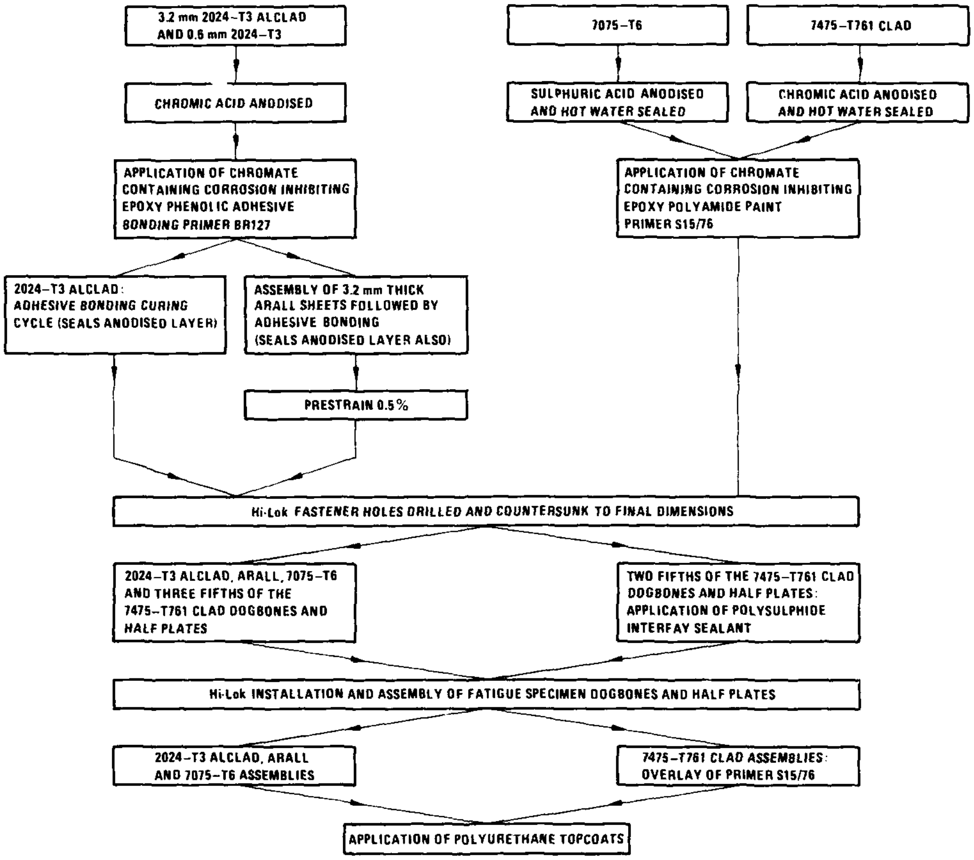


Fig. 7.1 Schematic of the application of corrosion protection systems and specimen assembly

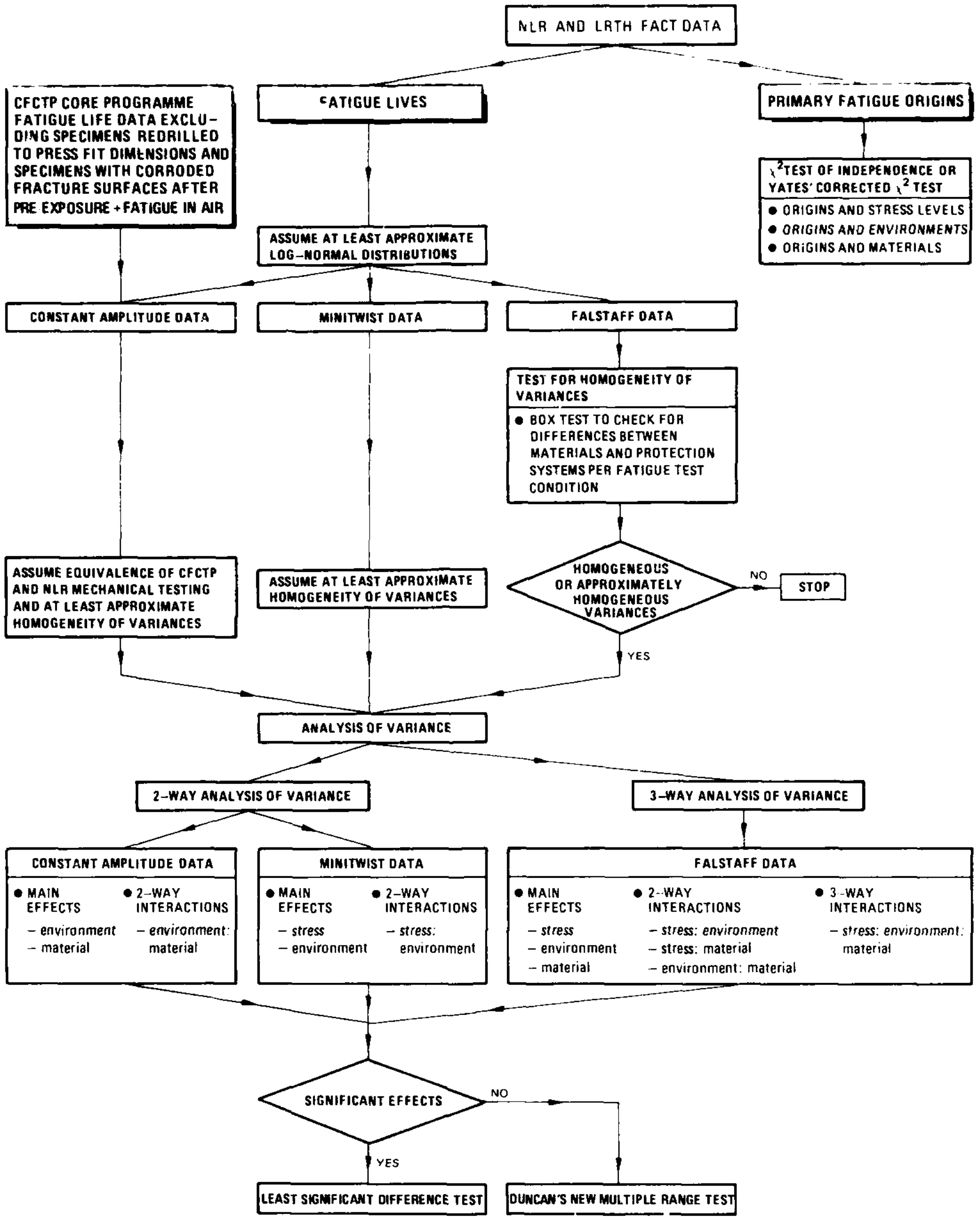


Fig. 7.2 Survey of statistical methods for analysing the NLR and LRTH data for FACT

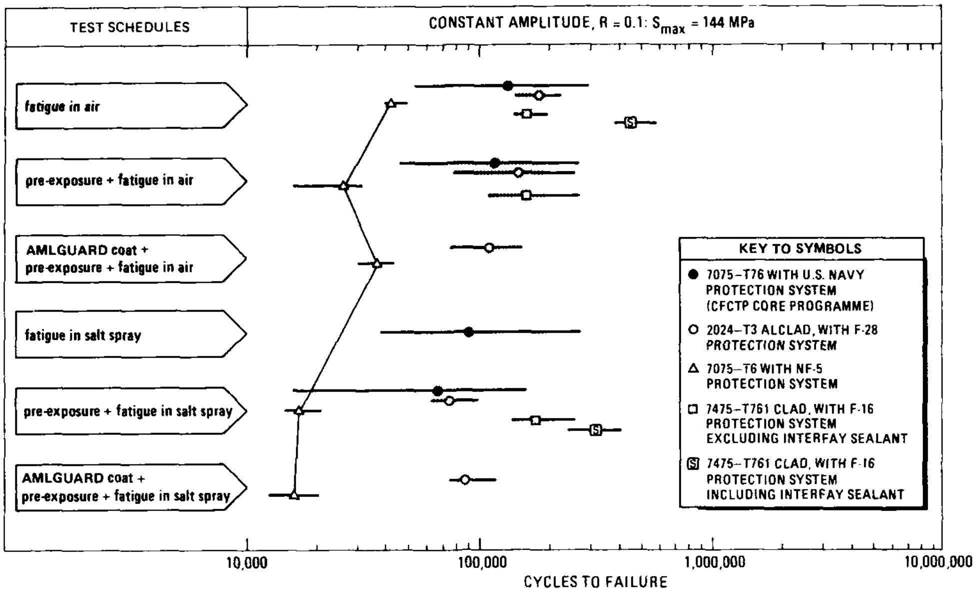


Fig. 7.3 Comparison of NLR FACT contribution and CFCTP core programme (●) constant amplitude fatigue life data. The CFCTP core programme data exclude specimens redrilled to press fit dimensions and specimens with corroded fracture surfaces after pre-exposure + fatigue in air. The shaded bar shows that the data fall into three groups with significant differences in fatigue life (see text)

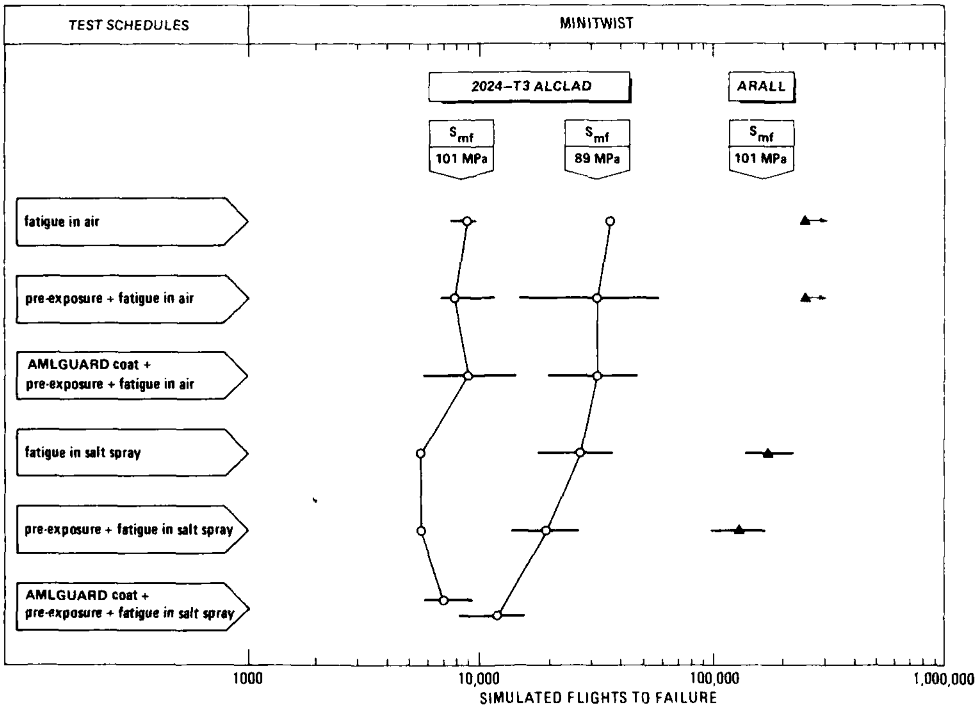


Fig. 7.4 NLR and LRTH fatigue life data for 2024-T3 Alclad and ARALL with an F-28 corrosion protection system and tested under gust spectrum loading (MINITWIST)

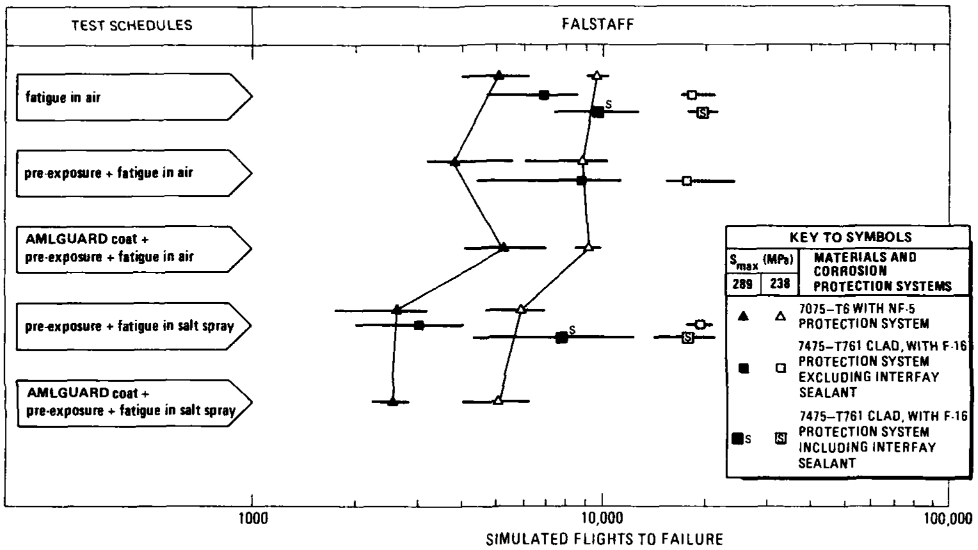


Fig. 7.5 NLR fatigue life data for testing under manoeuvre spectrum loading (FALSTAFF). The shaded bar indicates 7475-T761 clad specimens tested with S_{max} = 238 MPa

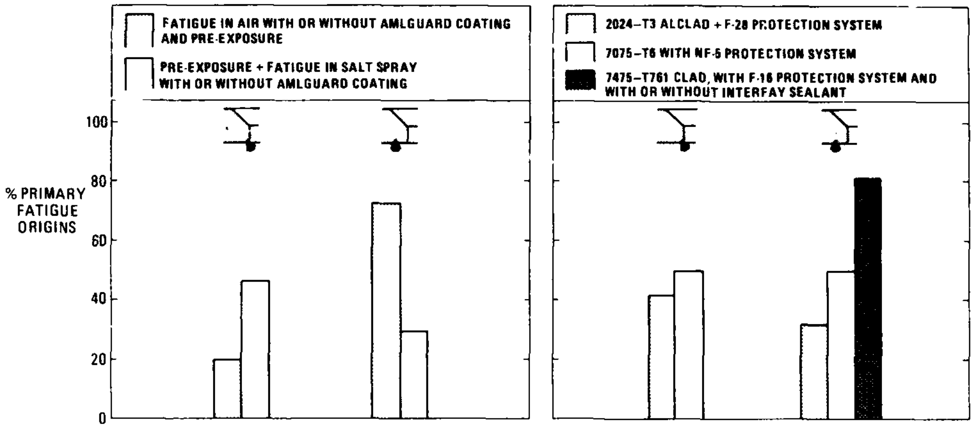


Fig. 7.6 Effects of environment and material on locations of primary fatigue origins for the NLR constant amplitude fatigue (R = 0.1, S_{max} = 144 MPa) contribution to FACT

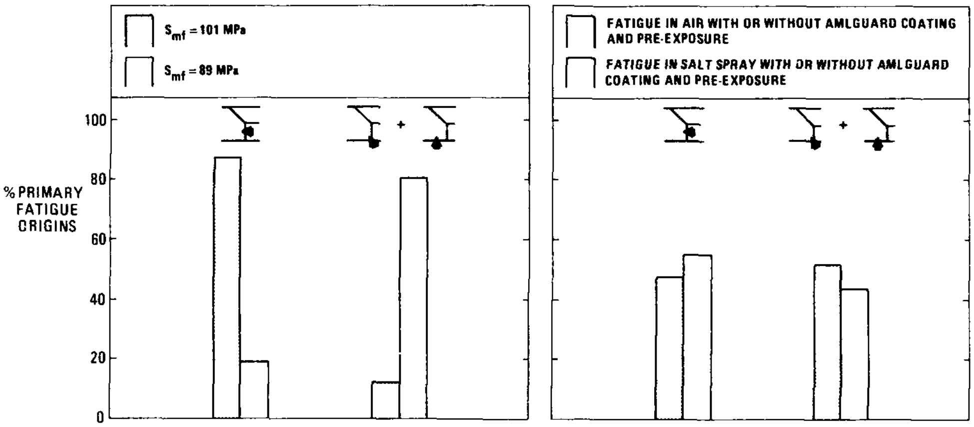


Fig. 7.7 Effects of stress and environment on locations of primary origins for monolithic 2024-T3 Alclad specimens tested as part of the NLR and LRTH MINITWIST fatigue contribution to FACT

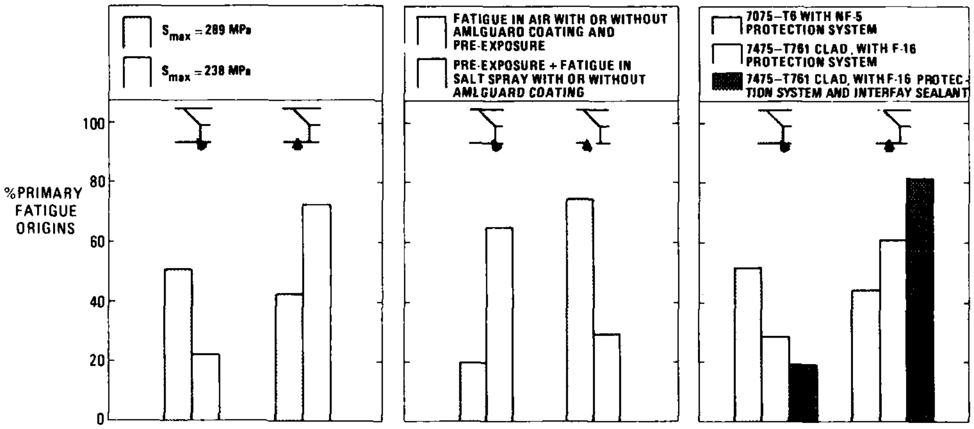


Fig. 7.8 Effects of stress, environment and material on locations of primary fatigue origins for the NLR FALSTAFF fatigue contribution to FACT

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVELS (S_{max}, S_{mf})	INFLUENCES ON FATIGUE LIVES		
		MATERIALS AND PROTECTION SYSTEMS	ENVIRONMENTAL EFFECTS	
			PRE-EXPOSURE	FATIGUE IN SALT SPRAY
CONSTANT AMPLITUDE, R = 0.1	144 MPa	● 7475–T761 CLAD + F-16 + INTERFAY SUPERIOR OVERALL ● 7075–T6 + NF-5 INFERIOR OVERALL ● 7075–T76 + U.S. NAVY, 2024–T3 ALCLAD + F-28 AND 7475–T761 CLAD + F-16 EQUIVALENT FOR FATIGUE IN AIR WITH OR WITHOUT PRE-EXPOSURE ● 7075–T76 + U.S. NAVY, 2024–T3 ALCLAD + F-28 EQUIVALENT FOR PRE-EXPOSURE + FATIGUE IN SALT SPRAY: 7475–T761 CLAD + F-16 SUPERIOR ● AMLGUARD NOT BENEFICIAL	● SIGNIFICANTLY DETRIMENTAL FOR 7075–T6 + NF-5 FATIGUED IN AIR	● SIGNIFICANTLY DETRIMENTAL FOR 7075–T76 + U.S. NAVY, 2024–T3 ALCLAD + F-28 AND 7075–T6 + NF-5 ● NOT SIGNIFICANT FOR 7475–T761 CLAD + F-16 WITH OR WITHOUT INTERFAY
MINITWIST	101 MPa	● ARALL MUCH SUPERIOR TO MONOLITHIC 2024–T3 ALCLAD ● AMLGUARD NOT BENEFICIAL	● NOT SIGNIFICANT	● SIGNIFICANTLY DETRIMENTAL MAINLY AT LOWER STRESS LEVEL AND IN COMBINATION WITH PRE-EXPOSURE
	89 MPa	● AMLGUARD NOT BENEFICIAL		
FALSTAFF	289 MPa	● 7475–T761 CLAD + F-16 + INTERFAY SUPERIOR OVERALL ● 7075–T6 + NF-5 AND 7475–T761 CLAD + F-16 EQUIVALENT ● INTERFAY SEALANT BENEFICIAL ● AMLGUARD NOT BENEFICIAL	● NOT SIGNIFICANT	● SIGNIFICANTLY DETRIMENTAL FOR 7075–T6 + NF-5 AND 7475–T761 CLAD + F-16 ● NOT SIGNIFICANT FOR 7475–T761 CLAD + F-16 + INTERFAY
	238 MPa	● 7475–T761 CLAD + F-16 AND 7475–T761 CLAD + F-16 + INTERFAY EQUIVALENT ● 7075–T6 + NF-5 INFERIOR OVERALL ● INTERFAY SEALANT NOT BENEFICIAL ● AMLGUARD NOT BENEFICIAL	● NOT SIGNIFICANT	● SIGNIFICANTLY DETRIMENTAL FOR 7075–T6 + NF-5 ● NOT SIGNIFICANT FOR 7475–T761 CLAD + F-16 WITH OR WITHOUT INTERFAY

Fig. 7.9 Overview of the effects of different materials and protection systems and environmental conditions on the fatigue lives of 1½ dogbone specimens from the CFCTP core programme and the NLR and LRTH contribution to FACT

TEST PARAMETER VARIATIONS		MAIN INFLUENCES ON PRIMARY FATIGUE ORIGINS *			GENERALLY SIGNIFICANT TRENDS
		FATIGUE LOAD HISTORY			
		CONSTANT AMPLITUDE, R = 0.1	MINITWIST	FALSTAFF	
HIGH STRESS LEVELS ↓ LOW STRESS LEVELS		● 7075–T76 + U.S. NAVY E/Q ↓ : F/R ↑ , G/S ↑	● 2024–T3 ALCLAD + F-28 E/Q ↓ : F/R ↑ , G/S ↑	● 7075–T6 + NF-5 NO SIGNIFICANT EFFECT ● 7475–T761 CLAD + F-16 WITH OR WITHOUT INTERFAY F/R ↓ : G/S ↑	● FAYING SURFACE (G/S) FAILURES INCREASED ● BORE/FAYING SURFACE CORNER (F/R) FAILURES DECREASED
FATIGUE IN AIR ↓ PRE-EXPOSURE AND/OR FATIGUE IN SALT SPRAY	HIGH STRESS LEVELS	● 7075–T76 + U.S. NAVY E/Q ↑ : G/S ↓	● 2024–T3 ALCLAD + F-28 NO SIGNIFICANT EFFECT	● 7075–T6 + NF-5 AND 7475–T761 CLAD + F-16 + INTERFAY F/R ↑ : G/S ↓ ● 7475–T761 CLAD + F-16 NO SIGNIFICANT EFFECT	● FAYING SURFACE (G/S) FAILURES DECREASED ● BORE/FAYING SURFACE CORNER (F/R) FAILURES INCREASED
	LOW STRESS LEVELS	● 7075–T76 + U.S. NAVY E/Q ↑ , F/R ↑ : G/S ↓ ● 2024–T3 ALCLAD + F-28 AND 7075–T6 + NF-5 F/R ↑ : G/S ↓ ● 7475–T761 CLAD + F-16 NO SIGNIFICANT EFFECT ● 7475–T761 CLAD + F-16 + INTERFAY G/S ↓ : B/N ↑	● 2024–T3 ALCLAD + F-28 E/Q ↑ , F/R ↑ : G/S ↓	● 7075–T6 + NF-5 F/R ↑ , B/N ↑ : G/S ↓ ● 7475–T761 CLAD + F-16 NO SIGNIFICANT EFFECT ● 7475–T761 CLAD + F-16 + INTERFAY *G/S ORIGINS SHIFTED* AWAY FROM FASTENER HOLES	

* KEY TO LOCATIONS OF FATIGUE ORIGINS

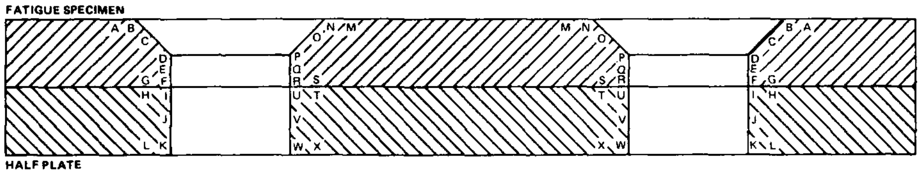


Fig. 7.10 Overview of the effects of stress level and environmental conditions on the locations of primary fatigue origins in 1½ dogbone specimens from the CFCTP core programme and the NLR and LRTH contribution to FACT

8. THE IABG CONTRIBUTION TO THE FACT PROGRAMME

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8.1 Introduction

The IABG contribution to FACT compared the fatigue and corrosion fatigue properties of 7475-T761 clad and 7075-T6 aluminium alloy sheet under the realistic manoeuvre load history FALSTAFF (references 1, 2). To try and place the results in a broader context it was arranged that the 7075-T6 material came from a common batch purchased by the NLR and supplied also to the NDRE and RAE, and the 7475-T761 clad material was shared with the NLR, see table 1.1 of the introduction to this part of the report.

8.2 The Test Programme

An overview of the test programme is given in table 8.1. All specimens were of the 1½ dogbone configuration discussed in detail in reference (3) and recommended for the FACT programme. Note that some tests on 7075-T76 specimens from the same batch as the CFCTP core programme specimens were included. In all cases cadmium plated steel Hi-Lok fasteners were used. The diameter of the holes for the fasteners was 6.306 ± 0.044 mm, which corresponds to a slight press fit, see figure 1.1 of the introduction to this part of the report.

8.2.1 Materials and properties

The materials were 3.2 mm thick sheets of aluminium alloys 7075-T76 (CFCTP core programme material), 7475-T761 clad and 7075-T6. Engineering property data were as follows:

MATERIALS	0.2 % YIELD STRESS (MPa)	UTS (MPa)	ELONGATION (%)
7075-T76	479 (max) 455 (min)	550 (max) 541 (min)	11.0
7475-T761 clad	422	498	12.6
7075-T6	547	582	11.2

8.2.2 Protection systems and specimen assembly

The 7075-T76 specimens had the same U.S. Navy paint scheme as in the CFCTP core programme, see reference (3) and Part II of this report. The 7475-T761 and 7075-T6 specimens were manufactured, painted and assembled by Messerschmitt-Bölkow-Blohm MBB in Augsburg, according to the following procedure:

- specimen parts machined, drilled and degreased
- chromate conversion coating "Alodine 1200" on all surfaces
- inhibited epoxy polyamide primer on all surfaces except fastener holes
- application of chromate-containing sealant "Celloseal" to faying surfaces and fastener holes
- Hi-Lok installation and wet assembly of fatigue specimen dogbones and half plates
- application of polyurethane topcoat.

The protection system applied by MBB was representative for the European Multi Role Combat Aircraft MRCA. During wet assembly the sealant was forced through the fastener holes, but post-test examination showed that the holes had remained coated with a layer of sealant.

8.2.3 Mechanical testing conditions (static prestressing and fatigue)

All stresses were defined in terms of the total cross-section (but excluding the cladding layers on 7475-T761) of the fatigue specimen dogbone at the location of the centreline between the fasteners, i.e. the fastener holes were included in the cross-sectional area.

Before environmental exposure and fatigue testing all specimens were prestressed at 209 ± 10 K by applying two load cycles up to 238 MPa. The procedure for this is discussed in reference (3). The purpose of this low temperature prestressing was to ensure that the paint and primer layers were brittle and would crack around the Hi-Lok fastener holes, thereby simulating service damage that enables corrosion and corrosion fatigue to occur.

The characteristic fatigue stress levels for the test programme have been indicated already in table 8.1. These stress levels were obtained from the pilot tests described in section 1.4 of this part of the report. The fatigue load history was the manoeuvre spectrum FALSTAFF (references 1, 2). A short description of this spectrum is given in section 1.3 of this part of the report.

Detailed procedures for fatigue testing are given in reference (3). All tests were done using a 64 kN load frame fitted to a SCHENCK electrohydraulic machine. The closed loop system was controlled by a SCHENCK GA-16/440 digital control computer. The generated load sequence was checked for each specimen type (7075-T76, 7475-T761 and 7075-T6) by classifying and comparing the actual and specified peak stresses for one complete block of 200 flights. Agreement between the actual and specified peak stresses was good.

8.2.4 Environmental conditions (pre-exposure, fatigue and corrosion fatigue)

Specimens scheduled for static exposure to an aggressive environment before fatigue testing were sealed at the faying surface side edges and Hi-Lok collars to prevent corrosion except in the fastener head areas. The sealant used was a silicone type and not Permagum as recommended in reference (3). The procedure for static pre-exposure is described in detail in reference (3). Most specimens were immersed for the recommended time of 72 hours in 5 % aqueous NaCl acidified by a predetermined amount of SO_2 gas and maintained at 315 ± 2 K. However, for comparison purposes some specimens were pre- exposed for multiples (3X, 4X and 5X) of 72 hours. The cleaning procedure after pre exposure followed the unamended procedure in section 7.4 of Part 1 of reference (3).

For fatigue testing all specimens were electrically insulated from the loading grips and bolts by polymeric liners and bushings. Specimens to be fatigued in salt spray were also sealed at the faying surface side edges and Hi-Lok collars. The fatigue environments were laboratory air and 5 % aqueous NaCl salt spray acidified with H_2SO_4 to pH 4, both at a nominal temperature of 295 K. The salt spray tests were done in a specially constructed cabinet, fully described in reference (3). The nominal cycle frequencies for fatigue testing with FALSTAFF were 15 Hz in air and 2 Hz in salt spray.

8.3 Results

The complete set of fatigue life and primary fatigue origin data for the IABG contribution to FACT is given in table 8.2. The way in which the test programme was set up and the results had consequences for the statistical methods used to analyse the data. This will be discussed in section 8.3.1.

The fatigue life results are presented and statistically analysed in section 8.3.2. This is followed by presentation and statistical analysis of the primary fatigue origin data in section 8.3.3.

8.3.1 Statistical methods for analysing the data

A survey of the statistical methods for analysing the IABG data is given in figure 8.1. Owing to the limited number and unequal sample sizes of the fatigue life data it had to be assumed that they at least approximated to random samples from log-normally distributed populations with equal variance. Unequal sample sizes also meant that modified versions of the least significant difference test and Duncan's new multiple range test had to be used for "fine tuning" the analysis of variance results. More details of the statistical methods are given in Appendix II.

8.3.2 Fatigue life data

The fatigue life data are shown in figure 8.2. In a general way these data indicate that stress level and environment had significant effects on fatigue lives (note that extended pre-exposures are considered equivalent). With regard to materials the only obvious differences were at S_{max} = 289 MPa, namely the shorter fatigue lives of 7075-T76 specimens compared to the 7475-T761 and 7075-T6 specimens.

The results of three-way analysis of variance of the data are summarised in table 8.3. According to the analysis the main variables of stress level, environment and material and their two-way interactions all had significant effects on the fatigue lives of the specimens. Since there were only two stress levels it is obvious that the significant difference is between them. Thus it was not necessary to "fine tune" this result using the least significant difference test. Also, owing to the dominating effect of stress level (compare the F_o and F distribution values in table 8.3) it was not worthwhile using the least significant difference test to compare environments and materials without introducing stress levels. In other words it was better to proceed directly to the two-way interactions, which will be discussed in the following order:

- effect of stress level per environment (fatigue testing schedule) and material
- effect of environment at each stress level
- effect of material at each stress level
- effect of environment per material
- effect of material per environment.

The importance of stress was confirmed in detail by using the least significant difference test to analyse the effect of stress level on fatigue life per environment and material. The results are given in table 8.4. In every case the effect of stress level was significant, as would be expected.

Least significant difference test results for the effects of environment and material at each stress level are summarised in tables 8.5 and 8.6. Significant environmental effects were found for both stress levels, but apart from this there was no general trend. Significant differences between materials occurred only at the higher stress level and were the result of shorter fatigue lives of 7075-T76 specimens compared to the 7475-T761 and 7075-T6 specimens.

For completeness the least significant difference test results concerning environment : material interactions are listed in table 8.7. There is a problem with interpreting these interactions. No distinction could be made between stress levels, since three-way interactions were not found significant by analysis of variance, see table 8.3. To include the effect of stress the data had to be analysed using Duncan's new multiple range test. The results are given in tables 8.8 and 8.9 and compared in table 8.10 with the least significant difference test results for environment : material interactions. There were several discrepancies, shown shaded, between the test indications. In all cases the discrepancies could be attributed to the importance of taking stress level into account. In other words, only the results from Duncan's test should be considered. These may be described as follows:

(1) Significant environmental effects were found for each material but there was no overall trend.

(2) For 7475-T761 and 7075-T76 the significant environmental effects were confined to fatigue with S_{max} = 289 MPa.

(3) Extended pre-exposure generally had no additional effect on fatigue life. An explanation of the one case for which extended pre-exposure was significant (7075-T6 fatigued with S_{max} = 238 MPa) is provided by the primary fatigue origin data in table 8.2. Extended pre-exposure sometimes resulted in enhanced corrosion attack at specimen corners remote from fastener holes. For 7075-T6 specimens fatigued at the lower stress level this corrosion was sufficiently severe to cause early initiation of fatigue cracking. At the higher stress level fatigue crack initiation was determined mainly by the stress concentrating effect of the fastener holes.

(4) Significant differences between materials occurred for fatigue with S_{max} = 289 MPa and for each environment in which all three materials were tested. As stated previously, these differences were due to shorter fatigue lives of 7075-T76 specimens compared to 7475-T761 and 7075-T6 specimens.

8.3.3 Primary fatigue origin data

The primary fatigue origin data were analysed using the χ^2 test of independence and the results are summarised in table 8.11. All three main variables of stress level, environment (fatigue testing schedule) and material had significant effects on the locations of primary fatigue origins, as follows:

(1) For S_{max} = 289 MPa most failures initiated in the bores (E/Q) and at the bore/faying surface corners (F/R) of the fastener holes in the specimens. For S_{max} = 238 MPa most failures initiated at the (G/S) faying surface locations.

(2) With or without pre-exposure the change from fatigue in air to fatigue in salt spray reduced the number of faying surface (G/S) failures. Pre-exposure and/or fatigue in salt spray promoted failures at the bore/faying surface corners (F/R) of the fastener holes and also promoted failures at specimen corners remote from the fastener holes.

(3) For 7075-T76 specimens there were relatively more failures in the bores (E/Q) and at the bore/faying surface corners (F/R) of the fastener holes. For 7475-T761 and 7075-T6 specimens a number of failures occurred remote from the fastener holes. This was not observed for the 7075-T76 specimens either in this investigation or in the CFCTP core programme (see table 2 in Part II of this report).

8.4 Discussion

This investigation has shown that 7475-T761 and 7075-T6 specimens assembled using the MRCA protection system have equivalent fatigue and corrosion fatigue properties when tested with a realistic load history (FALSTAFF). On the other hand, 7075-T76 CFCTP core programme-type specimens had significantly shorter lives at S_{max} = 289 MPa but not at S_{max} = 238 MPa.

The reason for this difference is not obvious. However, the primary fatigue origin data provide a clue. For the 7075-T76 specimens tested at S_{max} = 289 MPa there were relatively more failures in the bores and at the bore/faying surface corners of the fastener holes. In the CFCTP core programme it was found that these failure locations tended to result in shorter fatigue lives than other locations, see section 3.4 of Part II of this report.

The question now arises as to why there were relatively more failures in the bores and at the bore/faying surface corners of the fastener holes in the 7075-T76 specimens tested at S_{max} = 289 MPa. It is our opinion that the use of Celloseal sealant in assembling the 7475-T761 and 7075-T6 specimens was responsible. In other words, Celloseal prevented or postponed failure initiation at the characteristic shorter life locations and enabled the 7475-T761 and 7075-T6 specimens to reach significantly longer fatigue lives than the 7075-T76 specimens.

8.5 Conclusions

(1) 7475-T761 and 7075-T6 specimens assembled using the MRCA protection system had equivalent fatigue and corrosion fatigue properties under FALSTAFF loading. 7075-T76 CFCTP core programme-type specimens were significantly inferior at the higher stress level (S_{max} = 289 MPa) but equivalent at the lower stress level (S_{max} = 238 MPa).

(2) Wet assembly with Celloseal sealant can be beneficial to fatigue and corrosion fatigue life.

(3) Stress level had a predominant effect on fatigue life.

(4) Significant environmental effects occurred at both stress levels, but there was no overall trend.

(5) Extending the pre-exposure period to multiples of the specified 72 hours generally had no additional effect on fatigue life.

(6) All three main variables of stress level, environment, and material + protection system combinations had significant effects on the locations of primary fatigue origins. Celloseal prevented or postponed failure initiation at locations which are characteristically associated with shorter fatigue lives.

8.6 References

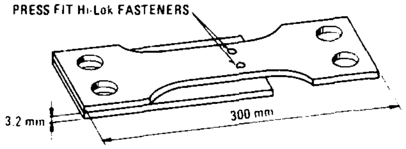
1. "Description of a Fighter Aircraft Loading STAndard For Fatigue evaluation", Combined Report of the F + W, LBF, NLR and IABG, March 1976.

2. J.B. de Jonge, "Additional information about FALSTAFF", NLR Technical Report TR 79056 U, June 1979.

3. R.J.H. Wanhill and J.J. De Luccia, "An AGARD-coordinated corrosion fatigue cooperative testing programme", AGARD Report No. 695, February 1982.

TABLE 8.1: OVERVIEW OF THE LABC TEST PROGRAMME FOR FACT

MATERIALS
- 3.2 mm thick 7075-T76 (CFCTP core programme material), 7475-T761 clad and 7075-T6 aluminium alloy sheets

SPECIMEN
- 

PROTECTION SYSTEMS
- 7075-T76 : chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat

  7475-T761 and 7075-T6: chromate conversion + inhibited epoxy polyamide primer (except fastener holes) + celloseal in fastener holes and at faying surfaces + polyurethane topcoat

PROTECTION SYSTEM DAMAGE
- two stress cycles at low temperature to crack paint and primer around the fastener heads

FATIGUE LOADING
- FALSTAFF

FATIGUE ENVIRONMENTS
- laboratory air; 5 % aqueous NaCl salt spray with pH 4

STATIC PRE-EXPOSURE
- multiples of 72 hours in 5 % aqueous NaCl + SO_2 at 315 K

TEST PROGRAMME
-

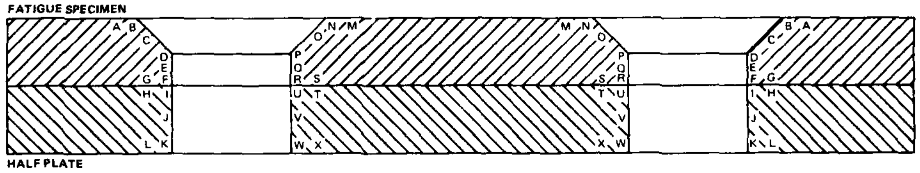
SCHEDULES	CHARACTERISTIC STRESS LEVEL	7475-T761	7075-T6	7075-T76
fatigue in air	S_{max} = 289 MPa	●	●	●
	S_{max} = 238 MPa	●	●	●
pre-exposure + fatigue in air	S_{max} = 289 MPa	●	●	
	S_{max} = 238 MPa	●	●	
fatigue in salt spray	S_{max} = 289 MPa	●	●	
pre-exposure + fatigue in salt spray	S_{max} = 289 MPa	●	●	●
	S_{max} = 238 MPa	●	●	●
extended pre-exposure + fatigue in salt spray	S_{max} = 289 MPa	●	●	●
	S_{max} = 238 MPa	●	●	

STATISTICAL ANALYSIS
- fatigue lives and primary fatigue origins

TABLE 8.2: FATIGUE LIFE AND PRIMARY FATIGUE ORIGIN DATA FOR THE IABG CONTRIBUTION TO FACT

MATERIALS AND CORROSION PROTECTION SYSTEMS	FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	FATIGUE LIFE TO FAILURE (FLIGHTS AND LOG MEAN VALUES)/LOCATIONS OF PRIMARY ORIGINS OF FATIGUE*				
			fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	extended pre-exposure + fatigue in salt spray
7475-T761 clad, with MRCA protection sysem	FALSTAFF	S_{max} = 289 MPa	9,608 S 9,630 F 12,764 ▪ 10,000 G ♦ 10,425	11,028 G,S ♦ 9,155 F ▪ 4,424 F,E ▪ 7,644	7,746 F 8,864 Q 11,634 • 5,178 R 8,020	3,134 R 5,155 E 4,895 F 4,292	5,468 G§ (3 X 72 hours pre-exposure)
		S_{max} = 238 MPa	14,626 G § 17,964 G,S ♦ 21,364 G,S ♦ 13,764 S ♦ 16,672	16,164 G,S ♦ 22,164 S § 18,928		12,934 B ■ 20,660 • 9,111 F 13,453	16,494 F (4 X 72 hours pre-exposure)
7075-T6 with MRCA protection system	FALSTAFF	S_{max} = 289 MPa	15,026 S 12,028 E 12,566 • 13,226 S ♦ 13,165	7,365 E 4,965 E 10,566 Q 7,283	7,365 E 3,418 E 7,564 - 5,753	3,155 Q 5,325 B ■ 2,964 F 3,679	3,590 E (4 X 72 hours pre-exposure)
		S_{max} = 238 MPa	29,964 G 21,345 E 20,564 Q 23,605	24,218 G 12,545 S ♦ 17,430		10,778 • 12,981 - 14,000 ▪ 11,553 •• 12,265	5,155 •• (4 X 72 hours pre-exposure) 5,626 •• (3 X 72 hours pre-exposure)
7075-T76 with U.S. Navy protection system (reference 3)	FALSTAFF	S_{max} = 289 MPa	4,155 R 4,626 E 4,384			1,226 E,Q 755 E 962	1,418 F (5 X 72 hours pre-exposure)
		S_{max} = 238 MPa	24,329 S			18,143 S	

* KEY TO LOCATIONS OF FATIGUE ORIGINS



- Fracture surfaces not available to the NLR.
- ♦ These failures were on the boundary of the area clamped by the fasteners
- § These failures were remote from the fastener holes
- • These failures occurred at specimen corners remote from the fastener holes.
- •• These failures occurred at specimen corners remote from the fastener holes but evidently from corrosion attack that lifted the protection system.
- ■ These failures *occurred from corrosion* pits that most probably developed during pre-exposure.
- ▪ These failures showed corroded fracture surfaces indicative of incomplete drying of the specimens after pre-exposure.

TABLE 8.3: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF VARIATION	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES (F_o > F DISTRIBUTION VALUE)
FALSTAFF	S_{max} = 289 MPa AND S_{max} = 238 MPa	● MAIN EFFECTS			
		· stress	4.13	156.84	yes
		· environment	2.65	23.62	yes
		· material	3.28	17.26	yes
		● 2-WAY INTERACTIONS			
		· stress · environment	2.88	[illegible]	yes
		· stress · material	3.28	14.14	yes
		· environment · material	2.38	2.56	yes
		● 3-WAY INTERACTIONS			
		· stress · environment · material	2.65	0.[illegible]	no

TABLE 8.4: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF STRESS LEVEL ON FATIGUE LIFE

FATIGUE TESTING SCHEDULE	fatigue in air		pre-exposure + fatigue in air		fatigue in salt spray		pre-exposure + fatigue in salt spray		extended pre exposure + fatigue in salt spray	
STRESS LEVEL	S_{max} = 289 MPa	S_{max} = 238 MPa	S_{max} = 289 MPa	S_{max} = 238 MPa	S_{max} = 289 MPa	S_{max} = 238 MPa	S_{max} = 289 MPa	S_{max} = 238 MPa	S_{max} = 289 MPa	S_{max} = 238 MPa
LOG MEAN FATIGUE LIFE	3.963	4.294	3.873	4.2[illegible]	3.86[illegible]	-	[illegible]	4.12[illegible]	3.682	3.893
SAMPLE SIZE n	10	8	6	4	[illegible]	-	8	8	3	3

$t_{0.025,34}$ = 2.03 $MS_{residual}$ = 0.016

FATIGUE TESTING SCHEDULE	COMPARISONS OF DATA FOR DIFFERENT STRESS LEVELS	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025,34}$)
fatigue in air	289 MPa, 238 MPa	[illegible]	yes
pre-exposure + fatigue in air	289 MPa, 238 MPa	4.[illegible]	yes
pre-exposure + fatigue in salt spray	289 MPa, 238 MPa*	10.[illegible]	yes
extended pre-exposure + fatigue in salt spray	289 MPa, 238 MPa*	3.96	yes

MATERIAL	2024-T361 clad (MRCA paint)		7075-T6 (MRCA paint)		7075-T76 (U.S. Navy paint)	
STRESS LEVEL	S_{max} = 289 MPa	S_{max} = 238 MPa	S_{max} = 289 MPa	S_{max} = 238 MPa	S_{max} = 289 MPa	S_{max} = 238 MPa
LOG MEAN FATIGUE LIFE	[illegible]	[illegible]	3.875	4.1[illegible]	4.287	4.322
SAMPLE SIZE n	15	19	14	13	5	2

$t_{0.025,34}$ = [illegible] $MS_{residual}$ = 0.017

MATERIAL	COMPARISONS OF DATA FOR DIFFERENT STRESS LEVELS	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025,34}$)
2024-T361 clad (MRCA paint)	289 MPa, 238 MPa	6.58	yes
7075-T6 (MRCA paint)	289 MPa, 238 MPa	[illegible]	yes
7075-T76 (U.S. Navy paint)	289 MPa, 238 MPa	[illegible]	yes

*Owing to equal sample size these comparisons can also be made using the unmodified least significant difference test. The same result is obtained

TABLE 8.5: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF ENVIRONMENT ON FATIGUE LIFE AT EACH STRESS LEVEL

STRESS LEVEL	S_{max} = 289 MPa					S_{max} = 238 MPa			
FATIGUE TESTING SCHEDULE	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	extended pre-exposure + fatigue in salt spray	fatigue in air	pre-exposure + fatigue in air	pre-exposure + fatigue in salt spray	extended pre-exposure + fatigue in salt spray
LOG MEAN FATIGUE LIFE	3 983	3 873	3.842	3 445	3 482	4 299	4.259	4 125	3.893
SAMPLE SIZE n	10	6	7	8	3	8	4	8	3

$t_{0.025;34}$ = 2.03 $MS_{residual}$ = 0.016

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	S_{max} = 289 MPa		S_{max} = 238 MPa	
	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)
fatigue in air/pre-exposure + fatigue in air	1.68	no	0.52	no
fatigue in air/fatigue in salt spray	2.26	yes	-	-
fatigue in air/pre-exposure + fatigue in salt spray*	8.97	yes	2.75	yes
fatigue in air/extended pre-exposure + fatigue in salt spray	6.02	yes	4.74	yes
pre-exposure + fatigue in air/fatigue in salt spray	0.44	no	-	-
pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	6.27	yes	1.73	no
pre-exposure + fatigue in air/extended pre-exposure + fatigue in salt spray	4.37	yes	3.79	yes
fatigue in salt spray/pre-exposure + fatigue in salt spray	6.06	yes	-	-
fatigue in salt spray/extended pre-exposure + fatigue in salt spray	4.12	yes	-	-
pre-exposure + fatigue in salt spray/extended pre-exposure + fatigue in salt spray	0.43	no	2.71	yes

*Owing to equal sample size for S_{max} = 238 MPa, this comparison can also be made using the unmodified least significant difference test. The same result is obtained

TABLE 8.6: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF MATERIAL ON FATIGUE LIFE AT EACH STRESS LEVEL

STRESS LEVEL	S_{max} = 289 MPa			S_{max} = 238 MPa		
MATERIAL	7475-T761 clad (MRCA paint)	7075-T6 (MRCA paint)	7075-T76 (U.S. Navy paint)	7475-T761 clad (MRCA paint)	7075-T6 (MRCA paint)	7075-T76 (U.S. Navy paint)
LOG MEAN FATIGUE LIFE	3 865	3 828	3.280	4 205	4 129	4.322
SAMPLE SIZE n	15	14	5	10	11	2

$t_{0.025;34}$ = 2.03 $MS_{residual}$ = 0.016

COMPARISONS OF MATERIALS	S_{max} = 289 MPa		S_{max} = 238 MPa	
	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)
7475-T761 clad/7075-T6	0.79	no	1.38	no
7475-T761 clad/7075-T76	8.96	yes	1.19	no
7075-T6/7075-T76	8.32	yes	1.99	no

TABLE 8.7: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR ENVIRONMENT : MATERIAL INTERACTIONS

MATERIAL	7475-T761 clad (MRCA paint)					7075-T6 (MRCA paint)					7075-T76 (U.S. Navy paint)		
FATIGUE TESTING SCHEDULE	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	extended pre-exposure + fatigue in salt spray	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	extended pre-exposure + fatigue in salt spray	fatigue in air	pre-exposure + fatigue in salt spray	extended pre-exposure + fatigue in salt spray
LOG MEAN FATIGUE LIFE	4.120	4.041	3.904	3.881	3.978	4.228	4.014	3.760	3.865	3.673	3.890	3.408	3.152
SAMPLE SIZE n	8	5	4	6	2	7	5	3	7	3	3	3	1

$t_{0.025;34} = 2.03$ $MS_{residual} = 0.016$

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	7475-T761 clad (MRCA paint)		7075-T6 (MRCA paint)		7075-T76 (U.S. Navy paint)	
	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)
fatigue in air/pre-exposure + fatigue in air	1.10	no	2.89	yes	–	–
fatigue in air/fatigue in salt spray	2.79	yes	5.36	yes	–	–
fatigue in air/pre-exposure + fatigue in salt spray*	3.50	yes	5.37	yes	4.67	yes
fatigue in air/extended pre-exposure + fatigue in salt spray	1.42	no	6.36	yes	5.05	yes
pre-exposure + fatigue in air/fatigue in salt spray	1.62	no	2.75	yes	–	–
pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	2.09	yes	2.01	no	–	–
pre-exposure + fatigue in air/extended pre-exposure + fatigue in salt spray	0.60	no	3.69	yes	–	–
fatigue in salt spray/pre-exposure + fatigue in salt spray	0.28	no	1.20	no	–	–
fatigue in salt spray/extended pre-exposure + fatigue in salt spray**	0.68	no	0.84	no	–	–
pre-exposure + fatigue in salt spray/extended pre-exposure + fatigue in salt spray	0.94	no	2.20	yes	1.75	no

COMPARISONS OF MATERIALS	fatigue in air		pre-exposure + fatigue in air		fatigue in salt spray		pre-exposure + fatigue in salt spray		extended pre-exposure + fatigue in salt spray	
	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;34}$)
7475-T761 clad/7075-T6	1.65	no	0.34[•]	no	1.49	no	0.23	no	2.64	yes
7475-T761 clad/7075-T76	2.69	yes	–	–	–	–	5.29	yes	5.33	yes
7075-T6/7075-T76	3.87	yes	–	–	–	–	5.24	yes	3.57	yes

[*] Owing to equal sample size this comparison can also be made for 7075-T6 and 7075-T76 using the unmodified least significant difference test. The same result is obtained.

[**] Owing to equal sample size this comparison can also be made for 7075-T6 using the unmodified least significant difference test. The same result is obtained.

[•] Owing to equal sample size this comparison can also be made using the unmodified least significant difference test. The same result is obtained.

TABLE 8.8: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF ENVIRONMENT PER STRESS LEVEL AND MATERIAL

MATERIAL	7475-T761 clad (MRCA paint)									
FATIGUE TESTING SCHEDULE	fatigue in air		pre-exposure + fatigue in air		fatigue in salt spray		pre-exposure + fatigue in salt spray		extended pre-exposure + fatigue in salt spray	
CHARACTERISTIC STRESS LEVEL S_{max} (MPa)	289	238	289	238	289	238	289	238	289	238
LOG MEAN FATIGUE LIFE	4.018	4.222	3.883	4.2[illegible]	3.904	-	3.633	4.129	3.738	4.217
SAMPLE SIZE n	4	4	3	2	4	-	3	3	1	1

MATERIAL	7075-T6 (MRCA paint)									
FATIGUE TESTING SCHEDULE	fatigue in air		pre-exposure + fatigue in air		fatigue in salt spray		pre-exposure + fatigue in salt spray		extended pre-exposure + fatigue in salt spray	
CHARACTERISTIC STRESS LEVEL S_{max} (MPa)	289	238	289	238	289	238	289	238	289	238
LOG MEAN FATIGUE LIFE	4.119	4.373	3.862	4.241	3.760	-	3.566	4.089	3.555	3.731
SAMPLE SIZE n	4	3	3	2	3	-	3	4	1	2

MATERIAL	7075-T76 (U.S. Navy paint)					
FATIGUE TESTING SCHEDULE	fatigue in air		pre-exposure + fatigue in salt spray		extended pre-exposure + fatigue in salt spray	
CHARACTERISTIC STRESS LEVEL S_{max} (MPa)	289	238	289	238	289	238
LOG MEAN FATIGUE LIFE	3.042	4.386	2.983	4.259	3.152	-
SAMPLE SIZE n	2	1	2	1	1	-

COMPARISONS OF DATA PER TEST PARAMETER		TEST PARAMETERS											
		7475-T761 clad (MRCA paint)				7075-T6 (MRCA paint)				7075-T76 (U.S. Navy paint)			
		P	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_in_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i-\bar{x}_j)\sqrt{\frac{2n_in_j}{n_i+n_j}} > SSR$	P	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_in_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i-\bar{x}_j)\sqrt{\frac{2n_in_j}{n_i+n_j}} > SSR$	P	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_in_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i-\bar{x}_j)\sqrt{\frac{2n_in_j}{n_i+n_j}} > SSR$
S_{max} = 289 MPa	fatigue in air/pre-exposure + fatigue in air	3	0.250	0.381	no	2	0.476	0.362	yes	-	-	-	-
	fatigue in air/fatigue in salt spray*	2	0.228	0.362	no	3	0.665	0.381	yes	-	-	-	-
	fatigue in air/pre-exposure + fatigue in salt spray**	5	0.713	0.401	yes	4	1.024	0.393	yes	3	0.932	0.381	yes
	fatigue in air/extended pre-exposure + fatigue in salt spray	4	0.354	0.393	no	5	0.713	0.401	yes	2	0.566	0.362	yes
	pre-exposure + fatigue in air/fatigue in salt spray***	2	0.039	0.362	no	2	0.177	0.362	no	-	-	-	-
	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray****	3	0.433	0.381	yes	3	0.513	0.381	yes	-	-	-	-
	pre-exposure + fatigue in air/extended pre-exposure + fatigue in salt spray	2	0.178	0.362	no	4	0.376	0.393	no	-	-	-	-
	fatigue in salt spray/pre-exposure + fatigue in salt spray***	4	0.502	0.393	yes	2	0.336	0.362	no	-	-	-	-
	fatigue in salt spray/extended pre-exposure + fatigue in salt spray	3	0.210	0.381	no	3	0.251	0.381	no	-	-	-	-
	pre-exposure + fatigue in salt spray/extended pre-exposure + fatigue in salt spray	2	0.12[illegible]	0.362	no	2	0.013	0.362	no	2	0.195	0.362	no
S_{max} = 238 MPa	fatigue in air/pre-exposure + fatigue in air	2	0.090	0.362	no	2	0.204	0.362	no	-	-	-	-
	fatigue in air/pre-exposure + fatigue in salt spray**	3	0.172	0.381	no	3	0.526	0.381	yes	2	0.12[illegible]	0.362	no
	fatigue in air/extended pre-exposure + fatigue in salt spray	2	0.006	0.362	no	4	0.995	0.393	yes	-	-	-	-
	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	4	0.229	0.393	no	2	0.248	0.362	no	-	-	-	-
	pre-exposure + fatigue in air/extended pre-exposure + fatigue in salt spray***	3	0.069	0.381	no	3	0.221	0.381	yes	-	-	-	-
	pre-exposure + fatigue in salt spray/extended pre-exposure + fatigue in salt spray	2	0.108	0.362	no	2	0.585	0.362	yes	-	-	-	-

*Owing to equal sample size this comparison can also be made for 7475-T761 clad using the unmodified version of Duncan's test The same result is obtained

**Owing to equal sample size these comparisons can also be made for 7075-T76 using the unmodified version of Duncan's test The same result is obtained

***Owing to equal sample size these comparisons can also be made for 7075-T6 using the unmodified version of Duncan's test The same result is obtained

****Owing to equal sample size this comparison can also be made for 7475-T761 clad and 7075-T6 using the unmodified version of Duncan's test The same result is obtained

TABLE 8.9: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF MATERIAL PER STRESS LEVEL AND ENVIRONMENT

CHARACTERISTIC STRESS LEVEL	S_{max} = 289 MPa													
FATIGUE TESTING SCHEDULE	fatigue in air			pre-exposure + fatigue in air		fatigue in salt spray		pre-exposure + fatigue in salt spray			extended pre-exposure + fatigue in salt spray		
MATERIAL	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)	7075-T76 (U.S. Navy paint)	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)	7075-T76 (U.S. Navy paint)	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)	7075-T76 (U.S. Navy paint)
LOG MEAN FATIGUE LIFE	4.018	4.119	3.642	3.883	3.862	3.904	3.760	3.633	3.566	2.983	3.738	3.555	3.152
SAMPLE SIZE n	4	4	2	3	3	4	3	3	3	2	1	1	1

TEST PARAMETER	p	COMPARISONS OF DATA PER TEST PARAMETER	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_i n_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i - \bar{x}_j)\sqrt{\frac{2n_i n_j}{n_i+n_j}} > SSR$
fatigue in air	2	7475-T761 clad/7075-T6*	0.202	0.362	no
	2	7475-T761 clad/7075-T76	0.614	0.362	yes
	3	7075-T6/7075-T76	0.729	0.381	yes
pre-exposure + fatigue in air	2	7475-T761 clad/7075-T6*	0.036	0.362	no
fatigue in salt spray	2	7475-T761 clad/7075-T6	0.267	0.362	no
pre-exposure + fatigue in salt spray	2	7475-T761 clad/7075-T6*	0.116	0.362	no
	3	7475-T761 clad/7075-T76	1.007	0.381	yes
	2	7075-T6/7075-T76	0.903	0.362	yes
extended pre-exposure + fatigue in salt spray	2	7475-T761 clad/7075-T6*	0.183	0.362	no
	3	7475-T761 clad/7075-T76*	0.586	0.381	yes
	2	7075-T6/7075-T76*	0.403	0.362	yes

CHARACTERISTIC STRESS LEVEL	S_{max} = 218 MPa										
FATIGUE TESTING SCHEDULE	fatigue in air			pre-exposure + fatigue in air		pre-exposure + fatigue in salt spray			extended pre-exposure + fatigue in salt spray	
MATERIAL	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)	7075-T76 (U.S. Navy paint)	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)	7075-T76 (U.S. Navy paint)	7475-T761 (MRCA paint)	7075-T6 (MRCA paint)
LOG MEAN FATIGUE LIFE	4.222	4.373	4.386	4.277	4.241	4.129	4.089	4.259	4.217	3.731
SAMPLE SIZE n	4	3	1	2	2	3	4	2	2	2

TEST PARAMETER	p	COMPARISONS OF DATA PER TEST PARAMETER	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_i n_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i - \bar{x}_j)\sqrt{\frac{2n_i n_j}{n_i+n_j}} > SSR$
fatigue in air	2	7475-T761 clad/7075-T6	0.280	0.362	no
	3	7475-T761 clad/7075-T76	0.207	0.381	no
	2	7075-T6/7075-T76	0.016	0.362	no
pre-exposure + fatigue in air	2	7475-T761 clad/7075-T6*	0.051	0.362	no
pre-exposure + fatigue in salt spray	2	7475-T761 clad/7075-T6	0.074	0.362	no
	2	7475-T761 clad/7075-T76	0.159	0.362	no
	3	7075-T6/7075-T76	0.215	0.381	no
extended pre-exposure + fatigue in salt spray	2	7475-T761 clad/7075-T6	0.561	0.362	yes

*Owing to equal sample size these comparisons can also be made using the unmodified version of Duncan's test. The same result is obtained

TABLE 8.10: COMPARISONS OF LEAST SIGNIFICANT DIFFERENCE TEST AND DUNCAN'S TEST RESULTS FOR THE EFFECTS OF ENVIRONMENT AND MATERIAL

COMPARISONS OF DIFFERENT FATIGUE TESTING SCHEDULES	SIGNIFICANT DIFFERENCES IN FATIGUE LIVES FROM DIFFERENT FATIGUE TESTING SCHEDULES								
	7475-T761 clad (MRCA paint)			7075-T6 (MRCA paint)			7075-T76 (U.S. Navy paint)		
	LSD test	Duncan's test		LSD test	Duncan's test		LSD test	Duncan's test	
		S_{max}			S_{max}			S_{max}	
		289 MPa	238 MPa		289 MPa	238 MPa		289 MPa	238 MPa
fatigue in air/pre-exposure + fatigue in air	no	no	no	yes	yes	no	-	-	-
fatigue in air/fatigue in salt spray	yes	no	-	yes	yes	-	-	-	-
fatigue in air/pre-exposure + fatigue in salt spray	yes	yes	no	yes	yes	yes	yes	yes	no
fatigue in air/extended pre-exposure + fatigue in salt spray	no	no	no	yes	yes	yes	yes	yes	-
pre-exposure + fatigue in air/fatigue in salt spray	no	no	-	yes	no	-	-	-	-
pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	yes	yes	no	no	yes	no	-	-	-
pre-exposure + fatigue in air/extended pre-exposure + fatigue in salt spray	no	no	no	yes	no	yes	-	-	-
fatigue in salt spray/pre-exposure + fatigue in salt spray	no	yes	-	no	no	-	-	-	-
fatigue in salt spray/extended pre-exposure + fatigue in salt spray	no	no	-	no	no	-	-	-	-
pre-exposure + fatigue in salt spray/extended pre-exposure + fatigue in salt spray	no	no	no	yes	no	yes	no	no	-

COMPARISONS OF MATERIALS	SIGNIFICANT DIFFERENCES IN FATIGUE LIVES FOR DIFFERENT MATERIALS														
	fatigue in air			pre-exposure + fatigue in air			fatigue in salt spray			pre-exposure + fatigue in salt spray			extended pre-exposure + fatigue in salt spray		
	LSD test	Duncan's test		LSD test	Duncan's test		LSD test	Duncan's test		LSD test	Duncan's test		LSD test	Duncan's test	
		S_{max}			S_{max}			S_{max}			S_{max}			S_{max}	
		289 MPa	238 MPa		289 MPa	238 MPa		289 MPa	238 MPa		289 MPa	283 MPa		289 MPa	238 MPa
7475-T761 clad/7075-T6	no	no	no	no	no	no	no	no	-	no	no	no	yes	no	yes
7475-T761 clad/7075-T76	yes	yes	no	-	-	-	-	-	-	yes	yes	no	yes	yes	-
7075-T6/7075-T76	yes	yes	no	-	-	-	-	-	-	yes	yes	no	yes	yes	-

TABLE 8.11: SUMMARY OF χ^2 TEST OF INDEPENDENCE FOR THE PRIMARY FATIGUE ORIGINS (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF ASSOCIATION	$\chi^2_{0.05;(r-1)(c-1)}$	χ^2_o	SIGNIFICANT ASSOCIATION $(\chi^2_o > \chi^2_{0.05;(r-1)(c-1)})$
FALSTAFF	S_{max} = 289 MPa AND S_{max} = 238 MPa	STRESS LEVEL	$\chi^2_{0.05;3} = 7.81$	16.10	yes
		ENVIRONMENT (FATIGUE TESTING SCHEDULE)	$\chi^2_{0.05;3} = 7.81$	18.06	yes
		MATERIAL (7475-T761 clad VERSUS 7075-T6)	$\chi^2_{0.05;3} = 7.81$	14.25	yes

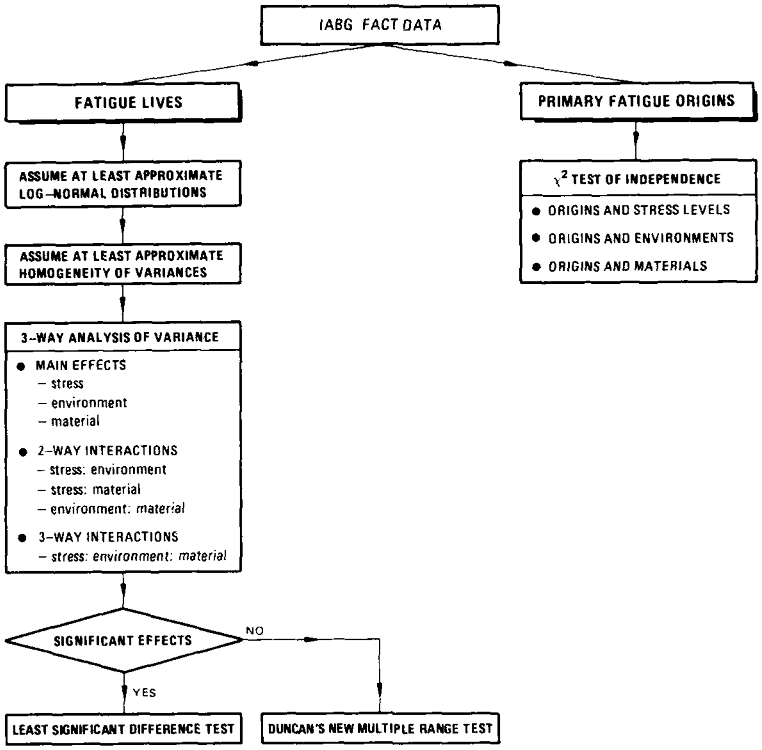


Fig. 8.1 Survey of statistical methods for analysing the IABG data for FACT

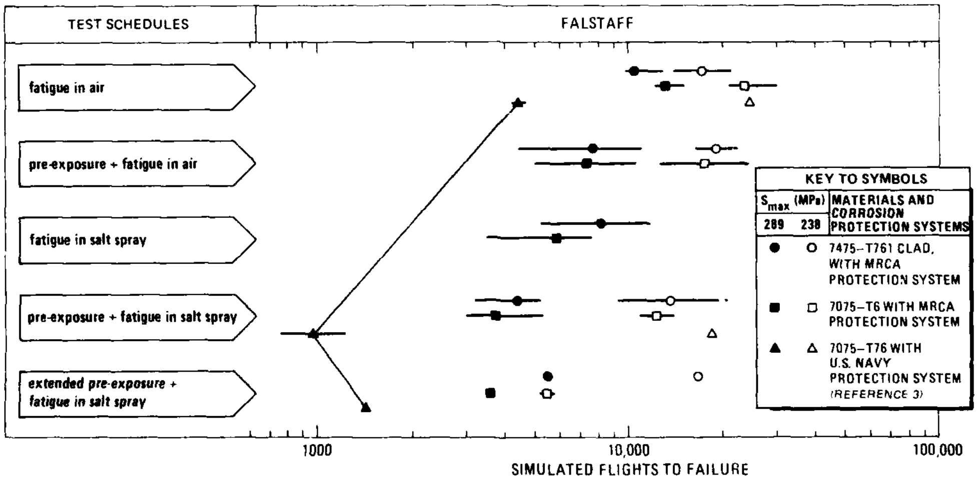


Fig. 8.2 IABG fatigue life data contribution to the FACT programme

9. THE RAE CONTRIBUTION TO THE FACT PROGRAMME

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9.1 Introduction

The high strength AlZnMgCuZr alloy 7010 has been developed for aerospace structural applications with the aim of combining high strength with resistance to corrosion and stress corrosion. The RAE contribution to the FACT programme concentrated on the fatigue and corrosion fatigue properties (fatigue strength and crack growth resistance) of 7010 in the T7651 and T7451 tempers.

In addition, the effectiveness of chromate-containing and non-chromate-containing primers in mitigating corrosion fatigue was compared using 1½ dogbone specimens of 7075-T6 aluminium alloy sheet. This material came from the same batch tested by the NDRE, NLR and IABG, see table 1.1 of the introduction to this part of the report.

9.2 The Test Programmes

An overview of the test programmes is given in table 9.1. There were three test programmes to compare

- fatigue and corrosion fatigue strengths of 7010-T7651 and 7010-T7451
- fatigue and corrosion fatigue crack growth resistances of 7010-T7651, 7010-T7451, 7475-T7351 and 7050-T7451
- corrosion fatigue resistance of 7075-T6 with protection systems including chromate-containing and non-chromate-containing primers.

9.2.1 Materials and properties

Engineering property data for all the materials were as follows:

MATERIALS		0.2 % YIELD STRESS (MPa)	UTS (MPa)	FLONGATION (%)
25 mm thick 7010 plate	T7651	472 (L) 488 (T)	536 (L) 548 (T)	13.3 (L) 11.8 (T)
	T7451	413 (L) 425 (T)	491 (L) 505 (T)	14.0 (L) 13.0 (T)
25 mm thick 7475-T7351 plate		451 (L) 449 (T)	519 (L) 519 (T)	11.0 (L) 12.0 (T)
40 mm thick 7050-T7451 plate		488 (L) 486 (T)	548 (L) 545 (T)	10.5 (L) 12.0 (T)
3.2 mm thick 7075-T6 sheet		547	582	11.2

Note that the two heat treatment conditions of 7010 were from the same plate.

9.2.2 Specimen configurations

The specimen configuration for the fatigue strength test programme is shown in figure 9.1. This specimen has a stress concentration factor $K_t = 2.52$. The burrs around the drilled holes were removed by gentle abrasion. Note that the specimen long axis is normal to the plate rolling direction.

The specimen configuration for the fatigue crack growth resistance test programme is shown in figure 9.2. The specimens were machined from the centre sections of the plates and with the long axis normal to the plate rolling direction.

The specimens for comparing chromate-containing and non-chromate-containing primers were of the 1½ dogbone configuration discussed in detail in reference (1) and recommended for the FACT programme. Cadmium plated steel Hi-Lok fasteners were used. The diameter of the holes for the fasteners was 6.248 ± 0.0127 mm, which corresponds to an interference fit, see figure 1.1 of the introduction to this part of the report.

9.2.3 1½ dogbone protection systems and specimen assembly

The 7075-T6 1½ dogbone specimens were originally manufactured, painted and assembled according to the following procedure:

- specimen parts machined
- chromic acid anodising and hot water sealing of all surfaces
- application of chromate-containing or non-chromate-containing epoxy primer on all surfaces
- fastener holes drilled
- application of polysulphide sealant to faying surfaces

- Hi-Lok installation and wet assembly of fatigue specimen dogbones and half plates
- application of acrylic topcoat.

During the test programme it became evident that the protection system with non-chromate-containing primer was insufficiently resistant to static pre-exposure. Drastic decohesion of the topcoat + primer indicated faulty application of the primer. Therefore some specimens were reprocessed according to Royal Air Force (RAF) practice as follows:

- solvent or chemical stripping, without disassembly, down to the anodised layers on exterior surfaces
- re-application of chromate-containing or non-chromate-containing epoxy primer on exterior surfaces
- application of polyurethane topcoat.

Finally, it should be noted that although in the original processing the polysulphide sealant was applied intentionally only to faying surfaces, post-test examination showed traces of sealant in the fastener holes of both dogbones and half plates.

9.2.4 Mechanical testing conditions (static prestressing and fatigue)

All stresses were defined in terms of loads on the total cross-sections of the specimens in the gauge length. This means that the central holes and notches in the fatigue strength and crack growth resistance specimens and the fastener holes in the dogbone specimens were included in the cross-sectional area.

Before environmental exposure and fatigue testing all 1½ dogbone specimens were prestressed at 209 ± 5 K by applying two load cycles up to 215 MPa. The procedure for this is discussed in reference (1). The purpose of this low temperature prestressing was to ensure that the paint and primer layers were brittle and would crack around the Hi-Lok fastener holes, thereby simulating service damage that enables corrosion and corrosion fatigue to occur.

All fatigue tests were done using an INSTRON 1342 electrohydraulic machine. The fatigue load histories were constant amplitude sinusoidal loading with a stress ratio $R = S_{min}/S_{max}$ of 0.1 and the manoeuvre spectrum FALSTAFF (references 2, 3). A short description of this spectrum is given in section 1.2 of this part of the report.

Details of the fatigue testing conditions are as follows:

(1) Fatigue strength tests were carried out over a range of stress levels at a nominal cycle frequency of 15 Hz for both constant amplitude and FALSTAFF loading.

(2) Fatigue crack growth resistance tests were done at similar load levels for constant amplitude loading and at a constant gross section S_{max} of 75 MPa for FALSTAFF loading. As shown in table 9.1, the cycle frequencies were 10 Hz and 1 Hz for constant amplitude loading and 10 Hz for FALSTAFF loading. Crack growth was monitored using a 2-wire pulsed direct current potential drop method. The current and voltage leads were taken out of the salt spray chamber via a sealed porthole as shown in figure 9.3. A microcomputer was used for data storage and analysis.

(3) The 1½ dogbone specimen fatigue tests were done with constant amplitude loading at an S_{max} of 210 MPa and cycle frequencies of 2 Hz in air and 0.5 Hz in salt spray. These testing conditions were based on those of the CFCTP core programme.

9.2.5 Environmental conditions (pre-exposure, fatigue and corrosion fatigue)

1½ dogbone specimens scheduled for static exposure to an aggressive environment before fatigue testing were sealed at the faying surface side edges and Hi-Lok collars to try and prevent corrosion except in the fastener head areas. The procedure for static pre-exposure is described in detail in reference (1). The specimens were immersed for 72 hours in 5 % aqueous NaCl acidified by a predetermined amount of SO_2 gas and maintained at 315 ± 2 K. The cleaning procedure after pre-exposure followed the amendment in section 4.4 of Part 2 of reference (1).

For fatigue testing the fatigue strength specimens were sealed off from the environment at the clamping area, while the crack growth resistance and 1½ dogbone specimens were electrically insulated from the loading grips and bolts by polymeric liners and bushings. 1½ dogbone specimens to be fatigued in salt spray were also sealed at the faying surface side edges and Hi-Lok collars. The fatigue environments were laboratory air (relative humidity ~ 50 %) and salt spray, both at a nominal temperature of 295 K. Depending on the test programme, the salt spray environment had different compositions and acidity, as shown in table 9.1 and listed here also:

FATIGUE TEST PROGRAMME	SALT SPRAY PARAMETERS	
	weight % NaCl	pH
(1) fatigue strength	3.5	7
(2) fatigue crack growth resistance	5	4,7
(3) effect of chromate in primers	5	4

The salt spray tests were done in a specially constructed cabinet illustrated in figure 9.3. A description of the cabinet, except for the sealed porthole for the crack growth monitoring leads, is given in reference (1).

The nominal cycle frequencies for each combination of fatigue load history and environment and for each test programme are given in table 9.1 and listed here also:

FATIGUE TEST PROGRAMME	FATIGUE LOAD HISTORY	NOMINAL CYCLE FREQUENCY		
		fatigue in air	fatigue in salt spray	
			pH 4	pH 7
(1) fatigue strength	constant amplitude, R = 0.1 FALSTAFF	15 Hz 15 Hz		15 Hz 15 Hz
(2) fatigue crack growth resistance	constant amplitude, R = 0.1 FALSTAFF	10 Hz 10 Hz	10 Hz, 1 Hz	1 Hz 10 Hz
(3) effect of chromate in primers	constant amplitude, R = 0.1	2 Hz	0.5 Hz	

9.2.6 Statistical methods for analysing the data

The way in which the test programmes were set up and the results had consequences for the statistical methods used to analyse the data. A survey of the statistical methods is given in figure 9.4. Only the notched fatigue strength data for FALSTAFF loading and the 1½ dogbone fatigue life and primary fatigue origin data were readily amenable to statistical analysis. Nevertheless, owing to the limited number and unequal sample sizes of the fatigue strength and life data it had to be assumed that they at least approximated to random samples from log-normally distributed populations with equal variance. Unequal sample sizes also meant that modified versions of the least significant difference test and Duncan's new multiple range test had to be used for "fine tuning" the analysis of variance results. More details of the statistical methods are given in Appendix II.

9.3 Results of the Fatigue Strength Test Programme

The complete set of fatigue life data for the RAE fatigue strength contribution to FACT is given in table 9.2.

9.3.1 Constant amplitude fatigue tests

The constant amplitude data are plotted in figure 9.5 and show the following:

- Fatigue in air: the high cycle notched fatigue strength of 7010-T7451 was slightly greater than that of 7010-T7651. However, at higher stress levels 7010-T7651 was superior.

- Fatigue in neutral (pH 7) salt spray: the high cycle notched fatigue strengths were reduced to a similar level less than half the fatigue strengths in air.

9.3.2 Manoeuvre spectrum (FALSTAFF) fatigue tests

The data for FALSTAFF loading are shown in figure 9.6. These data indicate that stress level had a significant effect on fatigue life and that 7010-T7651 was superior to 7010-T7451 at higher stress levels, as was the case for constant amplitude loading. However, neutral salt spray apparently had no significant effect on the fatigue lives. This is a remarkable result, especially for tests at lower stress levels, in view of the relatively long testing times. For example, 50,000 FALSTAFF flights require about 80 hours of testing at a nominal cycle frequency of 15 Hz.

The results of three-way analysis of variance of the data are summarised in table 9.3. According to the analysis the main variables of stress level, material and their two-way interactions had significant effects on the fatigue lives of the specimens. Since there were only two materials it is obvious that the significant difference is between them. Thus it was not necessary to "fine tune" this result using the least significant difference test.

The least significant difference test was used to "fine tune" the effect of stress level and the stress : material interactions. The results are given in table 9.4. Changing the stress level significantly altered the fatigue lives, as would be expected. At the two higher stress levels 7010-T7651 specimens had significantly longer fatigue lives than 7010-T7451 specimens.

The potential sources of variation not found to be significant by analysis of variance were:

- effect of environment

- effect of environment at each stress level

- effect of material in each environment

- effect of material per stress level and environment.

Because there were only two environments the lack of a significant difference between them did not require further analysis. The remaining potential sources of variation were investigated using Duncan's new multiple range test. The results are listed in table 9.5 and show:

(1) At each stress level the overall fatigue lives were unaffected by changing from fatigue in air to fatigue in salt spray. However, in one case there was a significant difference, namely for 7010-T7651 tested with S_{max} = 250 MPa.

(2) The previously mentioned result that 7010-T7651 specimens had significantly longer fatigue lives than 7010-T7451 specimens at the two higher stress levels must be qualified. Significant differences were found only for fatigue in air at S_{max} = 300 MPa and fatigue in salt spray at S_{max} = 250 MPa.

9.4 Results of the Fatigue Crack Growth Resistance Test Programme

9.4.1 Constant amplitude fatigue crack growth tests

The constant amplitude fatigue crack growth data are shown in figures 9.7 and 9.8. Figure 9.7 compares the fatigue crack growth resistances of 7010-T7651, 7010-T7451, 7475-T7351 and 7050-T7451 plate materials in air and acidified (pH 4) salt spray at a cycle frequency of 10 Hz. It is seen that

- in air the crack growth resistances of 7010-T7651, 7010-T7451 and 7475-T7351 were equivalent but 7050-T7451 had significantly higher crack growth rates
- acidified salt spray resulted in increased crack growth rates for 7010-T7651, 7010-T7451 and 7475-T7351 but not for 7050-T7451. The greatest sensitivity to changing the environment was shown by 7010-T7451.

Figure 9.8 shows the effects of changing the salt spray acidity and cycle frequency on the crack growth resistances of 7010-T7651 and 7010-T7451. For 7010-T7451 these effects were negligible, but 7010-T7651 crack growth rates depended strongly on salt spray pH and cycle frequency. These results can be explained partly by the generally higher sensitivity of 7010-T7451 to changing from fatigue in air to fatigue in salt spray, i.e. there is a strong environmental effect even at a cycle frequency of 10 Hz. However, it was unexpected that crack growth rates in neutral salt spray would be higher than in acidified salt spray.

9.4.2 Manoeuvre spectrum (FALSTAFF) fatigue crack growth tests

The FALSTAFF fatigue crack growth data are given in figure 9.9. 7010-T7651 and 7010-T7451 were tested in air and neutral salt spray at a nominal cycle frequency of 10 Hz. The results show

- no significant influence of the environment on crack growth
- similar crack growth rates and lives for 7010-T7651 and 7010-T7451
- the occurrence of tensile crack jumping (static crack extension during peak loads) at half crack lengths beyond about 20 mm. This corresponds to $K_{max} \geq 22$ MPa$\sqrt{m}$, which is significantly less than the fracture toughnesses of the two tempers (K_{Ic} in the appropriate T-L orientation was 31.9 and 37.7 MPa$\sqrt{m}$ for 7010-T7651 and 7010-T7451 respectively). Similar results have been reported and explained in reference (4).

The lack of an effect of environment on crack growth cannot be explained solely as a cycle frequency effect, since constant amplitude tests on 7010-T7451 at 10 Hz showed large differences in crack growth rates for fatigue in air and salt spray, see figure 9.8. Also, it is somewhat surprising that the manoeuvre spectrum crack growth rates and lives of 7010-T7651 and 7010-T7451 were similar. Generally it is found that within a class of materials the alloys and tempers with lower yield strengths (in this case 7010-T7451) exhibit more crack growth retardation following peak tensile loads and hence lower overall crack growth rates and longer lives.

9.5 Results of the Programme on the Effect of Chromate in Primers

The complete set of fatigue life and primary fatigue origin data for the RAE contribution to FACT on the effect of chromate in primers is given in table 9.6.

9.5.1 Fatigue life data

The fatigue life data are plotted in figure 9.10 and indicate that environment (fatigue testing schedule) had a significant effect on life. Pre-exposure + fatigue in salt spray was especially detrimental to specimens with non-chromate-containing primer + acrylic topcoat. As mentioned in section 9.2.3. the problem with these specimens was attributed to faulty application of the primer leading to drastic decohesion of the topcoat + primer during pre-exposure.

The results of two-way analysis of variance of the data are summarised in table 9.7. According to the analysis the main variables of environment and protection system had significant effects on the fatigue lives of the specimens. These effects were "fine tuned" by the least significant difference test. The results are given in table 9.8 and show that:

(1) Fatigue lives in air and salt spray were equivalent. This unusual result agrees with the FALSTAFF tests on unprotected notched specimens of 7010-T7651 and 7010-T7451 (see section 9.3.2).

(2) Pre-exposure + fatigue in salt spray significantly reduced the fatigue lives.

(3) The combination of chromate primer + acrylic topcoat appeared to be better than the other protection systems. There is a complication with this result: specimens with chromate primer + polyurethane topcoat were tested only by pre-exposure and fatigue in salt spray, so that a general comparison with specimens having other protection systems is not justified.

A more detailed analysis of environment : protection system interactions had to be done using Duncan's new multiple range test. The results are summarised in table 9.9 and can be described as follows:

(4) Pre-exposure + fatigue in salt spray significantly reduced the fatigue lives of specimens with acrylic topcoats whether or not the primers contained chromates.

(5) The only significant differences in fatigue lives per testing schedule occurred for pre-exposure + fatigue in salt spray and were due to the shorter lives of specimens with non-chromate-containing primer + acrylic topcoat.

9.5.2 Primary fatigue origin data

The primary fatigue origin data were analysed using Yates' corrected χ^2 test. The results are listed in table 9.10. Only the protection system was found to have a significant effect on the locations of primary fatigue origins. Specimens with non-chromate-containing primers had relatively more failures in the bores (E/Q) of the fastener holes and fewer failures at faying surface (G/S) locations as compared to specimens with chromate-containing primers.

9.6 Discussion

As shown in table 9.1, the present contribution to FACT consisted of three test programmes. The scope is broad and therefore the topics for discussion will be addressed separately in sections 9.6.1 - 9.6.3. These topics are:

- the effects of changing from fatigue in air to fatigue in salt spray
- comparisons of materials with respect to fatigue and corrosion fatigue strengths, lives and crack growth resistances
- the effect of chromate in primers.

9.6.1 Fatigue in air/fatigue in salt spray

In general it is to be expected that changing the fatigue environment from air to salt spray or salt water will result in lower fatigue strengths, shorter lives and higher crack growth rates, see for example references (5, 6). In the present test programmes several exceptions to this general trend were found. Table 9.11 reviews the comparisons of data for fatigue in air and salt spray. The results may be described as follows:

(1) High cycle notched fatigue strengths were significantly reduced by a salt spray environment.

(2) Fatigue lives of some specimens were unaffected by changing the environment from air to salt spray. In particular, it is remarkable that under manoeuvre spectrum (FALSTAFF) loading the fatigue lives of unprotected notched specimens were unaffected up to 60,000 simulated flights, corresponding to about 93 hours in the salt spray environment.

(3) For most of the materials tested, including 7010-T7651 and 7010-T7451, the constant amplitude fatigue crack growth rates were significantly increased by changing the environment from air to salt spray. But at the same nominal cycle frequency the fatigue crack growth rates of 7010-T7651 and 7010-T7451 under FALSTAFF loading were virtually the same in air and salt spray.

These results demonstrate the importance of conducting environmental fatigue tests with realistic load histories.

9.6.2 Comparisons of materials

The fatigue strength and life tests on 7010-T7651 and 7010-T7451 in air and salt spray showed that at higher stress levels 7010-T7651 was generally superior and at lower stress levels the alloys were equivalent. 7010-T7651 was also equivalent or superior to 7010-T7451 in fatigue and corrosion fatigue crack growth resistance at a cycle frequency of 10 Hz. However, from figure 9.8 it is seen that the corrosion fatigue crack growth resistance of 7010-T7651 was strongly affected by salt spray pH and cycle frequency. Reducing the cycle frequency to 1 Hz caused 7010-T7651 to have higher crack growth rates than 7010-T7451 over a wide range of ΔK.

Thus it is concluded that besides using realistic load histories (see section 9.6.1) it is important to conduct environmental fatigue tests with realistic stress levels and cycle frequencies.

Constant amplitude fatigue and corrosion fatigue crack growth tests were carried out for 7475-T7351 and 7050-T7451 as well as 7010-T7651 and 7010-T7451 at a cycle frequency of 10 Hz. In air the crack growth resistances of 7010-T7651, 7010-T7451 and 7475-T7351 were equivalent but 7050-T7451 had significantly higher crack growth rates. In salt spray 7010-T7651 was superior and 7010-T7451 was the least resistant. These latter results cannot be generalised because of the previously mentioned effects of salt spray pH and cycle frequency.

9.6.3 Effect of chromate in primers

The results of this test programme indicate that the absence of chromate in properly applied primer had no significant detrimental effect on the resistance to pre-exposure and/or fatigue in salt spray of painted 1½ dogbone specimens containing interference fit Hi-Loks. However there are some caveats. Owing to the high constant amplitude fatigue stress level (S_{max} = 210 MPa) most specimens failed in the bores or at bore/faying surface corners of the fastener holes where unprimed metal was present. Also the fatigue tests in salt spray lasted less than 14 hours.

It is possible that an effect of chromate in primers will be found for corrosion fatigue conditions under which failures initiate in areas where primer is more or less continuously present and there is plenty of time for chromate to leach out into the corrodent. With respect to the 1½ dogbone specimen the results of the CFCTP core programme (reference 1) indicate that these conditions can be obtained by lowering the constant amplitude fatigue stress level. Flight simulation loading should also be used, since besides being more realistic it also gives much longer testing times, see for example table 9.11.

9.7 Conclusions

The present investigation consisted of three test programmes to compare

- fatigue and corrosion fatigue strengths of 7010-T7651 and 7010-T7451
- fatigue and corrosion fatigue crack growth resistances of 7010-T7651, 7010-T7451, 7475-T7351 and 7050-T7451
- corrosion fatigue resistance of 7075-T6 with protection systems including chromate-containing and non-chromate-containing primers.

Conclusions drawn from the results of each programme are given in sections 9.7.1 – 9.7.3. Some additional and more general conclusions are given in section 9.7.4.

9.7.1 Conclusions for the fatigue strength programme

(1) In air the high cycle notched fatigue strength of 7010-T7451 was slightly greater than that of 7010-T7651.

(2) In salt spray the high cycle notched fatigue strengths of 7010-T7651 and 7010-T7451 were reduced to a similar level less than half the fatigue strengths in air.

(3) Under manoeuvre spectrum (FALSTAFF) loading in both air and salt spray the notched fatigue lives of 7010-T7651 specimens were equivalent to or longer than those of 7010-T7451 specimens.

(4) The notched fatigue lives of 7010-T7651 and 7010-T7451 under FALSTAFF loading were unaffected by changing the environment from air to salt spray.

9.7.2 Conclusions for the fatigue crack growth resistance programme

(5) In air the constant amplitude fatigue crack growth resistances of 7010-T7651, 7010-T7451 and 7475-T7351 were equivalent at a cycle frequency of 10 Hz. 7050-T7451 had significantly higher crack growth rates.

(6) Acidified salt spray increased the constant amplitude fatigue crack growth rates for 7010-T7651, 7010-T7451 and 7475-T7351, but not for 7050-T7451, at a cycle frequency of 10 Hz. The greatest sensitivity to environmental change was shown by 7010-T7451.

(7) Changing the salt spray acidity from pH 4 to pH 7 and the cycle frequency from 10 Hz to 1 Hz had negligible effects on constant amplitude fatigue crack growth rates for 7010-T7451. However, 7010-T7651 crack growth rates depended strongly on salt spray pH and cycle frequency.

(8) Under manoeuvre spectrum (FALSTAFF) loading the fatigue crack growth rates and lives of 7010-T7651 and 7010-T7451 specimens were similar. Changing the environment from air to neutral salt spray had no significant influence.

9.7.3 Conclusions for the programme on the effect of chromate in primers

(9) The absence of chromate in properly applied primer had no significant detrimental effect on the constant amplitude fatigue lives of painted 1½ dogbone specimens of 7075-T6 subjected to pre-exposure and/or fatigue in salt spray. However, owing the the high stress level the testing times were short and most specimens failed in the bores or at bore/faying surface corners of the fastener holes where unprimed metal was present.

(10) Fatigue lives in air and salt spray were equivalent, but pre-exposure + fatigue in salt spray significantly reduced the fatigue lives of specimens with acrylic topcoats.

(11) Specimens with non-chromate-containing primers had relatively more failures in the bores of the fastener holes and fewer failures at faying surface locations as compared to specimens with chromate-containing primers.

9.7.4 Additional conclusions

(12) The fatigue strength and life tests on 7010-T7651 and 7010-T7451 in air and salt spray at a cycle frequency of 15 Hz showed that at higher stress levels 7010-T7651 was generally superior and at lower stress levels the alloys were equivalent. 7010-T7651 was also equivalent or superior to 7010-T7451 in fatigue and corrosion fatigue crack growth resistance at a cycle frequency of 10 Hz. However, the results of changing cycle frequency and salt spray pH for crack growth tests show that a conclusion as to the overall superiority of 7010-T7651 cannot be made.

(13) Changing the fatigue environment from air to salt spray does not necessarily result in shorter fatigue lives and higher crack growth rates. Significant variables in this respect include the type of test; fatigue load history and stress level; cycle frequency; environmental pH and material response. Environmental fatigue tests should therefore be conducted with realistic load histories, stress levels and cycle frequencies. (There still remains the difficult problem of deciding what are the most realistic environments.)

(14) Further investigation of the effect of chromates in primers should include flight simulation fatigue tests on realistic specimens at stress levels that result in fatigue crack initiation in areas where primer is more or less continuously present. The tests should be of sufficient duration to allow time for chromate to leach out of chromate-containing primers into the corrodent.

9.8 References

1. R.J.H. Wanhill and J.J. De Luccia, "An AGARD-coordinated corrosion fatigue cooperative testing programme", AGARD Report No. 695, February 1982.

2. "Description of a Fighter Aircraft Loading STAndard For Fatigue evaluation", Combined Report of the F + W, LBF, NLR and IABG, March 1976.

3. J.B. de Jonge, "Additional information about FALSTAFF", NLR Technical Report TR 79056 U, June 1979.

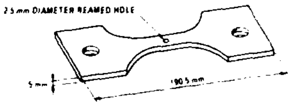
4. R.J.H. Wanhill, H.J. Kolkman and L. Schra, "Fatigue crack propagation and fracture in 7050 and 7091 aluminium alloy forgings", AGARD Conference Proceedings No. 376, Paper 5, November 1984.

5. Collected Papers in "Corrosion fatigue of aircraft materials", AGARD Report No. 659, October 1977.

6. Collected Papers in "Corrosion fatigue", AGARD Conference Proceedings No. 316, October 1981.

TABLE 9.1: OVERVIEW OF THE RAE TEST PROGRAMMES FOR FACT

FATIGUE STRENGTH



MATERIAL AND SPECIMEN
- 25 mm thick 7010 aluminium alloy plate in the T7651 and T7451 tempers

FATIGUE LOADING
- constant amplitude, S_{min}/S_{max} = 0.1, FALSTAFF cycle frequency 15 Hz in all cases

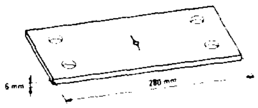
FATIGUE ENVIRONMENTS
- laboratory air; 3.5 % aqueous NaCl salt spray with pH 7

TEST PROGRAMME
-

SCHEDULES	7010-T7651	7010-T7451
fatigue in air	●	●
fatigue in salt spray	●	●

STATISTICAL ANALYSIS
- fatigue lives of specimens tested with FALSTAFF

FATIGUE CRACK GROWTH RESISTANCE



MATERIALS AND SPECIMEN
- 25 mm thick 7010 aluminium alloy plate in the T7651 and T7451 tempers, 25 mm thick 7475-T7351 aluminium alloy plate, 40 mm thick 7050-T7451 aluminium alloy plate

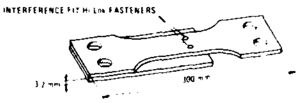
FATIGUE LOADING
- constant amplitude, S_{min}/S_{max} = 0.1, FALSTAFF

FATIGUE ENVIRONMENTS
- laboratory air, 3.5 % aqueous NaCl salt spray with pH 4 and pH 7

TEST PROGRAMME
-

SCHEDULES	FATIGUE LOAD HISTORY	pH	CYCLE FREQUENCY	7010-T7651	7010-T7451	7475-T7351	7050-T7451
fatigue in air	constant amplitude		10 Hz	●	●	●	●
	FALSTAFF		10 Hz	●	●		
fatigue in salt spray	constant amplitude	4	10 Hz	●	●	●	●
			1 Hz	●	●		
		7	1 Hz	●	●		
	FALSTAFF	7	10 Hz	●	●		

FATIGUE STRENGTH



MATERIAL AND SPECIMEN
- 3.2 mm thick 2024-T6 aluminium alloy sheet

PROTECTION SYSTEMS
- chromic acid anodising (except fastener holes) + chromate or non-chromate containing epoxy primer (except fastener holes) + polysulphide sealant + acrylic or polyurethane topcoat

PROTECTION SYSTEM DAMAGE
- two stress cycles at low temperature to crack paint and primer around the fastener heads

FATIGUE LOADING
- constant amplitude, S_{max} = [illegible] MPa, S_{min}/S_{max} = 0.1

FATIGUE ENVIRONMENTS
- laboratory air, 3.5 % aqueous NaCl salt spray with pH 4

STATIC PRE-EXPOSURE
- 72 hours in 5 % aqueous NaCl + SO_2 at 318 K

TEST PROGRAMME
-

SCHEDULES	CYCLE FREQUENCY	CHROMATE CONTAINING PRIMER		NON-CHROMATE CONTAINING PRIMER	
		acrylic topcoat	polyurethane topcoat	acrylic topcoat	polyurethane topcoat
fatigue in air	7 Hz	●		●	
fatigue in salt spray	0.5 Hz	●		●	
pre-exposure + fatigue in salt spray	0.5 Hz	●	●	●	●

STATISTICAL ANALYSIS
- fatigue lives and primary fatigue origins

TABLE 9.2: FATIGUE LIFE DATA FOR THE RAE FATIGUE STRENGTH CONTRIBUTION TO FACT

MATERIAL HEAT TREATMENT CONDITION	FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL S_{max} (MPa)	FATIGUE LIFE TO FAILURE (CYCLES OR FLIGHTS)	
			fatigue in air	fatigue in salt spray*
7010-T7651	constant amplitude, R = 0.1	250	14,035	
		200	44,850	24,329
		175	71,837	
		150	171,266	130,782
		135	181,586	
		125		305,809
		120	246,393	
		100	> 9,141,016	1,044,501
		75		1,480,738
		50		6,346,696
	FALSTAFF	300	5,311	4,077
		300	5,497	4,826
		250	6,734	14,825
		250	10,996	22,217
		175	36,352	59,735
		175	56,047	57,598
		175		52,823
7010-T7451	constant amplitude, R = 0.1	250	1,270	
		200	25,780	13,892
		175	7,800	25,779
		160	40,912	88,799
		150	83,220	
		140		96,849
		125	>12,673,484	188,026
		100		701,170
		75		1,848,773
		50		4,999,171
	FALSTAFF	300	1,914	2,283
		300	2,334	3,764
		250	6,958	3,431
		250	5,825	10,987
		175	60,727	33,713
		175	118,766	52,523
		87		94,659

*Neutral salt spray solution with pH 7

TABLE 9.3: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE) FOR THE FATIGUE STRENGTH TESTS WITH FALSTAFF

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF VARIATION	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES (F_o > F DISTRIBUTION VALUE)
FALSTAFF	S_{max} = 300 MPa AND S_{max} = 250 MPa AND S_{max} = 175 MPa	● MAIN EFFECTS			
		· stress	3.81	145.01	yes
		· *environment*	4.67	0.12	no
		· material	4.67	8.16	yes
		● 2-WAY *INTERACTIONS*			
		· stress : environment	3.81	1.49	no
		· stress : material	3.81	4.27	yes
		· environment : material	4.67	2.30	no
		● 3-WAY INTERACTIONS			
		· *stress : environment* : material	3.81	2.87	no

TABLE 9.4: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECT OF STRESS LEVEL ON FATIGUE STRENGTH TESTS WITH FALSTAFF

STRESS LEVEL	S_{max} = 300 MPa	S_{max} = 250 MPa	S_{max} = 175 MPa
LOG MEAN FATIGUE LIFE	3.543	3.946	4.742
SAMPLE SIZE n	8	8	9

$t_{0.025,13}$ = 2.16 $MS_{residual}$ = 0.021

COMPARISONS OF DATA FOR DIFFERENT STRESS LEVELS	t	*SIGNIFICANT DIFFERENCE* ($t > t_{0.025,13}$)
300 MPa/250 MPa*	5.56	yes
300 MPa/175 MPa	17.03	yes
250 MPa/175 MPa	11.30	yes

MATERIAL	7010-T7651	7010-T7451	7010-T7651	7010-T7451	7010-T7651	7010-T7451
LOG MEAN FATIGUE LIFE	3.690	3.396	4.097	3.296	4.714	4.777
SAMPLE SIZE n	4	4	4	4	5	4

$t_{0.025,13}$ = 2.16 $MS_{residual}$ = 0.021

STRESS LEVEL	*COMPARISONS OF MATERIALS*	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025,13}$)
300 MPa	7010-T7651/7010-T7451*	2.87	yes
250 MPa	7010-T7651/7010-T7451*	2.94	yes
175 MPa	7010-T7651/7010-T7451	0.65	no

*Owing to equal sample size these comparisons can also be made using the unmodified least significant difference test. The same result is obtained

TABLE 9.5: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR THE FATIGUE STRENGTH TESTS WITH FALSTAFF

MATERIAL	7010-T7651 AN[illegible] [illegible]010-T7451										7010-T7651						7010-T7451					
FATIGUE TESTING SCHEDULE	fatigue in air			fatigue in salt spray			fatigue in air		fatigue in salt spray		fatigue in air			fatigue in salt spray			fatigue in air			fatigue in salt spray		
CHARACTERISTIC STRESS LEVEL S_{max} (MPa) OR MATERIAL	300	250	175	300	250		7010-T7651	7010-T7451	7010-T7651	7010-T7451	300	250	175	300	250	175	300	250	175	300	250	175
LOG MEAN FATIGUE LIFE	3.529	3.869	4.792	3.557	4.023	4.[illegible]2	4.107	4.019	4.296	3.960	3.733	3.935	4.655	3.647	4.259	4.753	3.325	3.804	4.929	3.467	3.788	4.624
SAMPLE SIZE n	4	4	4	4	4	[illegible]	6	6	7	6	2	2	2	2	2	3	2	2	2	2	2	2

COMPARISONS OF DATA PER TEST PARAMETER		TEST PARAMETER	p	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_in_j}{n_i n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i - \bar{x}_j)\sqrt{\frac{2n_in_j}{n_i+n_j}} > SSR$
	fatigue in air/fatigue in salt spray	S_{max} = 300 MPa*	2	0.056	0.443	no
		S_{max} = 250 MPa*	2	0.308	0.443	no
		S_{max} = 175 MPa	2	0.190	0.443	no
	7010-T7651/7010-T7451	fatigue in air*	2	0.216	0.443	no
		fatigue in salt spray	2	0.854	0.443	yes
7010-T7651	fatigue in air/fatigue in salt spray	S_{max} = 300 MPa*	2	0.122	0.443	no
		S_{max} = 250 MPa*	2	0.458	0.443	yes
		S_{max} = 175 MPa	2	0.152	0.443	no
7010-T7451	fatigue in air/fatigue in salt spray	S_{max} = 300 MPa*	2	0.201	0.443	no
		S_{max} = 250 MPa*	2	0.023	0.443	no
		S_{max} = 175 MPa*	2	0.431	0.443	no
S_{max} = 300 MPa	7010-T7651/7010-T7451	fatigue in air*	2	0.577	0.443	yes
		fatigue in salt spray*	2	0.254	0.443	no
S_{max} = 250 MPa	7010-T7651/7010-T7451	fatigue in air*	2	0.185	0.443	no
		fatigue in salt spray*	2	0.666	0.443	yes
S_{max} = 175 MPa	7010-T7651/7010-T7451	fatigue in air*	2	0.387	0.443	no
		fatigue in salt spray	2	0.200	0.443	no

*owing to equal sample size these comparisons can also be made using the unmodified version of Duncan's test. The same result is obtained.

TABLE 9.6: FATIGUE LIFE AND PRIMARY FATIGUE ORIGIN DATA FOR THE RAE CONTRIBUTION TO FACT ON THE EFFECT OF CHROMATE IN PRIMERS. ALL TESTS WERE DONE UNDER CONSTANT AMPLITUDE LOADING WITH R = 0.1 AND S_{max} = 210 MPa

CORROSION PROTECTION SYSTEMS ON 7075-T6 ALUMINIUM ALLOY SHEET		FATIGUE LIFE TO FAILURE (CYCLES AND LOG MEAN VALUES)/LOCATIONS OF PRIMARY ORIGINS OF FATIGUE*		
		fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray
chromate-containing epoxy primer	interfay sealant + acrylic topcoat	32,870 S 15,367 R 20,192 F 21,686	12,004 R 13,647 E 15,260 G 24,549 G 13,335 S 15,226	8,433 R 6,111 Q,R 9,636 F 7,919
	interfay sealant + polyurethane topcoat			9,715 F 9,812 E 12,719 C 7,314 F 9,704
non-chromate-containing epoxy primer	interfay sealant + acrylic topcoat	15,956 E 15,002 E 18,989 Q 16,565	8,385 R 20,975 E,F 14,452 E 15,224 E 14,317 E 14,083	2,921 F 4,247 E,F 3,928 E,F 3,653
	interfay sealant + polyurethane topcoat			16,175 R 7,113 E 6,295 Q 11,330 Q 9,518

* KEY TO LOCATIONS OF FATIGUE ORIGINS

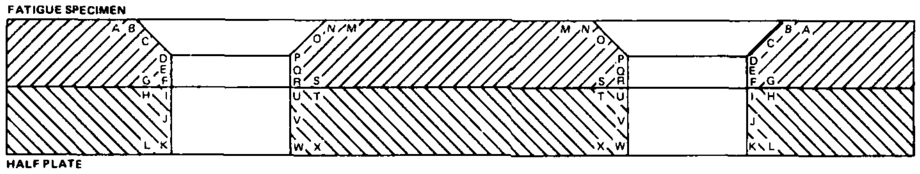


TABLE 9.7: SUMMARY OF ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE) FOR THE 1½ DOGBONE FATIGUE TESTS

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF VARIATION	F DISTRIBUTION VALUE	F_o	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES (F_o > F DISTRIBUTION VALUE)
constant amplitude, R = 0.1	$S_{max} = 210$ MPa	● MAIN EFFECTS - environment - protection system	 3.44 3.05	 30.58 6.36	 yes yes
		● 2-WAY INTERACTIONS - environment : protection system	3.44	2.55	no

TABLE 9.8: LEAST SIGNIFICANT DIFFERENCE TEST RESULTS (95 % CONFIDENCE) FOR THE EFFECTS OF ENVIRONMENT AND PROTECTION SYSTEM ON 1½ DOGBONE FATIGUE LIVES

FATIGUE TESTING SCHEDULE	fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray
LOG MEAN FATIGUE LIFE	4.278	4.166	3.875
SAMPLE SIZE n	6	10	14

$t_{0.025;25} = 2.07$ $MS_{residual} = 0.017$

COMPARISONS OF DATA FOR DIFFERENT FATIGUE TESTING SCHEDULES	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;22}$)
fatigue in air/fatigue in salt spray	1.66	no
fatigue in air/pre-exposure + fatigue in salt spray	6.33	yes
fatigue in salt spray/pre-exposure + fatigue in salt spray	5.39	yes

PROTECTION SYSTEM	chromate : acrylic	chromate : polyurethane	non-chromate : acrylic	non-chromate : polyurethane
LOG MEAN FATIGUE LIFE	4.147	3.987	4.008	3.979
SAMPLE SIZE n	11	4	11	4

$t_{0.025;22} = 2.07$ $MS_{residual} = 0.017$

COMPARISONS OF DATA FOR DIFFERENT PROTECTION SYSTEMS	t	SIGNIFICANT DIFFERENCE ($t > t_{0.025;22}$)
chromate primer + acrylic topcoat/chromate primer + polyurethane topcoat	2.10	yes
chromate primer + acrylic topcoat/non-chromate primer + acrylic topcoat*	2.50	yes
chromate primer + acrylic topcoat/non-chromate primer + polyurethane topcoat	2.21	yes
chromate primer + polyurethane topcoat/non-chromate primer + acrylic topcoat	0.28	no
chromate primer + polyurethane topcoat/non-chromate primer + polyurethane topcoat*	0.09	no
non-chromate primer + acrylic topcoat/non-chromate primer + polyurethane topcoat	0.38	no

*Owing to equal sample size these comparisons can also be made using the unmodified least significant difference test. The same result is obtained.

TABLE 9.9: SUMMARY OF DUNCAN'S NEW MULTIPLE RANGE TEST RESULTS (95 % CONFIDENCE) FOR THE 1½ DOGBONE FATIGUE TESTS

PRIMER	chromate				non-chromate			
TOPCOAT	acrylic			polyurethane	acrylic			polyurethane
FATIGUE TESTING SCHEDULE	fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	pre-exposure + fatigue in salt spray	fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	pre-exposure + fatigue in salt spray
LOG MEAN FATIGUE LIFE	4.336	4.183	3.899	3.987	4.219	4.149	3.563	3.978
SAMPLE SIZE n	3	5	3	4	3	5	3	4

TEST PARAMETER	COMPARISONS OF DATA PER TEST PARAMETER	p	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_in_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $(\bar{x}_i - \bar{x}_j)\sqrt{\frac{2n_in_j}{n_i+n_j}} > SSR$
chromate primer + acrylic topcoat	fatigue in air/fatigue in salt spray	2	0.296	0.381	no
	fatigue in air/pre-exposure + fatigue in salt spray*	3	0.757	0.401	yes
	fatigue in salt spray/pre-exposure + fatigue in salt spray	2	0.550	0.381	yes
non-chromate primer + acrylic topcoat	fatigue in air/fatigue in salt spray	2	0.136	0.381	no
	fatigue in air/pre-exposure + fatigue in salt spray*	3	1.136	0.401	yes
	fatigue in salt spray/pre-exposure + fatigue in salt spray	2	1.135	0.381	yes
fatigue in air	chromate primer + acrylic topcoat/non-chromate primer + acrylic topcoat*	2	0.203	0.381	no
fatigue in salt spray	chromate primer + acrylic topcoat/non-chromate primer + acrylic topcoat*	2	0.076	0.381	no
pre-exposure + fatigue in salt spray	chromate primer + acrylic topcoat/chromate primer + polyurethane topcoat	3	0.163	0.401	no
	chromate primer + acrylic topcoat/non-chromate primer + acrylic topcoat*	2	0.582	0.381	yes
	chromate primer + acrylic topcoat/non-chromate primer + polyurethane topcoat	2	0.146	0.381	no
	chromate primer + polyurethane topcoat/non-chromate primer + acrylic topcoat	4	0.785	0.413	yes
	chromate primer + polyurethane topcoat/non-chromate primer + polyurethane topcoat*	2	0.018	0.381	no
	non-chromate primer + acrylic topcoat/non-chromate primer + polyurethane topcoat*	3	0.768	0.401	yes

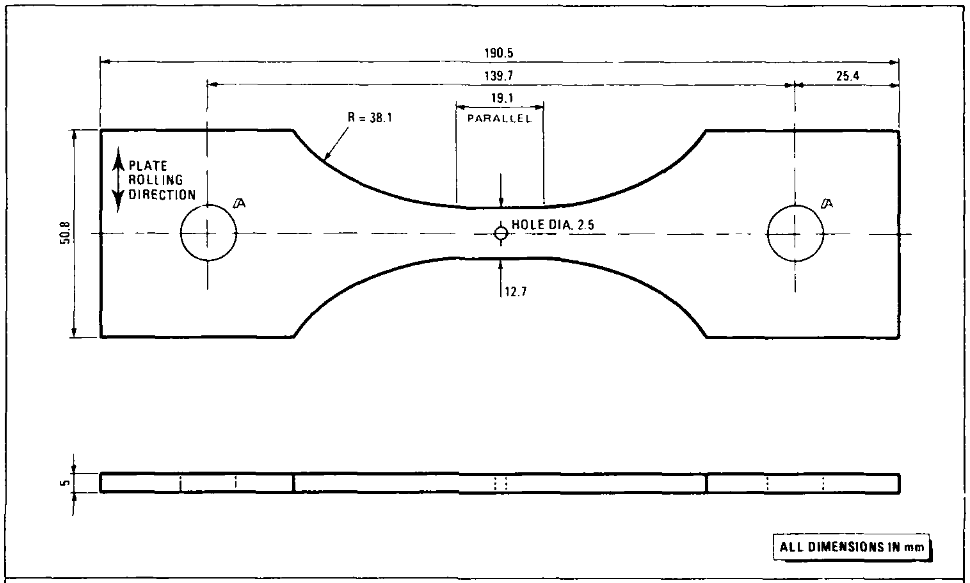
*Owing to equal sample size these comparisons can also be made using the unmodified version of Duncan's test. The same result is obtained.

TABLE 9.10: SUMMARY OF YATES' CORRECTED χ^2 TEST FOR THE PRIMARY FATIGUE ORIGINS IN 1½ DOGBONE SPECIMENS (95 % CONFIDENCE)

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL	SOURCE OF ASSOCIATION	CRITICAL VALUE OF $\chi^2_{0.05;1}$	χ^2_c	SIGNIFICANT ASSOCIATION $(\chi^2_c > \chi^2_{0.05;1})$
constant amplitude, R = 0.1	$S_{max} = 210$ MPa	ENVIRONMENT (FATIGUE TESTING SCHEDULE)	$\chi^2_{0.05;1} = 3.84$	0	no
		PROTECTION SYSTEM	$\chi^2_{0.05;1} = 3.84$	4.35	yes

TABLE 9.11: OVERVIEW OF COMPARISONS OF FATIGUE IN AIR AND FATIGUE IN SALT SPRAY

TYPE OF TEST	FATIGUE LOAD HISTORY	CYCLE FREQUENCY IN SALT SPRAY	SPECIMEN CONFIGURATION	RELEVANT CONDITIONS IN SALT SPRAY	MATERIAL	SIGNIFICANT DIFFERENCE BETWEEN FATIGUE IN AIR AND SALT SPRAY
fatigue strength and life tests	constant amplitude, R = 0.1	15 Hz	notched coupon	lives < 3 X 10^5 cycles ■ 5.5 hours	7010-T7651 7010-T7451	no no
				lives > 3 X 10^5 cycles ■ 5.5 hours	7010-T7651 7010-T7451	yes yes
		0.5 Hz	1½ dogbone	lives < 25,000 cycles ■ 14 hours	7075-T6	no
	FALSTAFF	15 Hz	notched coupon	lives < 60,000 flights ■ 93 hours	7010-T7651 7010-T7451	no no
fatigue crack growth tests	constant amplitude, R = 0.1	10 Hz	centre cracked panel	da/dn = 2.5 X 10^{-8} – 3.5 X 10^{-6} m/cycle $\Delta K = 6 - 20$ MPa$\sqrt{m}$	7010-T7651 7010-T7451 7475-T7351 7050-T7451	yes yes yes no
	FALSTAFF	10 Hz	centre cracked panel	da/df = 2.5 X 10^{-7} – 10^{-5} m/flight da/dn = 2.8 X 10^{-9} – 1.1 X 10^{-7} m/cycle	7010-T7651 7010-T7451	no no



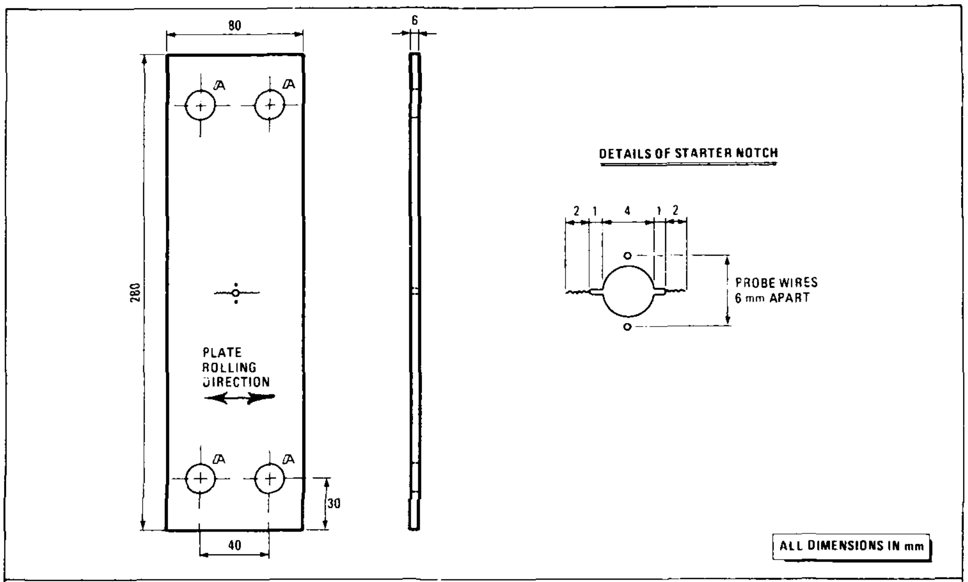
NOTES

(1) ALL HOLES REAMED.

(2) ALL HOLES MARKED THUS "Δ" ARE 12.7 mm DIAMETER.

(3) TOLERANCE INDICATIONS NOT INCLUDED

Fig. 9.1 Notched specimen configuration for the RAE fatigue strength test programme



NOTES

(1) STARTER NOTCH IS A CENTRAL HOLE WITH SAWCUTS AND FATIGUE PRECRACKS TO A TOTAL LENGTH OF 10 mm

(2) ALL HOLES MARKED THUS "Ⓐ" ARE 18 $^{+0\ 018}_{+0}$ mm DIAMETER.

(3) OTHER TOLERANCE INDICATIONS NOT INCLUDED.

Fig. 9.2 Specimen configuration for the RAE fatigue crack growth resistance test programme

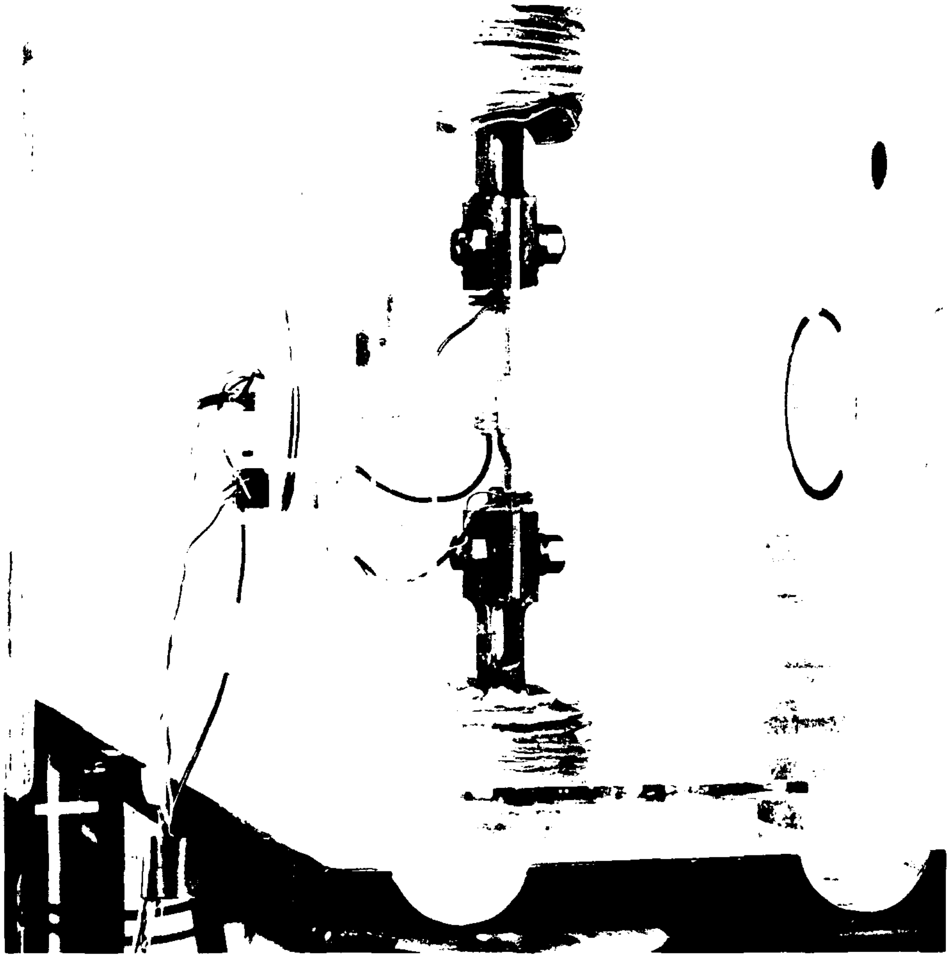


Fig. 9.3 Set-up for fatigue crack growth resistance tests in the salt spray chamber.
The crack growth monitoring leads have access to the chamber via a sealed porthole

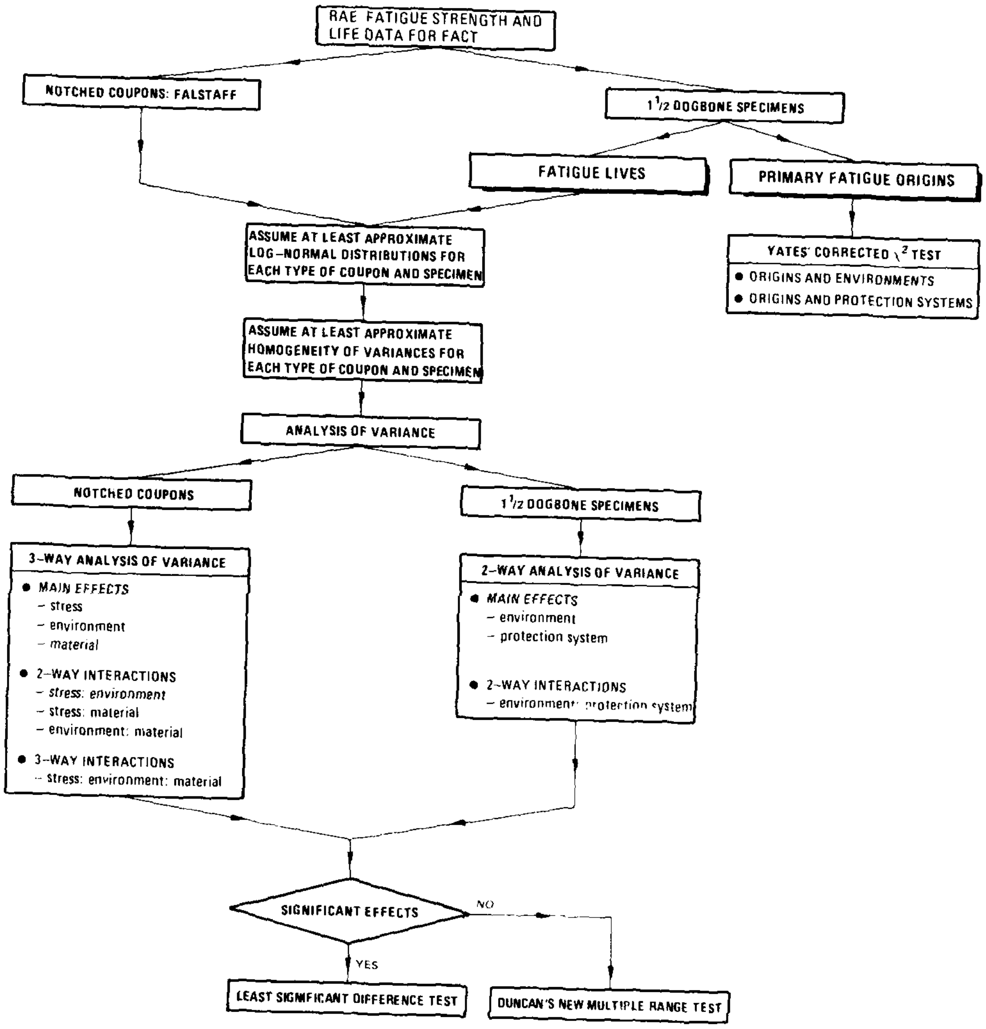


Fig. 9.4 Survey of statistical methods for analysing the RAE fatigue strength and life data for FACT

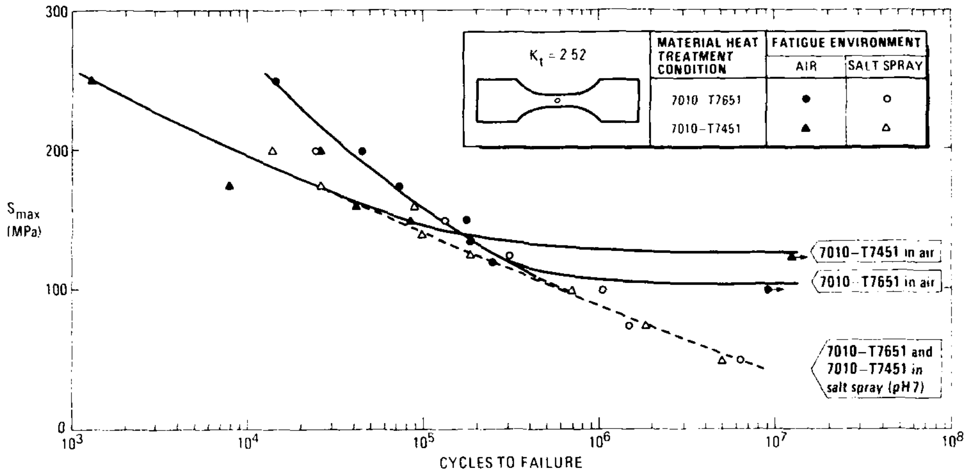


Fig. 9.5 RAE constant amplitude fatigue strength data contribution to the FACT programme. Cycle frequency 15 Hz; salt spray pH 7

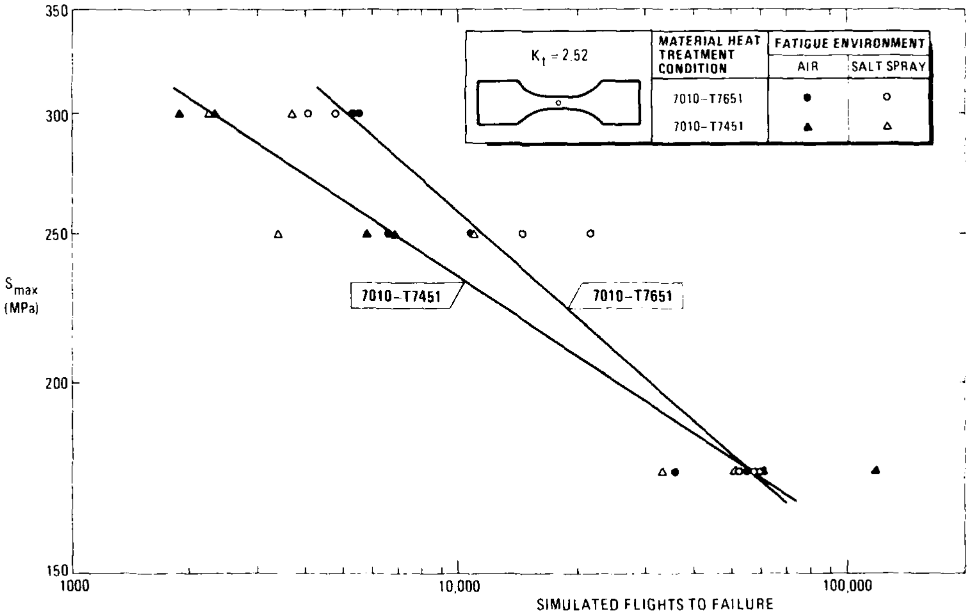


Fig. 9.6 RAE FALSTAFF fatigue strength data contribution to the FACT programme. Cycle frequency 15 Hz; salt spray pH 7

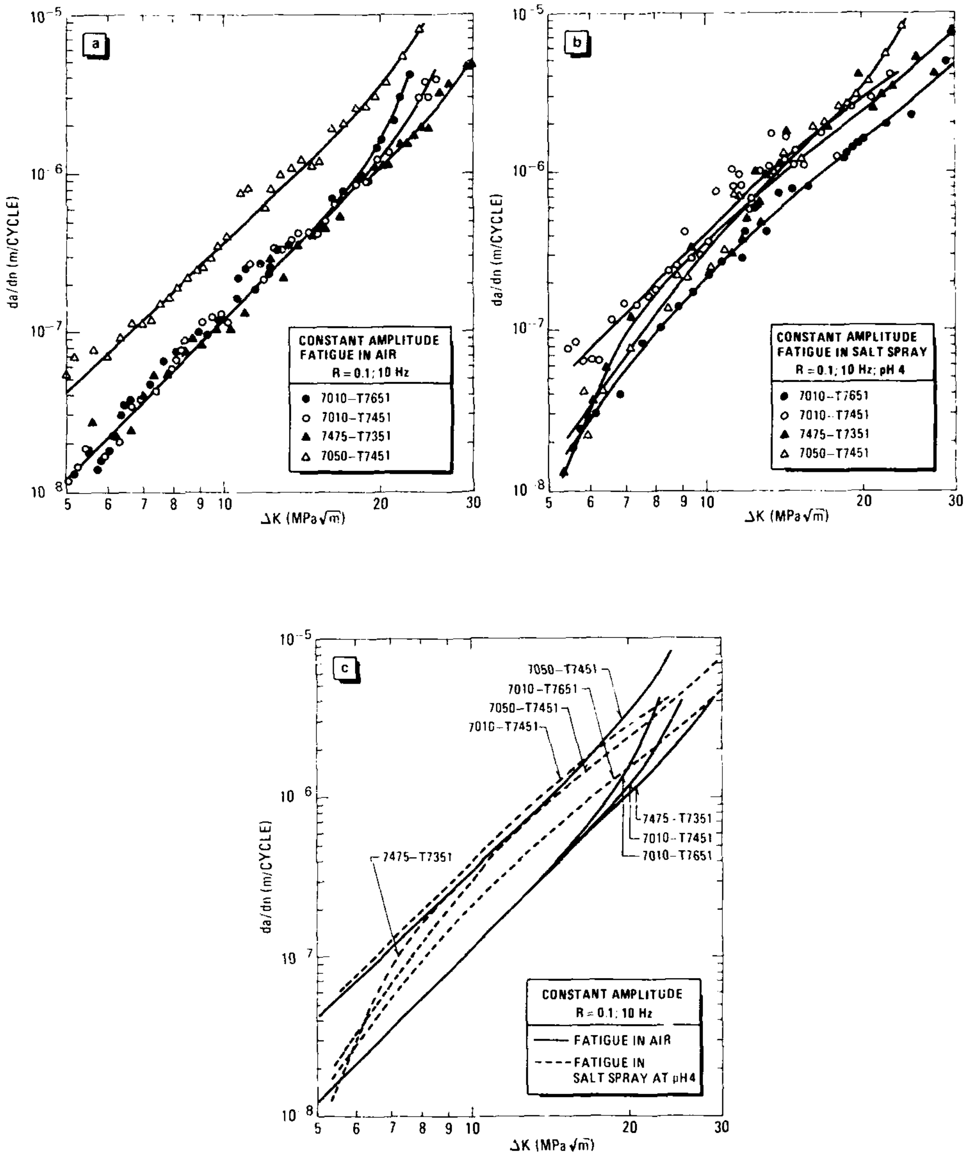


Fig. 9.7 Comparisons of constant amplitude fatigue and corrosion fatigue crack growth resistances of 7010-T7651, 7010-T7451, 7475-T7351 and 7050-T7451

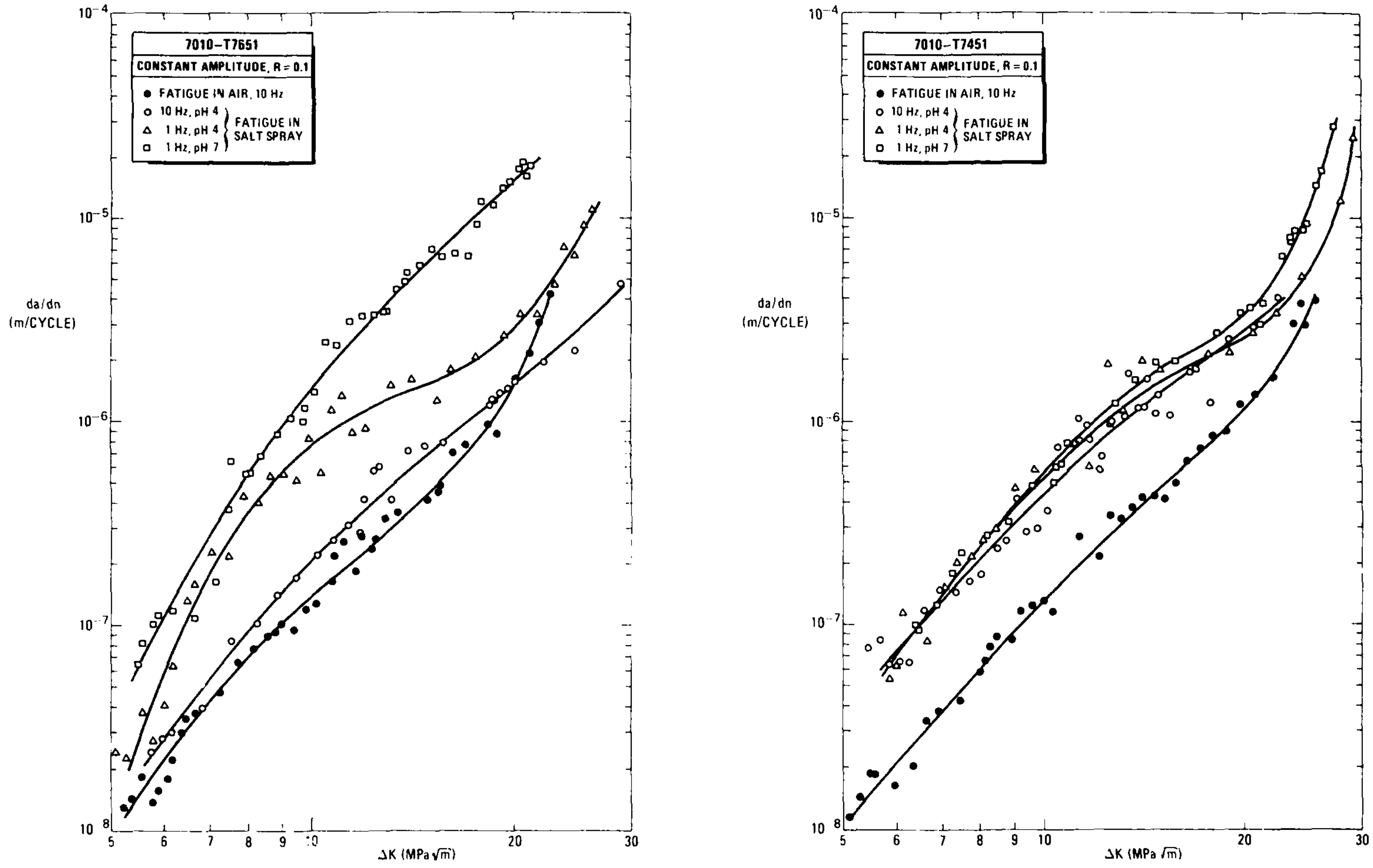
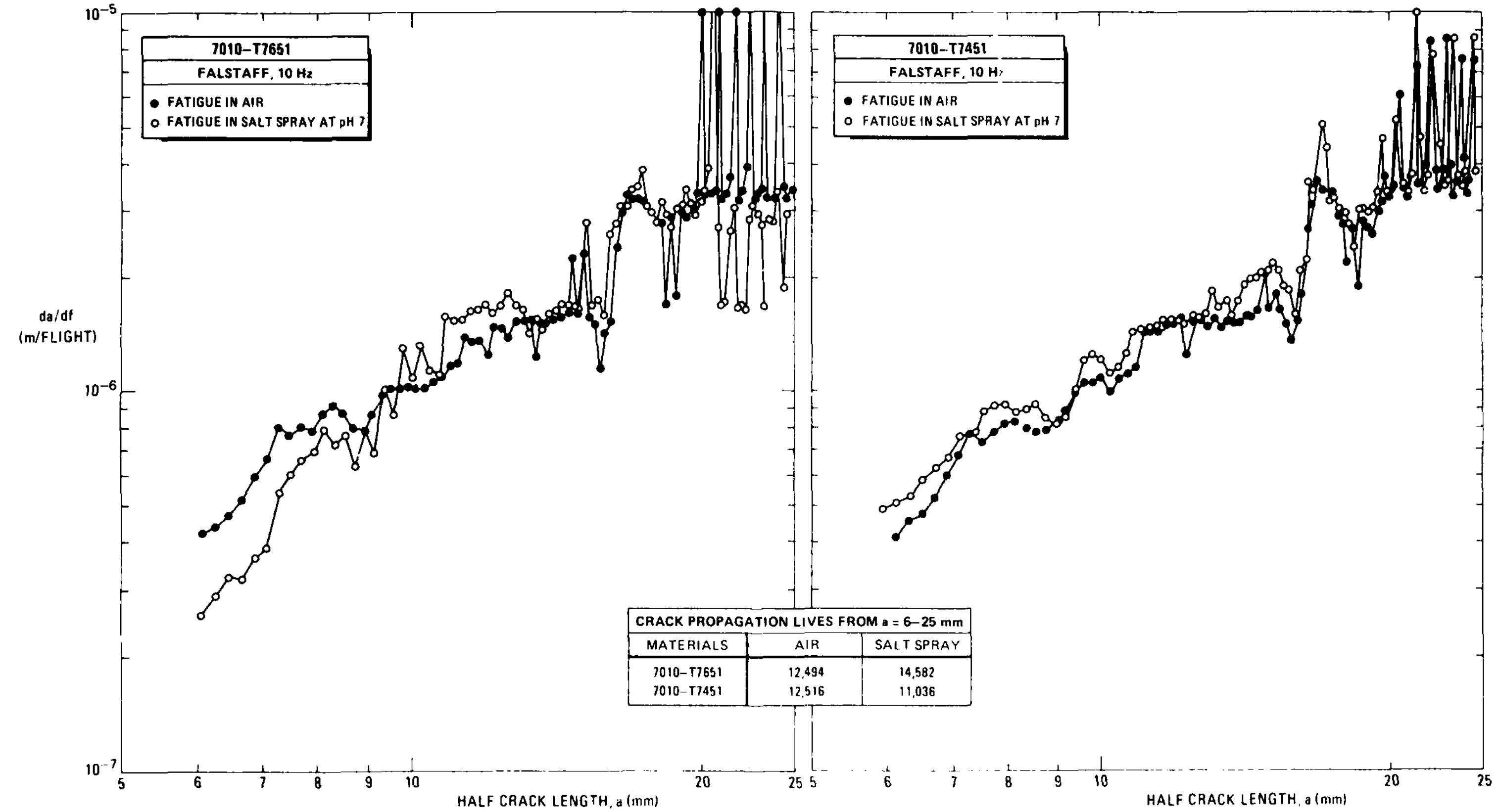


Fig. 9.8 Effects of environment and cycle frequency on the constant amplitude fatigue crack growth resistances of 7010-T7651 and 7010-T7451



CRACK PROPAGATION LIVES FROM a = 6–25 mm		
MATERIALS	AIR	SALT SPRAY
7010–T7651	12,494	14,582
7010–T7451	12,516	11,036

Fig. 9.9 Comparisons of manoeuvre spectrum (FALSTAFF) fatigue and corrosion fatigue crack growth resistances of 7010-T7651 and 7010-T7451

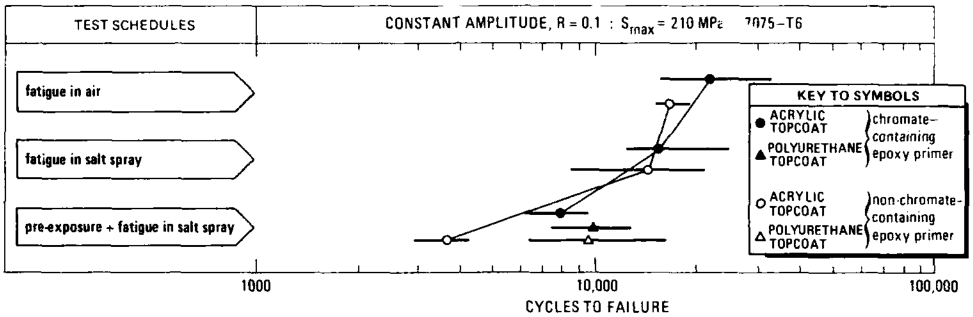


Fig. 9.10 RAE fatigue life data contribution to the FACT programme on the effect of chromate in primers. Cycle frequencies 2 Hz in air, 0.5 Hz in salt spray

10. THE NRC CONTRIBUTION TO THE FACT PROGRAMME

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10.1 Introduction

The NRC contribution to FACT was mainly a comparison of fatigue crack growth and corrosion fatigue crack growth properties of 7075 aluminium alloy plate in the T651, T7351 and RRA (retrogression and reage) conditions. Stress corrosion crack growth rate tests were also carried out on the same material. Some fatigue crack growth and corrosion fatigue crack growth tests were done with 7075 aluminium alloy sheet in the T651, T7351 and RRA conditions.

10.2 The Retrogression and Reageing (RRA) Process

The retrogression and reageing process was first described by Cina and Ranish (references 1, 2) and is a heat treatment designed for use with the 7000 series aluminium alloys. The RRA treatment was claimed to provide in a single temper the strength and stress corrosion resistance equivalent to the best features of the T6 and T73 tempers. The heat treatment is shown schematically in figure 10.1. It is applied to material in the T6 condition and involves two stages of treatment. The first stage, retrogression, requires heating for short times of the order of a few seconds or minutes at temperatures in the range 473 - 533 K. The second stage, reageing, is a repeat of the original T6 age, which typically involves heating for about 24 hours at 393 K.

Subsequent studies (references 3-8) have confirmed the essential features of the retrogression and reageing process. As indicated in figure 10.1, retrogression appears to involve three stages. During stage I the strength decreases from the initial T6 value and reaches a minimum at the start of stage II, where the strength begins to recover. A secondary hardening peak is reached at the onset of stage III. Continued heating through stage III causes a further loss of strength as the material effectively overages. Besides changes in strength, retrogression causes a progressive increase in electrical conductivity. After relatively short regression times the material can be reaged to recover strength, sometimes to levels higher than the initial T6 value, and electrical conductivity continues to increase and reaches values close to those obtained by conventional T73 heat treatment.

Cina and Ranish claimed that heating to the minimum in the retrogression curve, followed by reageing, produced a material with strength equivalent to the initial T6 value together with electrical conductivity and stress corrosion resistance equivalent to those of T73 processed material. A serious limitation of the process is that the retrogression times are very short, typically 5-120 seconds depending on temperature, and thus it is difficult to obtain uniform through-thickness properties in thick section parts. As originally formulated, the process is more suitable for very thin sections or as a surface modification treatment for thicker section parts. Wallace et al. (references 3-5, 7, 8) showed that lower temperatures and longer retrogression times as far as the secondary hardening peak could often be used to produce more effective combinations of strength and stress corrosion resistance in thicker section materials.

The effects of retrogression and reageing on microstructure have been studied using transmission electron microscopy of thin foils (references 4-6). Although some differences in interpretation exist, it appears that stage I of the retrogression process involves partial resolutioning of G.P. zones with little or no effect on the size or volume fraction of η or η' ($MgZn_2$) precipitates, see figure 10.2 and table 10.1. Continued retrogression through stages II and III causes an increase in size and volume fraction of $\eta + \eta'$ precipitates. Reageing causes a further increase in volume fraction of $\eta + \eta'$, but strength can be recovered only for short (to the end of stage I) or intermediate (to the end of stage II) retrogression times. In references (5) and (6) it is shown that the size of grain boundary precipitates increases substantially during retrogression and approaches the size of precipitates produced by the T73 heat treatment. It has been suggested that these coarse grain boundary precipitates play an important role in stress corrosion cracking by acting as trapping sites for hydrogen (reference 5). Thus hydrogen produced by hydrolysis at a crack tip and entering the metal would be encouraged to precipitate, forming molecular gas bubbles at the trapping sites and hence lowering the concentration of atomic hydrogen (presumed to be the damaging species) in the grain boundary region ahead of the crack tip. Several workers have reported observations consistent with the presence of hydrogen bubbles at large grain boundary precipitates in aluminium-zinc-magnesium alloys exposed to water vapour (references 5, 9, 10).

10.3 The Test Programme

An overview of the test programme is given in table 10.2. Tests were originally planned for both 7075 and 7475 material. But testing of 7475 was discontinued because residual stresses introduced during heat treatment resulted in spurious fatigue crack growth behaviour, which is explained in section 10.4.4. There were two parts to the programme:

- investigation of stress corrosion crack growth resistance of 7075 plate as a function of heat treatment, including several T6RRA conditions
- comparisons of fatigue crack growth and corrosion fatigue crack growth resistances of 7075 sheet and plate in the T651, T7351 and optimum T6RRA conditions.

10.3.1 Materials, heat treatments and specimen configurations

The materials used in this investigation were 7075 and 7475 aluminium received in the T651 and T7351 tempers respectively. The 7075 alloy was received in the form of 3.2 mm thick sheet and 102 mm thick plate. The 7475 alloy was received in the form of 63.5 mm thick plate.

Retrogression and reageing treatments were carried out on unnotched specimens blanks using silicone oil baths. For the 7075 sheet and plate retrogression was carried out directly for the as-received T651 materials. However, since the 7475 plate was received in the T7351 condition it was necessary to do a full solution treatment and age in order to obtain a T6 starting condition before retrogression and reageing. The 7475 plate was quenched into cold water at 273 K after solution treatment at 753 ± 5 K, but no stress relieving was done before ageing at 393 K. Retrogression treatments were carried out at 493 K and 533 K for various times before ageing for 24 hours at 393 K.

There were three types of specimen, illustrated schematically in table 10.2. For stress corrosion crack growth tests the specimens were of the bolt-loaded double cantilever beam (DCB) type described by Speidel (references 11, 12). The specimens were 127 mm long, 19 mm high and 31 mm thick and orientated with the loading direction parallel to the short transverse (S) direction and with crack growth in the longitudinal (L) rolling direction of the plate. This is the most sensitive orientation with respect to environmentally enhanced fracture.

For fatigue crack growth tests centre cracked tension (CCT) specimens were machined from the 3.2 mm thick sheet. Loading was in the longitudinal (L) direction and crack growth in the long transverse (T) direction. Compact tension (CT) specimens conforming to ASTM Standard E647-83 (B = 12.7 mm, W = 63.5 mm) were machined from fully heat treated plate specimen blanks. The CT specimens were loaded either in the longitudinal (L) or short transverse (S) directions and crack growth was in the long transverse (T) or longitudinal (L) directions respectively.

10.3.2 Fatigue testing conditions

Constant amplitude fatigue crack growth rates were obtained for tests in laboratory air, dry argon and flowing 3.5 % aqueous NaCl under the conditions of stress ratio ($R = S_{min}/S_{max}$) and cycle frequency shown in table 10.2. CCT specimen crack lengths were measured optically and also using two FRACTOMAT KRAK gauges bonded on either side of the centre crack starter. For the CT specimens crack lengths were calculated from compliance measurements made periodically during the tests.

Since previous work (references 13-15) showed that the most pronounced effects of heat treatment on fatigue crack growth in aluminium alloys are observed at low growth rates in the threshold regime ($da/dn < 10^{-8}$ m/cycle) the present work on CT specimens concentrated on this regime. Crack growth rates were determined for both ΔK-increasing and ΔK-decreasing conditions using a computer controlled test system with automatic data acquisition and analysis (reference 16). For the ΔK-decreasing tests a technique described by Saxena et al. (reference 17) was used to keep the rate of change of plastic zone size constant as the crack propagates. Thus the load shedding followed an exponential curve given by

$$\Delta K(a) = \Delta K_o \exp [C(a-a_o)]$$

where the subscript "o" denotes initial values of crack length a and ΔK, and the constant C determines the rate of decrease.

In addition, the software continually checked the load versus crack opening displacement (COD) data sets, used in the compliance technique to measure crack growth, for the occurrence of crack closure. The compliance data were scanned from the maximum load downwards for a 2.5 % positive change in slope. This point on the load-COD curve was taken to be the closure load, which was then used to define an effective ΔK:

$$\Delta K_{eff} = K_{max} - K_{closure}$$

Detailed descriptions of the test system and methods are given in references (16, 18).

10.4 Results

10.4.1 Effects of RRA on microstructure, mechanical properties and electrical conductivity

The microstructures, short transverse mechanical properties and electrical conductivities of the 7075 alloy plate in the T651, T6RRA and T7351 conditions are shown in figure 10.3. As found previously (reference 5) both RRA and overageing to the T7351 condition increased the size of grain boundary precipitates. The grain boundary precipitates had diameters ~ 20, 75 and 65 nm for the T651, T6RRA and T7351 conditions respectively. A general increase in size of the intragranular (matrix) precipitates is also apparent in proceeding from the T651 to the T6RRA and T7351 conditions.

It is not the purpose of this contribution to the FACT programme to interpret these microstructures in detail, but it is worthwhile pointing out that the T6RRA treatment appears to give a microstructure combining the preferred features of fine matrix precipitates characteristic of the T651 temper with coarse grain boundary precipitates characteristic of the T7351 temper. These features are believed to be responsible for the combination of high strength and stress corrosion resistance of the T6RRA material. As shown in figure 10.3, the yield strengths of the T651 and T6RRA materials were similar and about 8 % greater than that of the T7351 material, while the tensile strength of the T6RRA material was halfway between the T651 and T7351 tensile strengths.

10.4.2 Stress corrosion crack growth rates

A series of heat treatments involving retrogression and retrogression and reageing, with retrogression temperatures of 493 K and 533 K, was carried out with 7075-T651. The Vickers hardness values (VPN) and electrical conductivities (% IACS) of these materials are listed in table 10.3. Retrogression treatments for times up to 8 minutes at 493 K and 2 minutes at 533 K were effective in providing hardness values comparable to that (~ 180 VPN) of the T651 starting material. Also, the retrogression times of 8 minutes at 493 K and 2 minutes at 533 K resulted in electrical conductivities higher than that of 7075-T651 (33-34 % IACS) and similar to values expected for 7075-T7351 (38-42 % IACS).

Stress corrosion crack growth rates are shown in figure 10.4 for 7075-T651, T7351 and T6RRA materials with retrogression times of 1, 2, 4, 6 and 12 minutes at 493 K. The plateau (stress independent) crack growth rate for 7075-T651 was about 8 x 10^{-9} m/s, and the transition from stress independent to stress dependent crack growth occurred at a stress intensity factor value of about 10 MPa m. The effect of increasing retrogression time at 493 K was to progressively lower the plateau crack growth rate and move the transition to higher stress intensity factor values.

Material retrogressed for 6 minutes at 493 K had stress corrosion crack growth rates of about 2-4 x 10^{-10} m/s. This is slightly higher than crack growth rates in 7075-T7351 but much lower than the plateau crack growth rate for 7075-T651. In view of this result, and also the results of the hardness and electrical conductivity measurements listed in table 10.3, it appears that an optimum balance of strength and stress corrosion resistance is obtained with retrogression times of 6-8 minutes at 493 K.

Thus for the second and main part of this investigation, fatigue crack growth and corrosion fatigue crack growth resistance tests, it was decided in the case of T6RRA material to concentrate on retrogression times of 6-8 minutes at 493 K before reageing.

10.4.3 Fatigue and corrosion fatigue crack growth rates for centre cracked tension (CCT) specimens

The fatigue and corrosion fatigue crack growth results for CCT sheet specimens are given in figures 10.5-10.7. There are three trends:

(1) For each combination of fatigue environment and cycle frequency the data fall into fairly narrow scatter bands.

(2) 7075-T7351 had the lowest crack growth rates in air. T6RRA material was intermediate, and 7075-T651 had the highest crack growth rates.

(3) The overall effect of a lower cycle frequency was to shift the fatigue crack growth rates to slightly higher values. This effect is more noticeable for fatigue in 3.5 % aqueous NaCl.

10.4.4 Fatigue and corrosion fatigue crack growth rates for compact tension (CT) specimens

As mentioned at the beginning of section 10.3, residual stresses introduced into the 7475 plate material during heat treatment resulted in spurious fatigue crack growth behaviour. Specifically, the 7475-T6 and -T6RRA specimens required abnormally long times for initiation of fatigue precracks; the precracks often initiated away from the machined chevron notches and grew on planes not perpendicular to the loading direction; and the crack length values determined by computer from the compliance plots often varied in an apparently random way. The load-COD plots for these specimens often showed marked non-linearities even in the higher ranges of load employed. In contrast, load-COD plots for 7475-T7351, 7075-T651, -T6RRA or -T7351 were essentially linear and showed only minor indications of curvature at very low loads, most probably as a normal consequence of fatigue crack closure.

It is suspected that the anomalous behaviour of 7475-T6 and -T6RRA was a consequence of having to do a full solution treatment and age to obtain the T6 and T6RRA conditions from the original T7351 temper. In particular, it is thought that residual stresses were introduced by the cold water quench after solution treatment. Because of this all subsequent work was done with 7075, which had been received in the stress relieved T651 condition and could be converted to T6RRA and T7351 without full solution treatment.

Fatigue and corrosion fatigue crack growth rates for 7075 are given in figures 10.8-10.11, which show the following:

- figure 10.8 : fatigue crack growth in dry argon (no environmental effect)
- figure 10.9 : comparisons of fatigue and corrosion fatigue crack growth
- figure 10.10: effect of cycle frequency on corrosion fatigue crack growth
- figure 10.11: effect of stress ratio on corrosion fatigue crack growth.

Figure 10.8 shows that fatigue crack growth rates for SL orientation specimens fall into narrow scatter bands with 7075-T651 the most resistant at low values of ΔK and ΔK_{eff}. LT orientation 7075-T651 specimens had greater resistance to fatigue crack growth than SL orientation 7075-T651 specimens at ΔK and ΔK_{eff} values below 8 MPa m. However, LT orientation 7075-T6RRA specimens were less resistant than SL specimens, apparently because there was less crack closure.

Figure 10.9 shows the very large environmental effect of fatigue in salt water. There was more crack closure in salt water than in argon. Consequently, plotting crack growth rates against ΔK_{eff} resulted in an even greater difference between the sets of salt water and argon data. Also the apparent "knees" in the salt water da/dn - ΔK plots at about 10^{-8} m/cycle are less evident when the data are corrected for crack closure. With respect to alloy temper, in salt water 7075-T651 was more resistant than 7075-T6RRA and 7075-T7351 at low values of ΔK and ΔK_{eff}, but less resistant at higher values.

Figure 10.10 shows that lowering the cycle frequency from 20 Hz to 2 Hz tended to result in higher crack growth rates at higher values of ΔK and ΔK_{eff}, and lower crack growth rates at low values of ΔK and ΔK_{eff}. It was expected that lower crack growth rates at low ΔK might be due to enhanced crack closure at 2 Hz, owing to a greater wedging effect of thicker corrosion products formed at this lower frequency. However, correcting for crack closure did not change the relative positions of the data sets. The da/dn - ΔK plots show knees at about 10^{-8} m/cycle. When corrected for crack closure the data show knees at slightly lower crack growth rates of about 5 x 10^{-9} m/cycle. Interestingly, the ranking of alloy tempers at low values of ΔK and ΔK_{eff} changed with cycle frequency: 7075-T651 was the most resistant at 20 Hz but the least resistant at 2 Hz.

Figure 10.11 shows a significant effect of stress ratio on fatigue crack growth rates in salt water at 2 Hz. The range in crack growth rates plotted against ΔK covers about one order of magnitude. Correcting for crack closure reduces the data spread to a factor of 3-5 in growth rates. There are knees in the da/dn - ΔK plots at about 10^{-8} m/cycle. Below the knees the crack growth rates fall away rapidly, indicating threshold ΔK values in the range 2.5 - 3.5 MPa m. Values for the three tempers tested at $R = 0.5$ were towards the low end of this range, while at $R = 0.1$ the indicated values were towards the high end. 7075-T651 was generally the least resistant temper at both R values.

10.5 Discussion and Conclusions

Retrogression and reageing of 7075-T651 alloy results in significant increases in resistance to stress corrosion crack growth when retrogression is continued to the region of the secondary hardening peak. For the particular heat treatments used in this investigation the retrogression times were about 6-8 minutes at 493 K. Plateau stress corrosion crack growth rates were more than an order of magnitude lower than that of the T651 material.

In argon the fatigue crack growth rates in SL orientation specimens were similar for all three tempers. However, below about 10^{-8} m/cycle there were indications that 7075-T651 was more resistant than 7075-T6RRA and 7075-T7351. This is consistent with the results of other investigators who found that in the threshold region the fatigue crack growth resistance of various tempers of 7075 increases in going from overaged to peak aged to underaged material. These other studies were done with vacuum (reference 15), laboratory air (references 14, 15) and moist air at 95 % relative humidity (reference 13), and at relatively high frequencies in the range 25-40 Hz.

When tests were done in salt water at 20 Hz the ranking of the tempers remained the same. At the lowest crack growth rates the T651 (peak aged) material still appeared to be more resistant to fatigue crack growth than the overaged T7351 material and the T6RRA material. In this respect the T6RRA material behaves more like an overaged material than its peak aged T651 equivalent. At higher crack growth rates 7075-T651 was the least resistant to fatigue crack growth. This was also observed by Suresh et al. (reference 13) for tests in moist air.

For fatigue in salt water at 2 Hz the differences in crack growth rates between the three tempers in the near threshold regime were much less than those observed for fatigue in argon or salt water at 20 Hz. Also, the ranking of the tempers changed. 7075-T651 was the most resistant at 20 Hz but the least resistant at 2 Hz. This indicates that the T7351 and T6RRA materials have greater resistance to corrosion fatigue crack growth.

The longer test durations at 2 Hz would be expected to result in a greater contribution of corrosion fatigue crack growth to the overall crack growth process than at 20 Hz. However, this was observed only for higher crack growth rates and higher values of ΔK and ΔK_{eff}, and not for the lower crack growth rates in the near threshold regime. This unusual behaviour was not caused by differences in crack closure and therefore some other process such as crack tip blunting by anodic dissolution may be responsible. No firm conclusions on this can be reached at present, and the phenomenon is under investigation.

10.6 References

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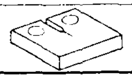
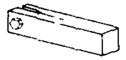
TABLE 10.1: VOLUME FRACTION OF $\eta + \eta'$ AFTER RETROGRESSION AT 473 K AND AFTER RETROGRESSION AND REAGEING (REFERENCE 4)

HEAT TREATMENT CONDITION OF 7075	VOLUME FRACTION OF $\eta + \eta'$ PRECIPITATES
T6	0.029
Retrogressed - 5 minutes	0.031
Retrogressed - 5 minutes and reaged	0.047
Retrogressed - 30 minutes	0.071
Retrogressed - 60 minutes	0.120

TABLE 10.2: OVERVIEW OF THE NRC TEST PROGRAMME FOR FACT

STARTING MATERIALS	•	3.2 mm thick 7075-T651 aluminium alloy sheet; 102 mm thick 7075-T651 and 63.5 mm thick 7475-T7351 aluminium alloy plate*
FATIGUE LOADING	•	constant amplitude
FATIGUE ENVIRONMENTS	•	laboratory air; dry argon; flowing 3.5 % aqueous NaCl with pH 7
TEST PROGRAMME	•	

TYPE OF TEST	ENVIRONMENT	$\frac{S_{min}}{S_{max}}$	CYCLE FREQUENCY	MATERIALS AND SPECIMENS		SPECIMEN ORIENTATION	HEAT TREATMENT CONDITION		
							T651	T6RRA	T7351
FATIGUE CRACK GROWTH RESISTANCE	air and 3.5 % aqueous NaCl	0.1	0.2 and 2 Hz	7075 sheet		LT	●	●	●
	argon and 3.5 % aqueous NaCl	0.1 and 0.5	2 and 20 Hz	7075 plate		LT and SL	●	●	●
STRESS CORROSION CRACK GROWTH RESISTANCE	intermittent wetting with 3.5 % aqueous NaCl			7075 plate		SL	●	●	●

*Originally included in the test programme but not tested (see text)

TABLE 10.3: HARDNESS AND ELECTRICAL CONDUCTIVITY OF 7075 AFTER RETROGRESSION AND RETROGRESSION AND REAGEING, WITH RETROGRESSION TEMPERATURES OF 493 K AND 533 K

RETROGRESSION TIME (MINUTES)	RETROGRESSION ONLY, 493 K		T6RRA, 493 K		T6RRA, 533 K	
	VPN	% IACS	VPN	% IACS	VPN	% IACS
1	190	34.3	179.4	34.8	190.5	39.0
2	185	34.3	186.0	35.1	186.7	40.1
4	190	35.6	174.2	36.6	166.9	41.7
8	186	37.9	181	38.8	139.6	43.5
16	171.[illegible]	39.8	163.9	40.3	127.5	44.4
32	144.2	42.4	145.4	42.[illegible]	104.6	45.4

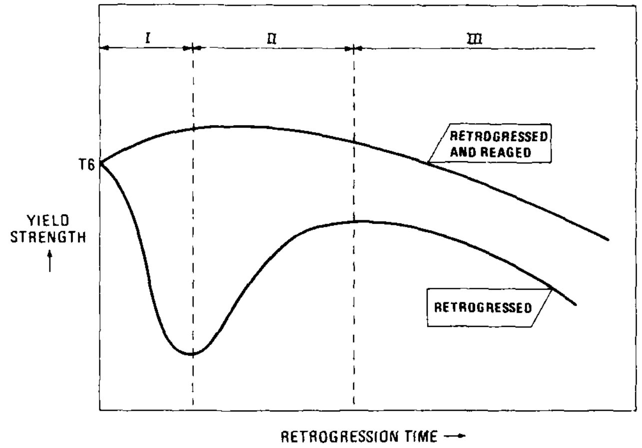


Fig. 10.1 Schematic of the retrogression and reageing process, showing the three stages of retrogression (reference 3)

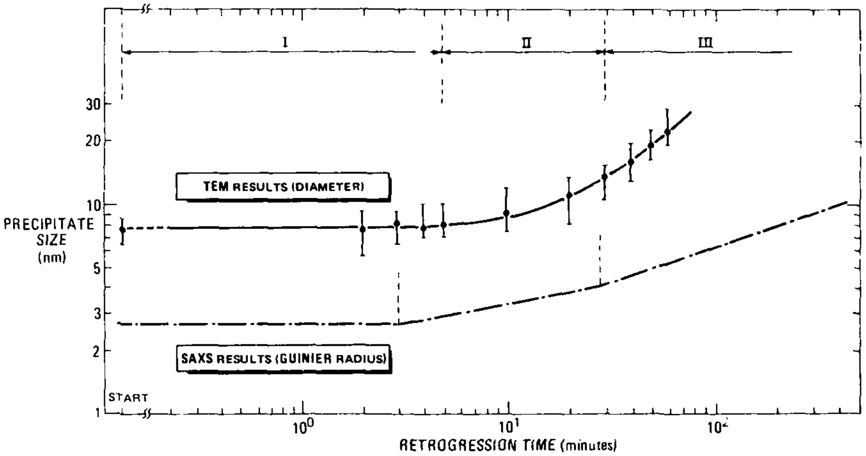
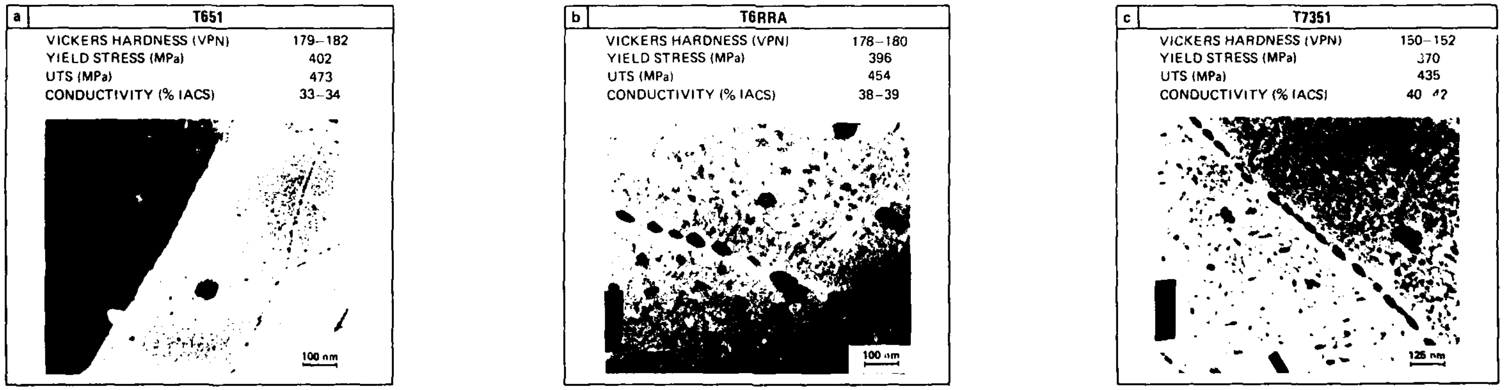


Fig. 10.2 Variation in size of the intragranular (matrix) η and η′ precipitates as a function of retrogression time at 473 K. Results from transmission electron microscopy (TEM) are compared with those from small angle X-ray scattering (SAXS), (reference 4)



T651	
VICKERS HARDNESS (VPN)	179–182
YIELD STRESS (MPa)	402
UTS (MPa)	473
CONDUCTIVITY (% IACS)	33–34

T6RRA	
VICKERS HARDNESS (VPN)	178–180
YIELD STRESS (MPa)	396
UTS (MPa)	454
CONDUCTIVITY (% IACS)	38–39

T7351	
VICKERS HARDNESS (VPN)	150–152
YIELD STRESS (MPa)	370
UTS (MPa)	435
CONDUCTIVITY (% IACS)	40–42

Fig. 10.3 Microstructures and mechanical properties (short transverse) for 7075 plate in the T761, T6RRA and T7351 conditions

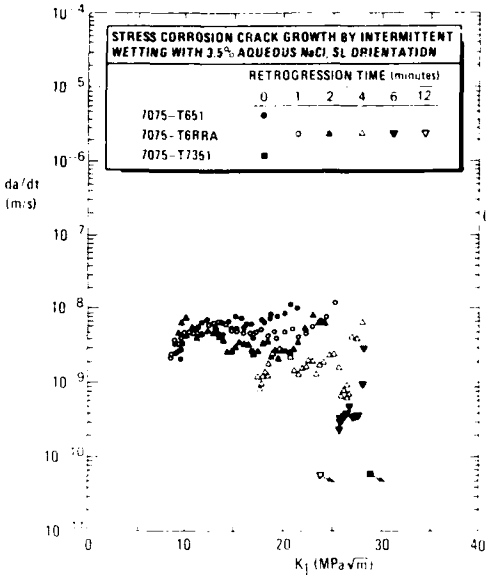


Fig. 10.4 Influence of retrogression time at 493 K on stress corrosion crack growth rates for 7075-T6RRA

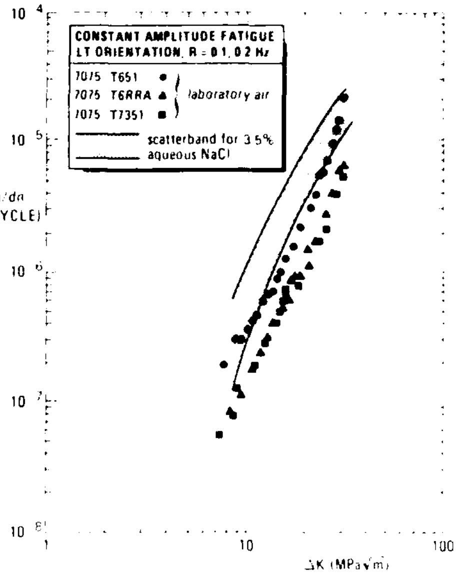


Fig. 10.5 Comparisons of constant amplitude fatigue and corrosion fatigue crack growth resistances of 7075-T651, T6RRA and T7351 sheet at 0.2 Hz

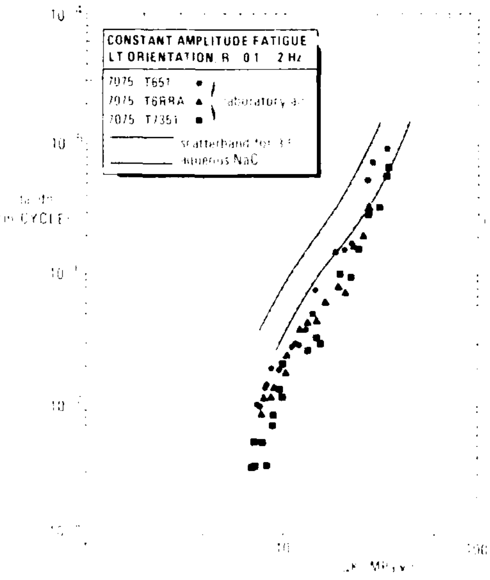


Fig. 10.6 Comparisons of constant amplitude fatigue and corrosion fatigue crack growth resistances of 7075-T651, T6RRA and T7351 sheet at 2 Hz

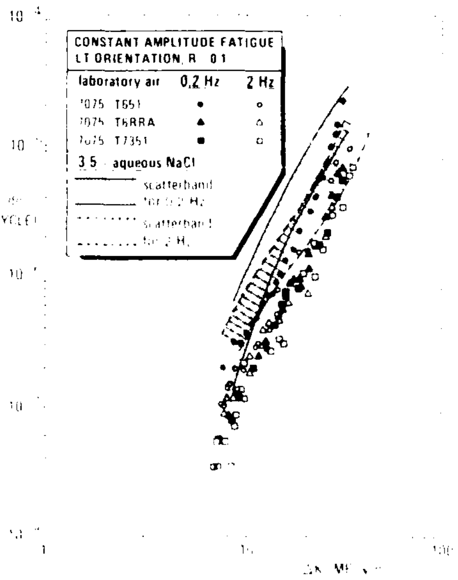


Fig. 10.7 Comparisons of constant amplitude fatigue and corrosion fatigue crack growth resistances of 7075-T651, T6RRA and T7351 sheet at different frequencies (0.2 and 2 Hz)

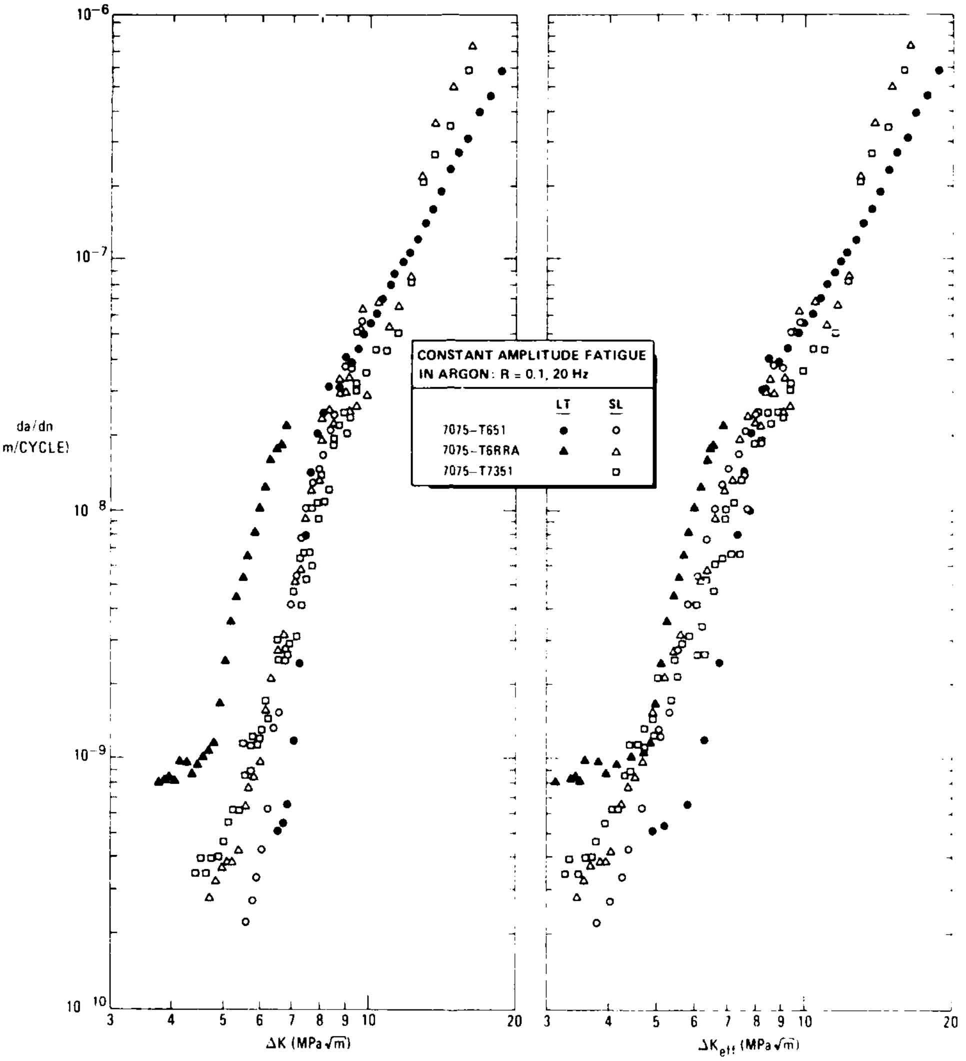


Fig. 10.8 Comparisons of constant amplitude fatigue crack growth resistances of 7075-T651, T6RRA and T7351 plate in dry argon

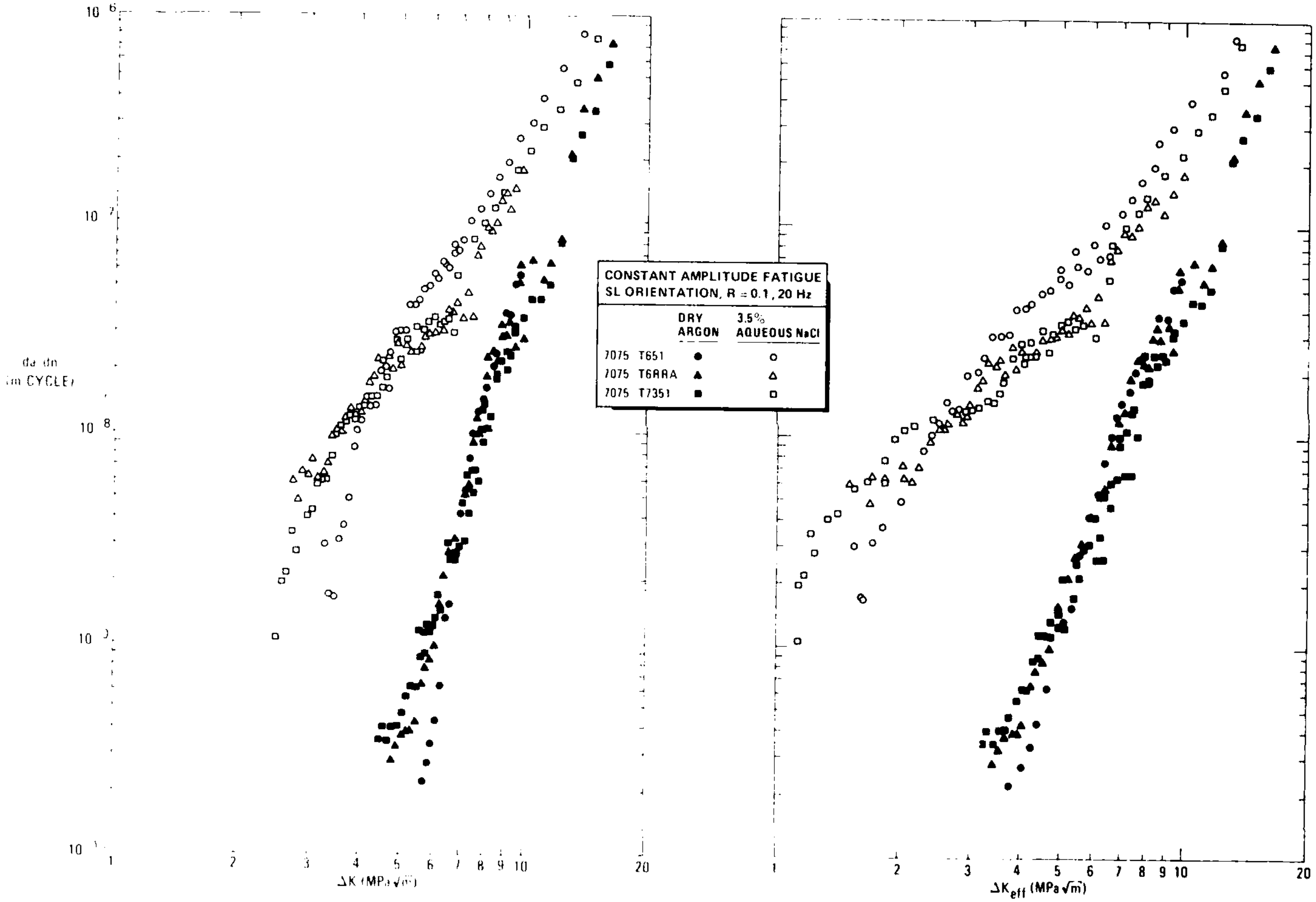


Fig. 10.9 Comparison of constant amplitude fatigue and corrosion fatigue crack growth resistances of 7075-T651, T6RRA and T7351 plate

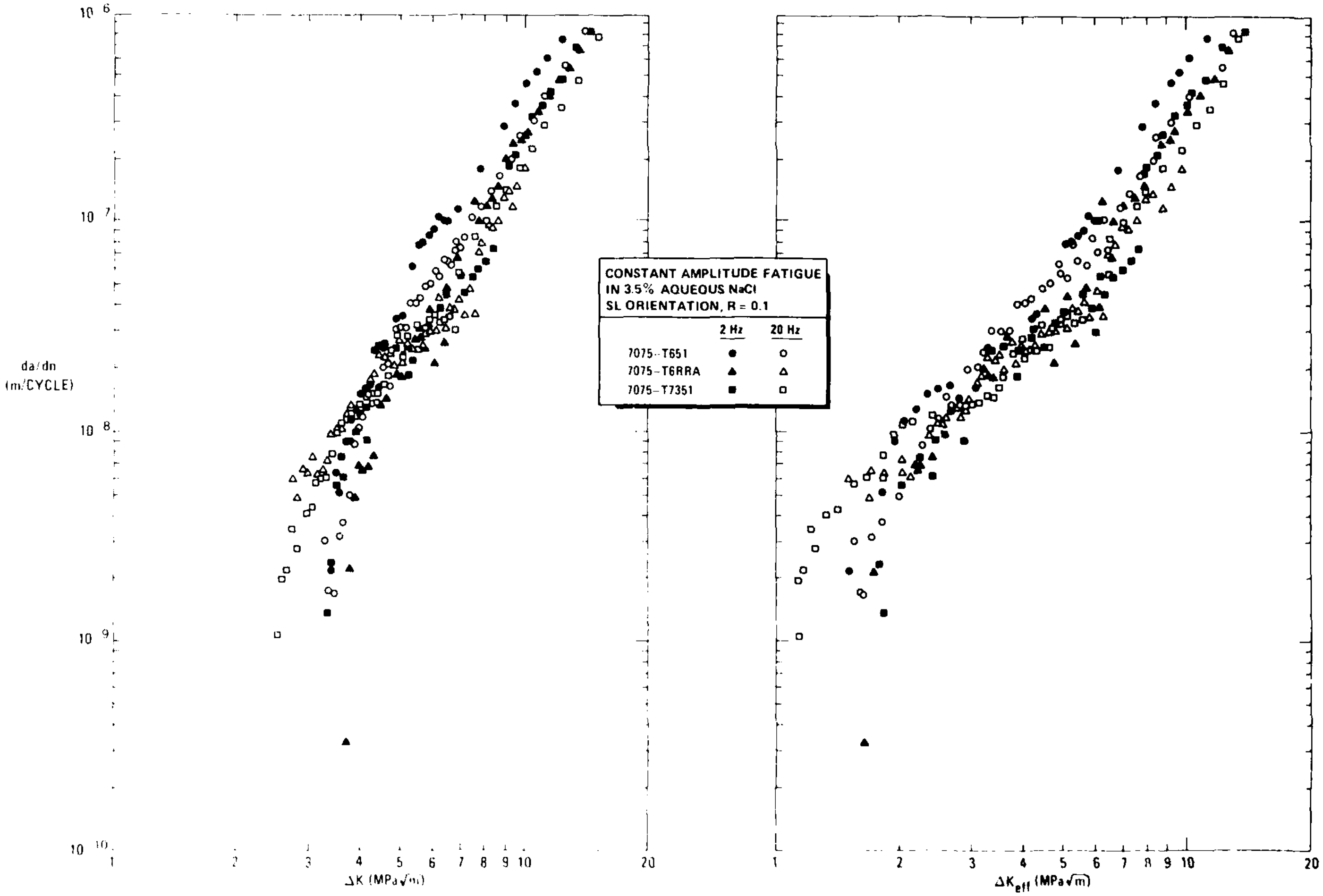


Fig. 10.10 Comparisons of constant amplitude corrosion fatigue crack growth resistances of 7075-T651, T6RRA and T7351 plate at different frequencies (2 Hz and 20 Hz)

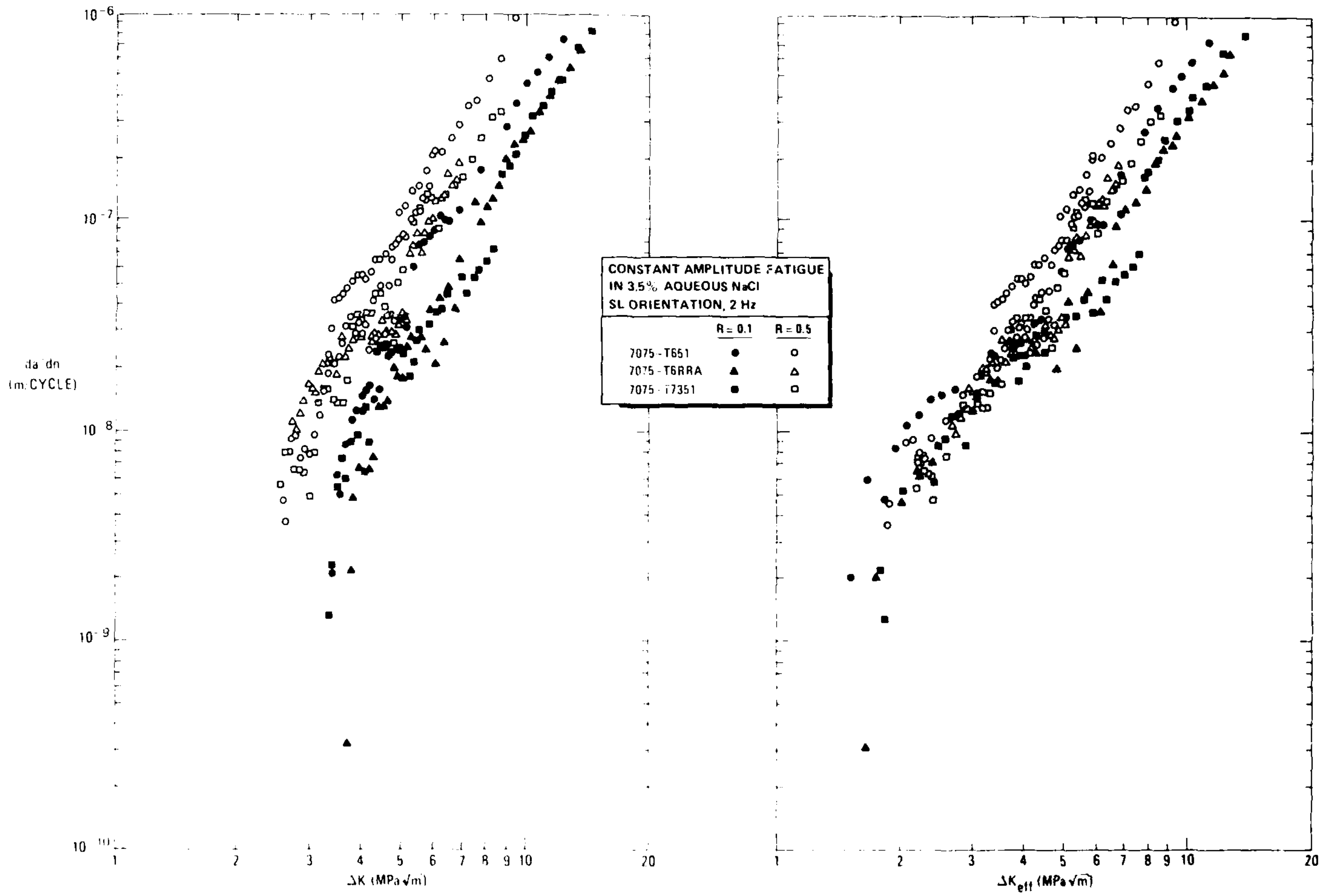


Fig. 10.11 Comparisons of constant amplitude corrosion fatigue crack growth resistances of 7075-T651, T6RRA and T7351 plate at different stress ratios (R = 0.1 and 0.5)

PART IV

EVALUATION OF THE CFCTP AND FACT PROGRAMMES

1. INTRODUCTION

In this final Part of the report we shall endeavour to assess the total effort involved in the CFCTP and FACT programmes. First we wish to thank the AGARD Structures and Materials Panel (SMP) for enabling the setting up of an internationally coordinated programme on corrosion fatigue. As figure 1 shows, this was a formidable task that has taken more than a decade to accomplish.

2. THE CFCTP CORE PROGRAMME

In Parts I and II of this report it was stated that the CFCTP core programme consisted of round-robin testing whose primary purpose was to establish whether participants could obtain confidence in one another's fatigue testing capabilities, especially when using a controlled atmospheric corrosion environment (salt spray). There were originally eight participants: NADC, University of Saskatchewan, VOUGHT, AFWAL, NLR, DFVLR, NDRE and RAE. These were subsequently joined by two more, SIFFRL and the University of Pisa.

The later participants obtained results significantly different from the rest. This was at least partly due to their being supplied with new specimens which, because they had to be redrilled from interference to press fit dimensions, turned out to have significantly inferior fatigue properties compared to the first batch. The differences are regrettable but instructive. They show how important and necessary it was to do the CFCTP core programme and, as first intended, to supply participants with specimens from one batch.

An innovative combination of statistical methods was used to analyse the CFCTP core programme data, both with respect to fatigue lives and the locations of primary origins of fatigue initiation and fracture. A detailed evaluation, described in Part II of this report, demonstrated the following:

(1) The original eight participants could be confident in one another's environmental fatigue testing capabilities. Thus the primary purpose of the CFCTP core programme was achieved.

(2) The first batch of CFCTP core programme specimens and the mechanical and environmental testing conditions were highly reproducible except for the way specimens were originally cleaned and dried after pre-exposure to acidified salt water. The cleaning and drying procedure was amended to be reproducible, and this amended procedure was stipulated for the FACT programme.

(3) Environmental effects on fatigue lives were significant and consistent. Most importantly it was found that environmental effects were greater at a higher stress level. This is the opposite of what many literature data show. This discrepancy is explained in section 4.2.1 of Part II and is due to the fact that the majority of specimens used in environmental fatigue testing are simple coupons, whereas the CFCTP specimens were designed to be realistic representations of a fatigue critical structural joint.

It is therefore concluded that realistic specimens are necessary for correct assessment of environmental fatigue effects.

(4) Examination of failed specimens to determine the locations of primary fatigue origins proved to be essential for understanding the fatigue behaviour.

3. THE FACT SUPPLEMENTAL PROGRAMME

As stated in Part III of this report, the intention of the FACT supplemental programme was to allow individual participants to investigate corrosion fatigue problems of particular relevance to their own interests and yet maintain a high degree of commonality. To achieve this it was recommended that

- the same specimen configuration (1½ dogbone) be used as for the CFCTP core programme
- mechanical and environmental testing conditions be identical
- efforts be made to obtain materials of mutual interest from one heat.

An overview of the FACT programme is given in figure 2. There were ten participants: VOUGHT, SAAB, NADC, AFWAL, NDRE, NLR, LRTH, IABG, RAE and NRC. Six had also taken part in the CFCTP core programme, namely VOUGHT, NADC, AFWAL, NDRE, NLR and RAE. Figure 2 shows similarities and commonalities in the individual programmes. Most participants tested 1½ dogbone specimens under nominally identical mechanical and environmental conditions. The fatigue loadings were constant amplitude, as in the CFCTP, the manoeuvre spectrum FALSTAFF (references 1-3) and the gust spectrum MINITWIST (reference 4). The environmental conditions generally included two or more of those in the CFCTP. Notable exceptions were in the SAAB and NRC programmes.

The main interest of several participants was to compare - in their individual programmes - the environmental fatigue properties of a number of aluminium alloys in various tempers. However, owing to the calibratory function of the CFCTP and the participants' active cooperation in obtaining the many similarities and commonalities within the FACT programme, it is possible to make inter-participant comparisons of materials, protection systems and fasteners as well. Furthermore, the total testing effort provided many data for comparing fatigue effects under constant amplitude and FALSTAFF loading, the latter being a realistic cyclic load history for tactical aircraft.

For detailed analyses of the results, discussions and conclusions of the individual contributions to the FACT programme we refer the reader to Part III of this report. Here we shall discuss inter-participant comparisons of materials, protection systems and fasteners in section 3.1, and comparisons of environmental fatigue effects under constant amplitude and spectrum loading in section 3.2.

3.1 Inter-Participant Comparisons of Materials, Protection Systems and Fasteners

The possibilities for inter-participant comparisons of materials, protection systems and fasteners are summarised in table 1. Comparisons of fatigue lives per fatigue testing schedule, load history and stress level are made in figures 3-6 and show the following:

(1) For constant amplitude fatigue at a higher stress level (S_{max} = 210 MPa) the fatigue lives of 7075-T6 and 7075-T76 specimens were equivalent. Fatigue lives were not significantly prolonged by the use of interference fit fasteners, a flexible primer (Koreflex) or interfay sealant.

(2) For constant amplitude fatigue at a lower stress level (S_{max} = 144 MPa) the rankings of materials, protection systems and fasteners depend on environment, except that 7075-T6 specimens had significantly shorter average fatigue lives than the rest.

For fatigue in air the fatigue lives of 7075-T6RRA, 7075-T76 and 7475-T761 clad specimens were equivalent. The use of interference fit fasteners (7075-T76) and interfay (7475-T761 clad) was beneficial to fatigue lives.

For pre-exposure + fatigue in salt spray the 7475-T761 clad specimens had longer average fatigue lives; 7075-T6RRA, 7075-T76 and 2024-T3 Alclad specimens had equivalent fatigue lives; and 7075-T6 specimens had shorter average fatigue lives. The use of interference fit fasteners and sealant in fastener holes (7075-T76) was not beneficial. However, interfay sealant prolonged the fatigue lives of 7475-T761 clad specimens.

(3) For FALSTAFF fatigue at a higher stress level (S_{max} = 289 MPa) the average fatigue lives of specimens with interfay sealant were longer (sealant in fastener holes was most probably not beneficial). The relatively good performance of 7075-T6 specimens is noteworthy. The reason for this may be that a high yield strength helps to postpone fatigue crack initiation at high stress levels.

(4) For FALSTAFF fatigue at a lower stress level (S_{max} = 238 MPa) the fatigue lives of most specimens were equivalent. The average fatigue lives of 7075-T6 specimens with the NF-5 protection system were shorter than the rest, including 7075-T6 specimens with the MRCA protection system and interfay sealant. Since these 7075-T6 specimens were from the same batch of material, it may be concluded that the MRCA protection system with interfay sealant enabled significantly longer fatigue lives than the NF-5 protection system. However, in general there was no consistent benefit from using an interfay sealant. Nor was the use of interference fit fasteners or sealant in fastener holes beneficial.

It is clear from the foregoing observations that there are no overall trends with respect to material and protection system rankings. Nevertheless, significant improvements in environmental fatigue resistance are obtainable through choice of improved materials, heat treatments and protection systems. In particular, the use of an interfay sealant can be recommended because it is sometimes very beneficial. There are several possible reasons for this. Inhibition of corrosion and fretting can postpone fatigue crack initiation at faying surfaces. And improved load transfer (via the sealant) can reduce the stress concentrations at fastener holes. This has been observed in preliminary work at the NLR using a SPATE 8000 thermoelastic stress analysis camera.

Since there are no overall trends with respect to materials and protection systems, it may be concluded that their evaluation requires realistic load histories, stress levels and environments. This conclusion adds to one in section 2 concerning the CFCTP core programme, namely that realistic specimens are necessary for correct assessment of environmental fatigue effects.

There was, however, an overall trend with respect to fastener fit. The use of interference fit Hi-Loks and SLEEVbolts instead of press fit Hi-Loks was not beneficial to fatigue lives. A similar result was obtained in the AGARD-coordinated Fatigue Rated Fastener Systems programme (reference 5) for specimens with moderate to high values of secondary bending ratio (SBR). As discussed in Appendix I, the SBR for 1½ dogbone specimens varies from 0.2 for press fit Hi-Loks to 0.4-0.5 for interference fit SLEEVbolts and Hi-Loks. Thus it is most likely that any potential improvement in fatigue life from using interference fit fasteners was counteracted by an increase in SBR.

In view of the foregoing, it may be questioned whether the 1½ dogbone specimen configuration is suitable for the evaluation of different fastener systems. Insofar as this specimen type is realistic for certain types of aircraft structural joints, the answer is yes. However the present results, i.e. no significant differences in fatigue lives for specimens with press and interference fit fasteners, should not be extrapolated to other types of joints, particularly those with low secondary bending ratios.

3.2 Inter-Participant Comparisons of Environmental Fatigue Effects

Inter-participant comparisons of environmental fatigue effects under constant amplitude and manoeuvre spectrum (FALSTAFF) loading at different stress levels are shown in figure 7. Environmental effects were greater at higher stress levels. This is the same trend found for the CFCTP core programme and, as mentioned in section 2, it is the opposite of what one would expect from literature data, which refer mostly to simple coupon specimens.

The reason for this discrepancy is as follows (see also section 4.2.1 of Part II of this report). Higher stress levels and environmental fatigue testing (pre-exposure + fatigue in salt spray) promoted fatigue initiation in the bores and at bore/faying surface corners of the fastener holes in 1½ dogbone specimens. On the other hand, lower stress levels favoured fatigue initiation at the faying surfaces. It is most likely that environmental effects will be greater when they promote characteristic failure modes. This explains why the observed environmental effects were greater - on the average - at higher stress levels.

As before, it is concluded that this distinct difference in environmental fatigue behaviour between simple coupons and 1½ dogbone specimens, which were designed to simulate an actual joint, shows that realistic specimens are necessary for correct assessment of environmental fatigue effects.

4. CONCLUSIONS AND RECOMMENDATIONS

The main objectives of the CFCTP and FACT programmes were:

- assessment of the effectiveness of state-of-the-art protection schemes for aluminium alloys with respect to corrosion fatigue and corrosion + fatigue
- stimulation of the development of new protection products, procedures and techniques
- bringing together researchers on both sides of the Atlantic in a common testing effort that would result in a better understanding of the corrosion fatigue phenomenon and the means of mitigating it for aerospace alloys
- enabling participating laboratories to add to their fatigue testing capabilities by using a controlled atmospheric corrosion environment.

This report demonstrates that the first, third and fourth objectives have been achieved. It also provides many data on a broad, international basis for achieving the second objective.

Much remains to be done to increase the understanding of aircraft corrosion fatigue and the effectiveness of protection systems. The incentive is present in the FACT programme results: significant improvements in corrosion fatigue resistance are obtainable.

The degree of improvement depends on specimen configuration, fatigue load history, stress level and environment. It is therefore essential to evaluate potential improvements in materials, protection systems and fasteners by testing realistic specimens under representative fatigue load histories with environments simulating mission service conditions as closely as possible.

5. REFERENCES

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4. H. Lowak, J.B. de Jonge, J. Franz and D. Schütz, "MINITWIST. A shortened version of TWIST", Combined Report of the LBF and NLR, NLR Miscellaneous Publication MP 79018 U, May 1979.

5. H.H. van der Linden, "Fatigue rated fastener systems", AGARD Report No. 721, November 1985.

TABLE 1: SUMMARY OF POSSIBILITIES FOR INTER-PARTICIPANT COMPARISONS OF MATERIALS, PROTECTION SYSTEMS AND FASTENERS PER FATIGUE TESTING SCHEDULE

FATIGUE LOAD HISTORY	CHARACTERISTIC STRESS LEVEL S_{max} (MPa)	FASTENER INSTALLATION CONDITIONS					
		fatigue in air			pre-exposure + fatigue in salt spray		
		press fit : dry	press fit : wet	interference fit : dry	press fit : dry	press fit : wet	interference fit : dry
constant amplitude, R = 0 1	210	CFCTP 7075-T76/U S NAVY		NADC 7075-T76/U S NAVY 7075-T76/Koroflex/U S NAVY RAE 7075-T6/Cr/acrylic/interfay 7075-T6/nonCr/acrylic/interfay	CFCTP 7075-T76/U S NAVY		NADC 7075-T76/U.S NAVY 7075-T76/Koroflex/U S NAVY RAE 7075-T6/Cr/acrylic/interfay 7075-T6/Cr/polyu/interfay 7075-T6/nonCr/acrylic/interfay 7075-T6/nonCr/polyu/interfay
	144	CFCTP 7075-T76/U S NAVY NDRE 7075-T76 (conv)/U S NAVY 7075-T6RRA/U S NAVY NLR 2024-T3 Alclad/F 28 7075-T6/NF 5 7475-T761 clad/F 16 7475-T761 clad/F 16/interfay		AFWAL 7075-T76/U S NAVY/SLEEVbolts	CFCTP 7075-T76/U S NAVY NDRE 7075-T76 (conv)/U S NAVY 7075-T6RRA/U S NAVY NLR 2024-T3 Alclad/F 28 7075-T6/NF 5 7475-T761 clad/F 16 7475-T761 clad/F 16/interfay	AFWAL 7075-T76/U S NAVY	AFWAL 7075-T76/U.S. NAVY/SLEEVbolts
FALSTAFF	284	NDRE 7075-T76 (conv)/U S NAVY 7075-T6RRA/U S NAVY NLR 7075-T6/NF 5 7475-T761 clad/F 16 7475-T761 clad/F 16/interfay IABG 7075-T76/U S NAVY	IABG 7475-T761 clad/MRCA/interfay 7075-T6/MRCA/interfay		NDRE 7075-T76 (conv)/U S NAVY 7075-T6RRA/U S NAVY NLR 7075-T6/NF 5 7475-T761 clad/F 16 7475-T761 clad/F 16/interfay IABG 7075-T76/U S NAVY	IABG 7475-T761 clad/MRCA/interfay 7075-T6/MRCA/interfay	
	[illegible]	AFWAL 7075-T76/U S NAVY NDRE 7075-T76 (conv)/U S NAVY 7075-T6RRA/U S NAVY NLR 7075-T6/NF 5 7475-T761 clad/F 16 7475-T761 clad/F 16/interfay IABG 7075-T76/U S NAVY	IABG 7475-T761 clad/MRCA/interfay 7075-T6/MRCA/interfay	AFWAL 7075-T76/U S NAVY/SLEEVbolts	AFWAL 7075-T76/U S NAVY NDRE 7075-T76 (conv)/U S NAVY 7075-T6RRA/U S NAVY NLR 7075-T6/NF 5 7475-T761 clad/F 16 7475-T761 clad/F 16/interfay IABG 7075-T76/U S NAVY	AFWAL 7075-T76/U S NAVY IABG 7475-T761 clad/MRCA/interfay 7075-T6/MRCA interfay	AFWAL 7075-T76/U S NAVY SLEEVbolts

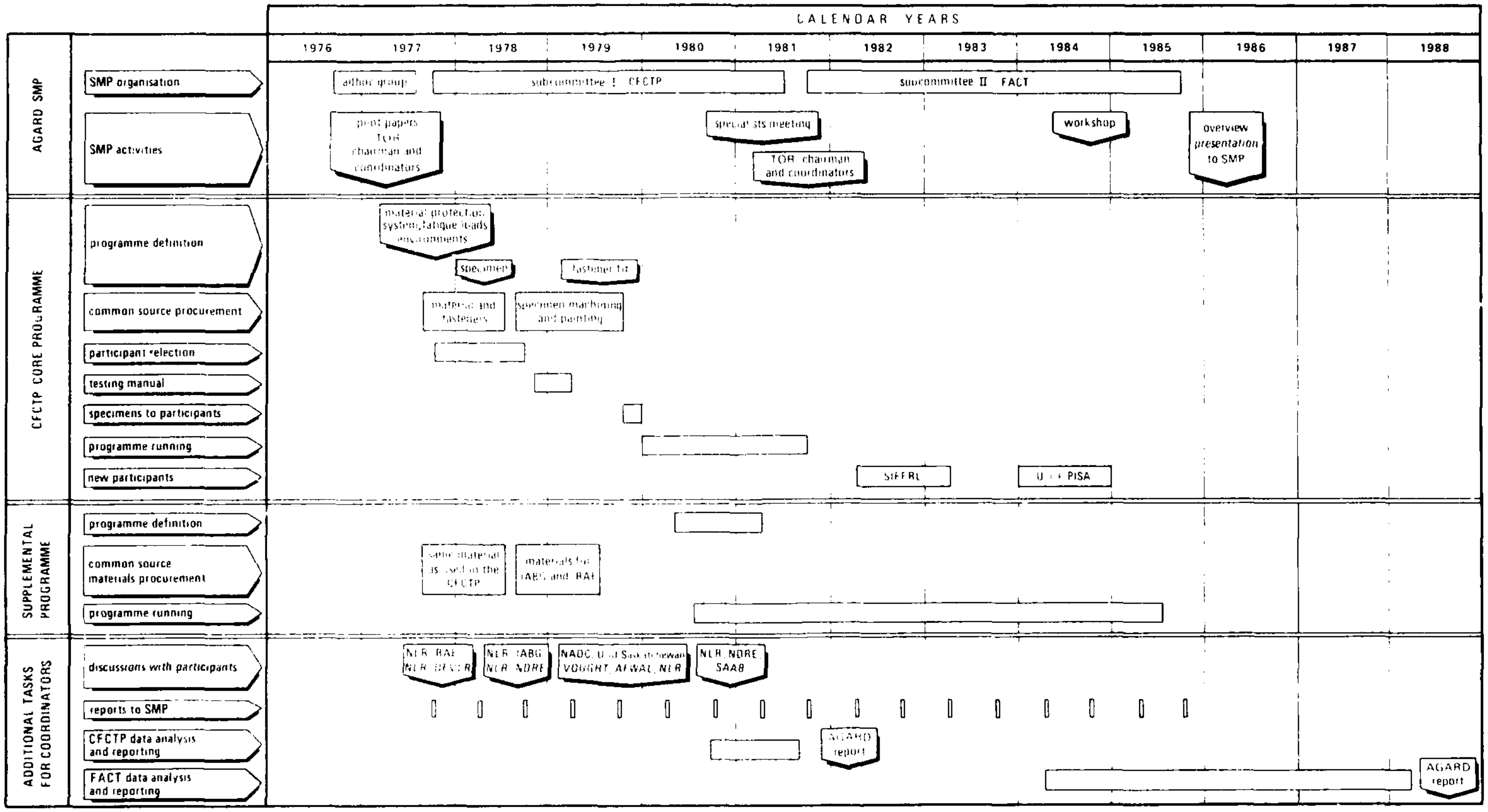

Fig. 1 Overview of the corrosion fatigue programme milestones and activities

PARTICIPANTS			VOUGHT	SAAB	NADC	AFWAL	NDRE	NLR/LRTH	IABG	RAE	NRC
MAIN ASPECTS OF THE INDIVIDUAL PROGRAMMES	IDENTICAL MATERIALS			●	●	●	◑	◑ ○	● ◑ ○	◑	
	IDENTICAL PROTECTION SYSTEM		●	●	●	●	●		●		
	MATERIAL COMPARISONS	DIFFERENT MATERIALS		●				●	●	●	●
		DIFFERENT HEAT TREATMENTS					●			●	●
	PROTECTION SYSTEM COMPARISONS			●	●	●		●	●	●	
	FASTENER COMPARISONS				●	●					
	FATIGUE LOAD HISTORY COMPARISONS					●	●	●		●	
TYPES OF TESTS	FATIGUE LIFE AND STRENGTH	1½ DOGBONE		●	●	●	●	●	●	●	
		NOTCHED COUPONS	●							●	
		UNNOTCHED COUPONS		●							
	FATIGUE CR[illegible] G[illegible]TH	CENTRE CRACKED TENSION (CCT)	●							●	●
		COMPACT TENSION (CT)									●
	FATIGUE LOADINGS	CONSTANT AMPLITUDE	●	●	●	●	●	●		●	●
		FALSTAFF				●	●	●	●	●	
		MINITWIST						●			
	ENVIRONMENTAL CONDITIONS	AS PER CFCTP	●		●	●	●	●	●	●	
		OTHER	●	●							●

Fig. 2 Overview of the FACT supplemental programme

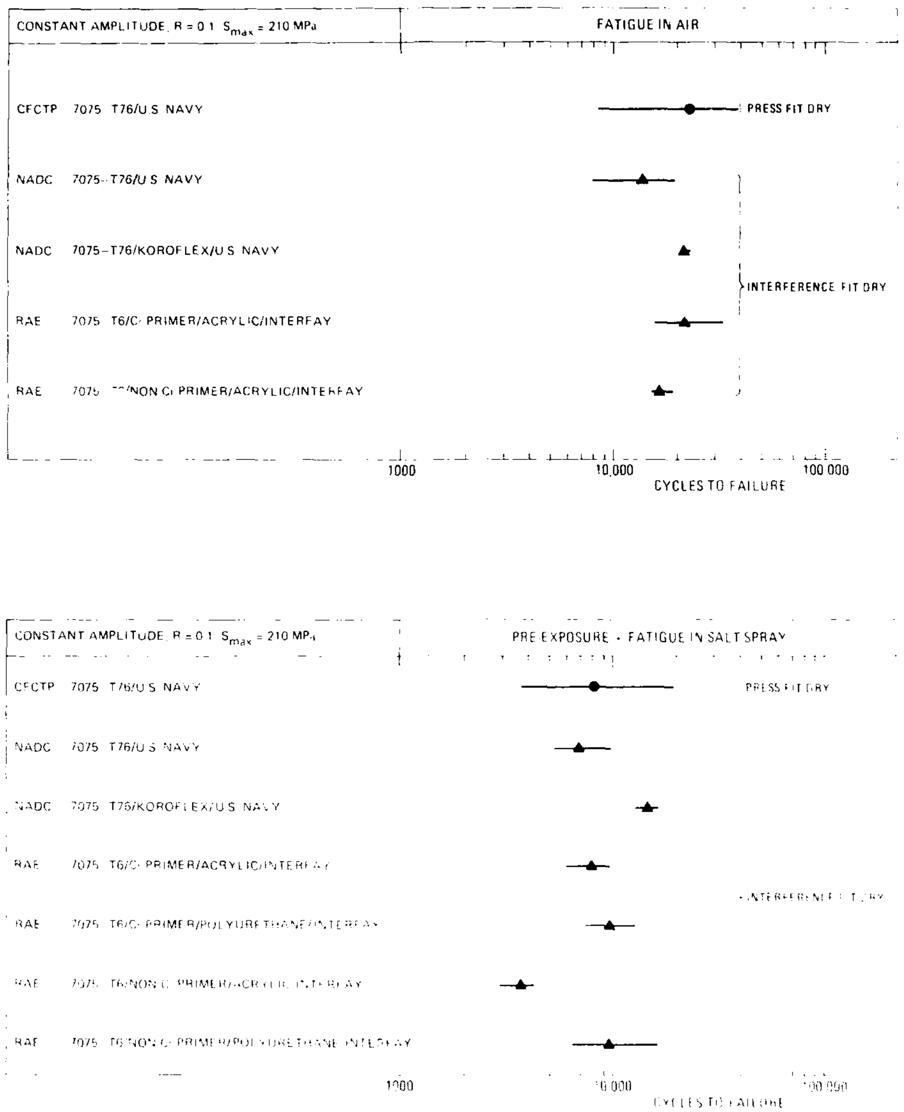

Fig. 3 Inter-participant comparisons of FACT and CFCTP constant amplitude fatigue lives at a higher stress level (S_{max} = 210 MPa). The CFCTP core programme data exclude specimens redrilled to press fit dimensions

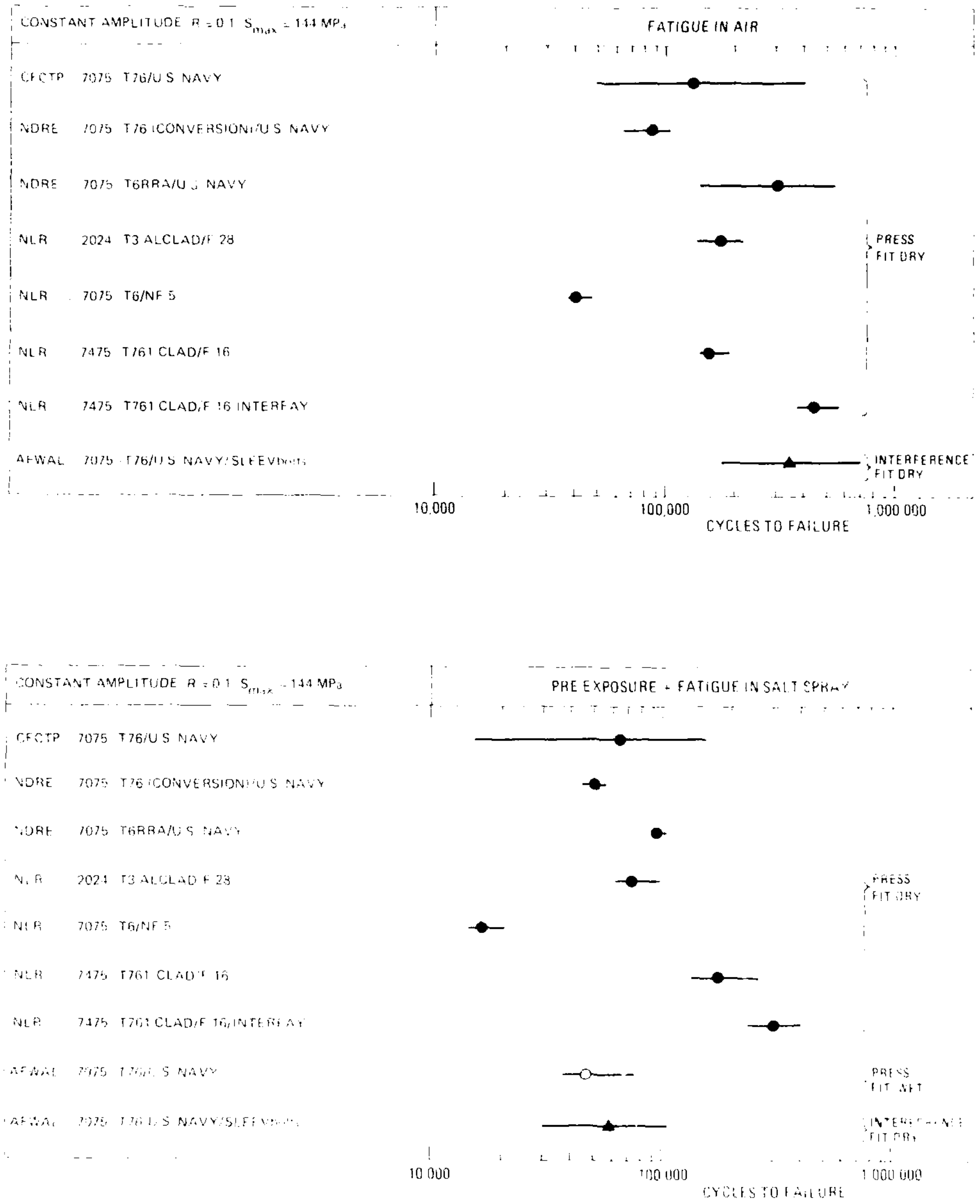

Fig. 4 Inter-participant comparisons of FACT and CFCTP constant amplitude fatigue lives at a lower stress level (S_{max} = 144 MPa). The CFCTP core programme data exclude specimens redrilled to press fit dimensions

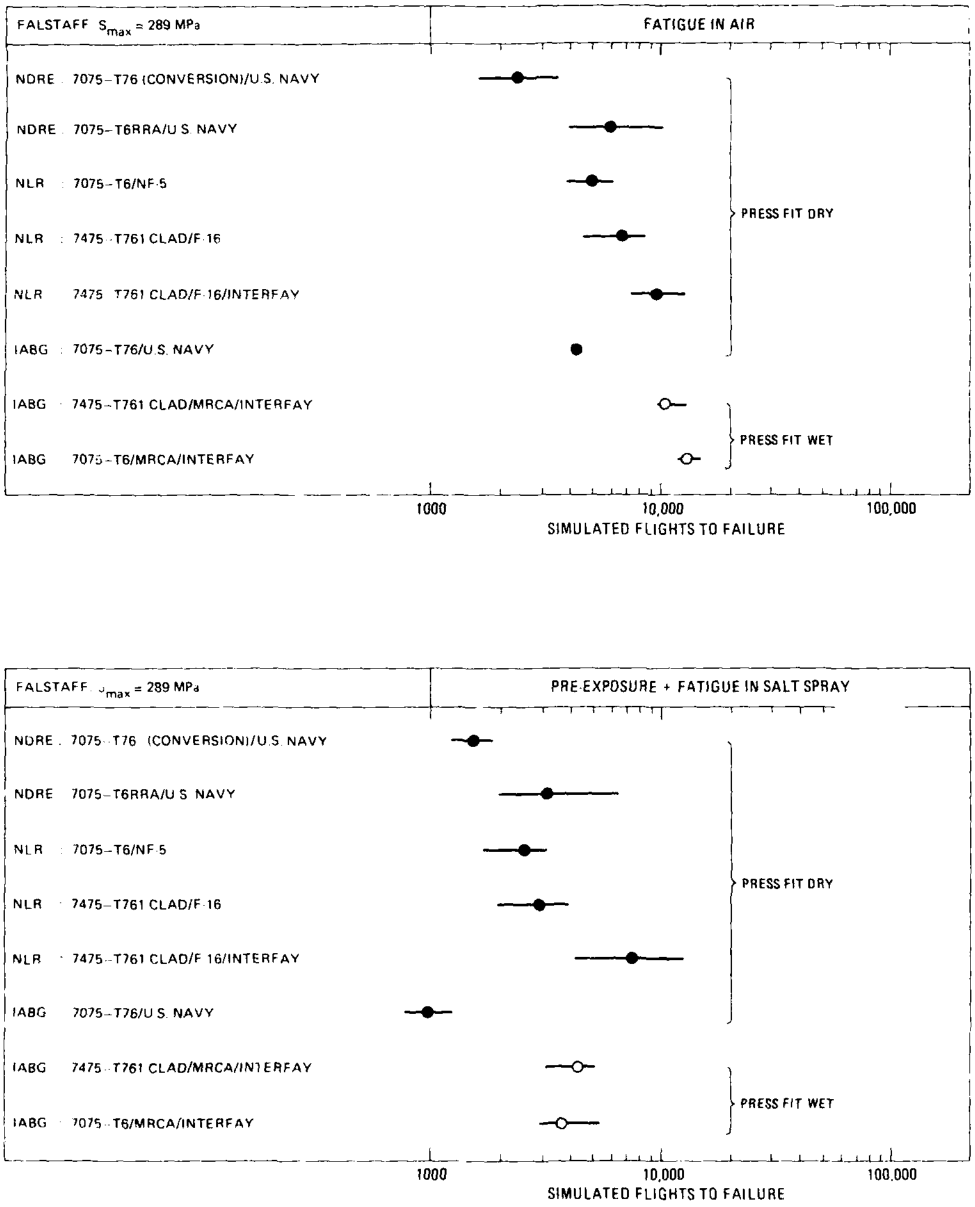

Fig. 5 Inter-participant comparisons of FACT manoeuvre spectrum (FALSTAFF) fatigue lives at a higher stress level (S_{max} = 289 MPa)

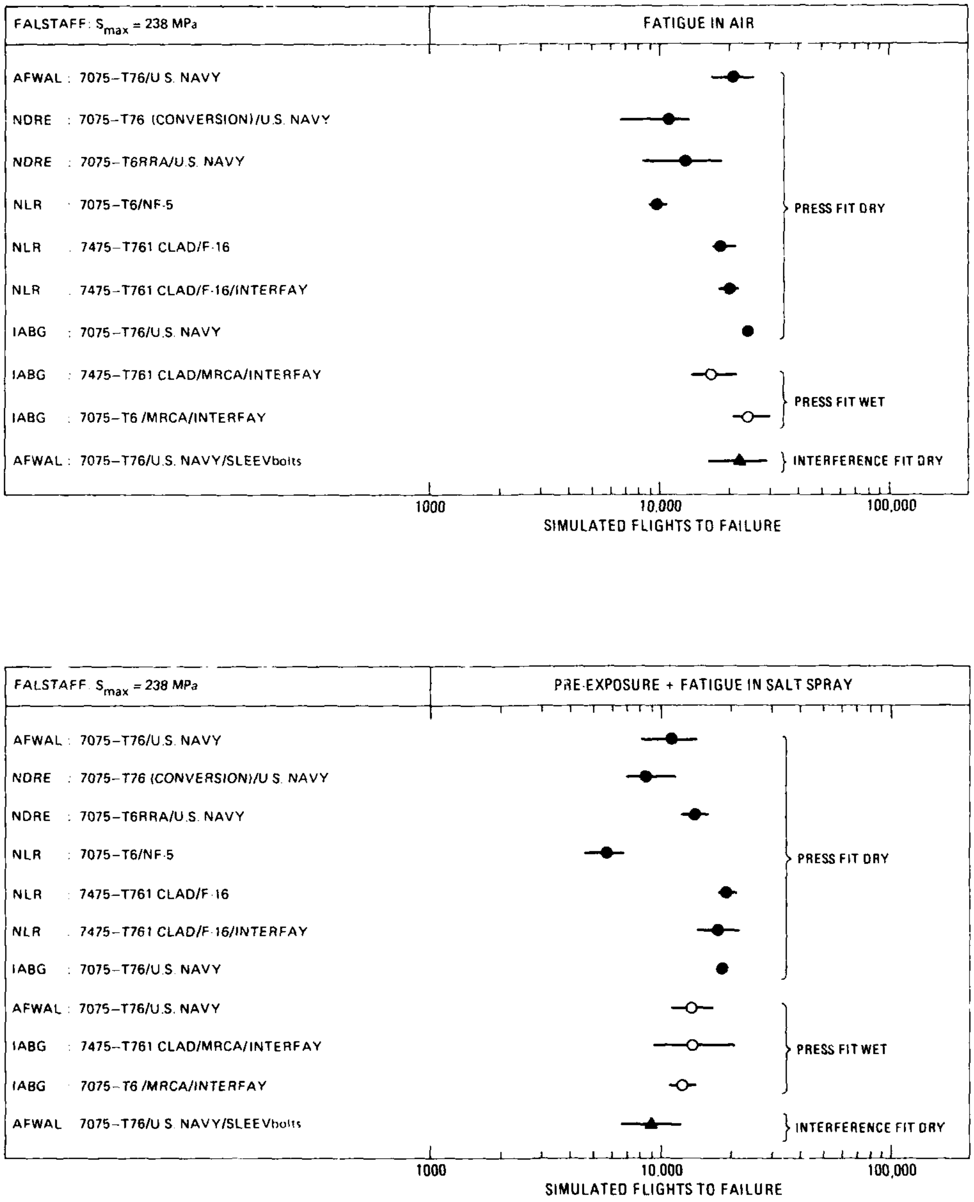

Fig. 6 Inter-participant comparisons of FACT manoeuvre spectrum (FALSTAFF) fatigue lives at a lower stress level (S_{max} = 238 MPa)

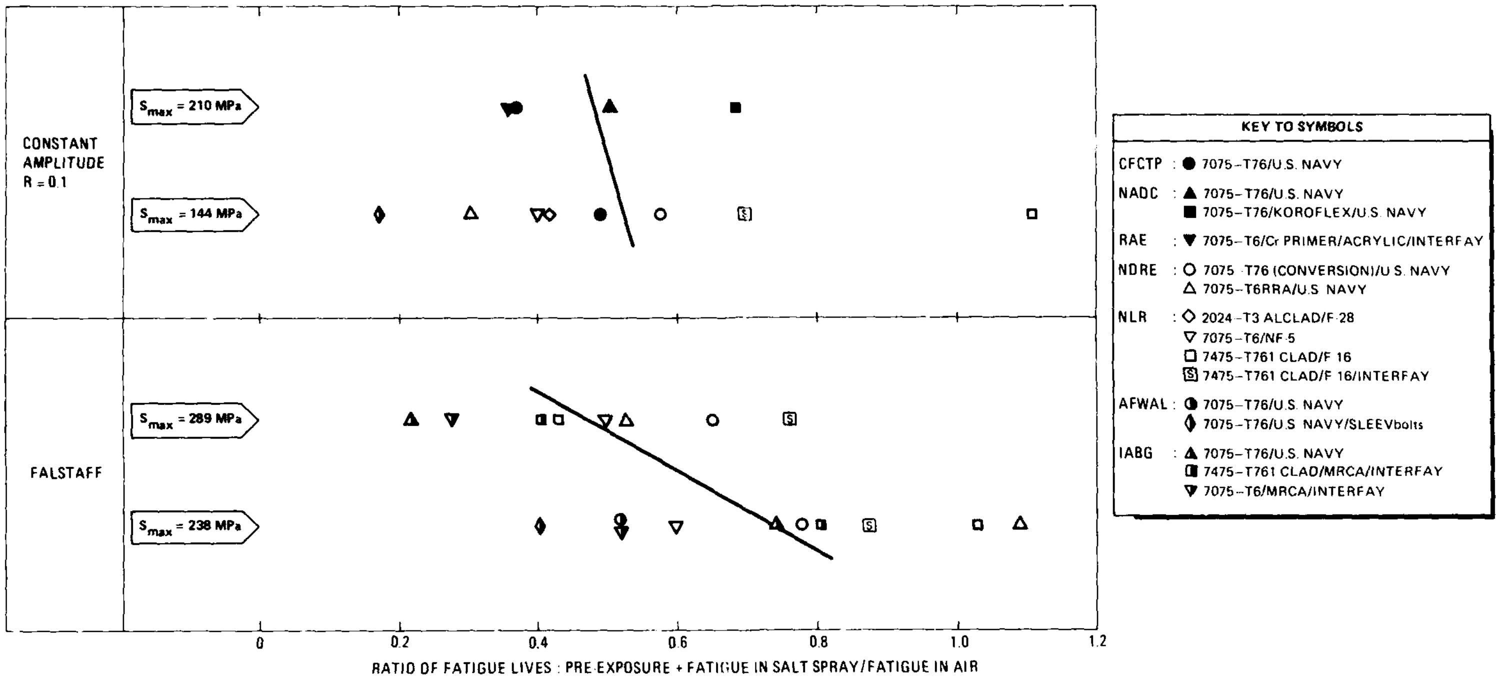

Fig. 7 Inter-participant comparisons of environmental fatigue effects. The CFCTP core programme data exclude specimens redrilled to press fit dimensions. RAE data for 7075-T6/non-Cr primer/acrylic/interfay are also excluded owing to faulty application of primer (see section 9.2.3 of part III of this report)

APPENDIX I

LOAD TRANSFER AND SECONDARY BENDING IN THE 1½ DOGBONE SPECIMEN

1. INTRODUCTION

This Appendix describes the load transfer and secondary bending characteristics of 1½ dogbone specimens similar to those used in the CFCTP core programme and recommended for the FACT supplemental programme. The CFCTP and FACT specimen configuration is illustrated in figure 1. The specimen configuration was designed to simulate the load transfer and secondary bending characteristics of runouts of stiffeners attached to the outer skin of an airframe structure. The design goals were a load transfer of 40 % and secondary bending ratio of 0.5 (reference 1). These parameters are defined in figure 2.

The NLR and the University of Pisa conducted a programme to determine the actual values of load transfer (LT) and secondary bending ratio (SBR) in 1½ dogbone specimens (references 2,3). This programme was based on specimen requirements for the AGARD-coordinated Fatigue Rated Fastener Systems (FRFS) programme (reference 2). The specimen configuration was identical to that in figure 1 except for the aluminium alloy sheet thickness and fastener fit, as follows:

	CFCTP AND FACT	LT AND SBR PROGRAMME	
ALUMINIUM ALLOY SHEET THICKNESS	3.2 mm	5 mm	
FASTENER TYPE	Hi-Lok	Hi-Lok	Hi-Tigue
NOMINAL FIT OF FASTENERS *	slight press : - 0.019 interference : - 0.077	clearance : + 0.020 interference : - 0.025	interference : - 0.070

* Dimensions in millimetres. + = clearance, - = interference.

Despite the differences in specimen configuration the results of the load transfer and secondary bending ratio programme are relevant to the behaviour of the 1½ dogbone specimens used in the CFCTP and FACT programmes.

2. OVERVIEW OF THE LOAD TRANSFER AND SECONDARY BENDING RATIO PROGRAMME

An overview of the load transfer and secondary bending ratio (LT and SBR) programme is given in table 1. The number, positions and dimensions of the strain gauges on the fatigue specimen -1 are important. A detailed discussion of these aspects is given in reference (2). An example of strain gaugeing the fatigue specimen -1 is given in figure 3a. The strain gauges and wire leads at the faying surface were accommodated by shallow recesses milled in the half plate -2, figure 3b.

The strain gauges were bonded to the fatigue specimens after priming and before assembly into 1½ dogbones. Assembly was done using the appropriate fasteners and with polysulphide sealant at the faying surfaces and in the fastener holes.

The specimens were fatigue cycled under constant amplitude loading with maximum stress S_{max} = 250 MPa and a stress ratio R = S_{min}/S_{max} of 0. Fatigue cycling was interrupted at fixed intervals, e.g. cycles 1, 5, 100, 1000, 5000 and 10,000, in order to measure strains in a "static" loading test with S_{max} = 250 MPa and S_{min} = - 67 MPa.

3. RESULTS

The results of the LT and SBR programme are compiled in references (2,3). Figure 4 presents characteristic values of load transfer and secondary bending ratio at S_{max} = 250 MPa. The following trends can be observed:

(1) Load transfer is almost independent of fastener fit, with a typical value of 27 %. This is lower than the design goal of 40 %.

(2) Secondary bending ratio depends strongly on fastener fit, reaching a maximum of about 0.47 for an interference fit of - 0.070 mm. Again the values are lower than the design goal of 0.5.

4. ESTIMATION OF LOAD TRANSFER AND SECONDARY BENDING RATIO IN THE CFCTP AND FACT SPECIMENS

Most 1½ dogbone specimens for the CFCTP and FACT programmes were assembled using Hi-Loks and a slight press fit resulting in a nominal interference of - 0.019 mm. The NADC, AFWAL and RAE contributions to the FACT programme also included specimens with higher interference fit fasteners, see sections 4, 5 and 9 of Part III of this report. Estimates of the load transfer and secondary bending characteristics of the three specimen types have been made using the LT and SBR programme data, specifically the correlations between fastener fit, load transfer and secondary bending ratio. These estimates are as follows:

	FASTENER TYPE	NOMINAL FIT OF FASTENERS *	S_{max} = 250 MPa	
			LOAD TRANSFER	SECONDARY BENDING RATIO
CFCTP AND FACT PROGRAMMES	Hi-Lok	slight press : - 0.019	24 %	0.20
NADC AND RAE CONTRIBUTIONS TO FACT	Hi-Lok	interference : - 0.077	30 %	0.51
AFWAL CONTRIBUTION TO FACT	SLEEVbolt	interference : - 0.064	29 %	0.44

* Dimensions in millimetres. - = interference.

5. REFERENCES

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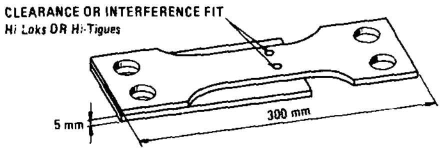
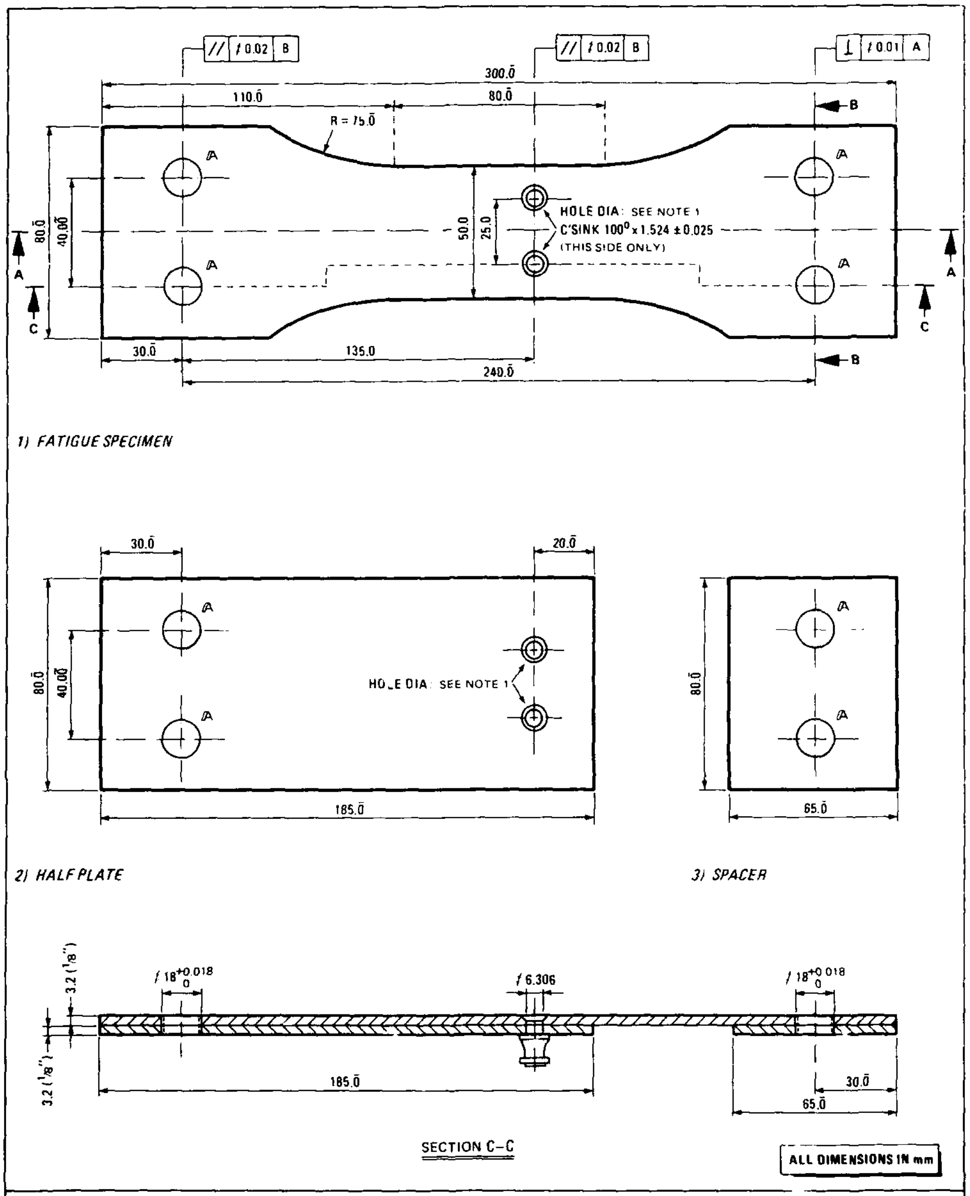
2. H.H. van der Linden, "Fatigue rated fastener systems", AGARD Report No. 721, November 1985.

3. H.H. van der Linden, L. Lazzeri and A. Lanciotti, "Fatigue rated fastener systems in 1½ dogbone specimens", NLR Technical Report TR 86082 U, August 1986.

TABLE 1: OVERVIEW OF THE LOAD TRANSFER AND SECONDARY BENDING RATIO PROGRAMME

MATERIAL	• 5 mm thick 7075-T76 aluminium alloy sheet
SPECIMEN	• 
FASTENER HOLE QUALITY	• Reamed with or without prior cold work
PROTECTION SYSTEM	• Chromate containing epoxy primer + polysulphide sealant in fastener holes and at interfays
SPECIMEN INSTRUMENTATION	• Strain gauges on fatigue specimen -1
LOADING CONDITIONS	• Constant amplitude fatigue cycling with intermittent measurements of strains
TEST PROGRAMME	•

REFERENCE	2		3	
NUMBER OF STRAIN GAUGES PER SPECIMEN	18		22	
FASTENER HOLE QUALITY	reamed	cold worked + reamed	reamed	cold worked + reamed
FASTENER	Hi-Lok	Hi-Lok	Hi-Tigue	Hi-Tigue
FASTENER FIT	clearance	low interference	high interference	high interference



NOTES

(1) HOLE DIAMETERS 6.306 ±0.044 mm FOR CORE PROGRAMME SPECIMENS (SLIGHT PRESS FIT).
HOLE DIAMETERS 6.248 ± 0.0127 mm (INTERFERENCE FIT) OR 6.306 ± 0.044 mm (SLIGHT PRESS FIT) FOR SUPPLEMENTAL TESTING SPECIMENS.

(2) ALL HOLES MARKED THUS " A " ARE $18^{+0.018}_{0}$ mm DIAMETER.

(3) *SPECIAL TOLERANCE INDICATIONS ARE*. $25.0 = 25 \pm 0.05$
$25.\bar{0} = 25 \pm 0.1$
$25.\tilde{0} = 25 \pm 0.2$

Fig. 1 The CFCTP core programme and recommended FACT supplemental programme specimen

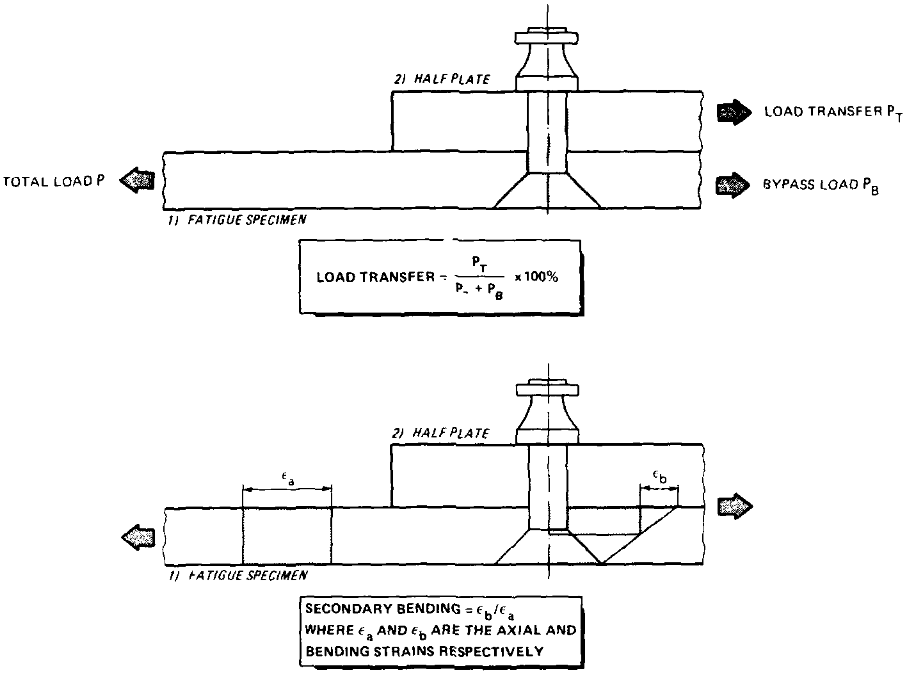


Fig. 2 Definition of load transfer and secondary bending for the 1½ dogbone specimen

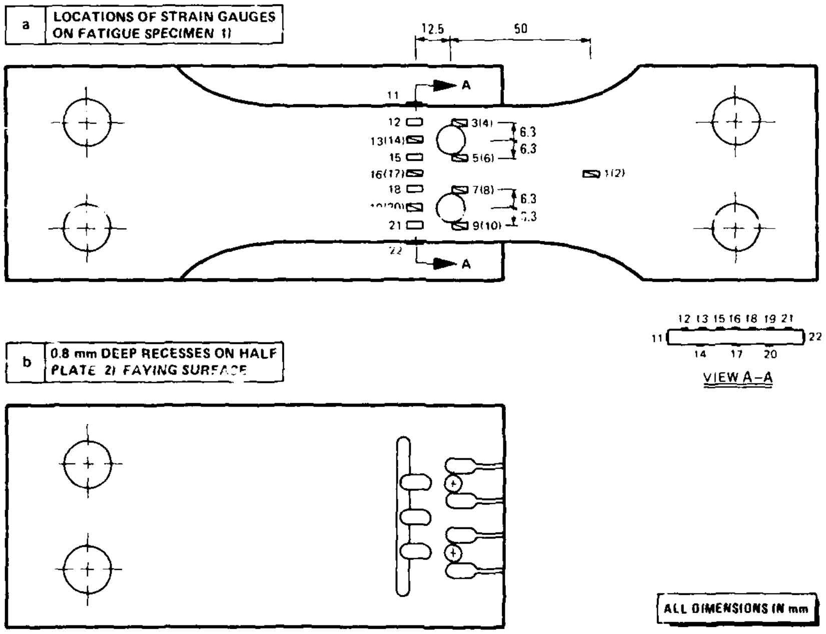


Fig. 3 Example of strain gaugeing a 1½ dogbone specimen for measurement of load transfer and secondary bending ratio

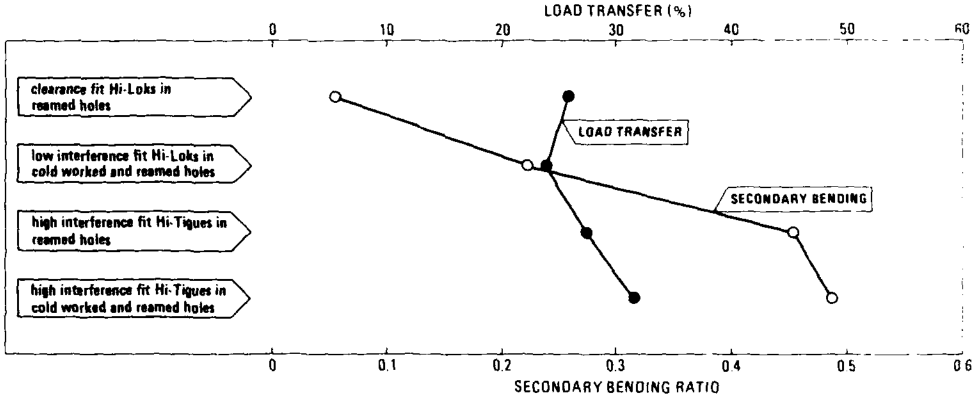


Fig. 4 Load transfer and secondary bending characteristics of 1½ dogbone specimens at $S_{max} = 250$ MPa

APPENDIX II

STATISTICAL METHODS

1. INTRODUCTION

The statistical methods used to analyse the CFCTP core programme and FACT supplemental programme data are described in this Appendix. It is sufficient to refer to the procedure used for the CFCTP core programme since the methods were the same, although the amount of statistical analysis for the FACT programme varied according to each participant's contribution.

A survey of the statistical methods and procedure for analysing the CFCTP core programme fatigue life and primary fatigue origin data is given in figure 1. The fatigue life data were first checked for normality and homogeneity of variances (approximate compliance with these conditions is sufficient) as a prerequisite to further treatment. The main analysis was multiple factor analysis of variance. This was followed by "fine tuning" using the least significant difference test or Duncan's new multiple range test. To avoid possible misuse the least significant difference test was applied only when analysis of variance indicated significant effects. Duncan's new multiple range test can be used whether or not analysis of variance indicates significant effects. However, because the least significant difference test is more powerful it was decided to use Duncan's test only when analysis of variance did not indicate significant effects. In addition the Lipson and Sheth method was used to check for adequate sample size based on scatter in the fatigue life data.

The primary fatigue origin data were analysed using the χ^2 test of independence, Yates' corrected χ^2 test or Fisher's exact test, whichever was appropriate. For these tests it is sufficient to assume only that the data constitute a random sample. These tests were also used (as appropriate) to check whether there were significant correlations between fatigue lives and primary fatigue origins for each of the eight combinations of fatigue stress levels and testing schedules, which are given here for reference:

S_{max} MPa	CFCTP CORE PROGRAMME FATIGUE TESTING SCHEDULES			
	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray
[illegible]	●	●	●	●
[illegible]	●	●	●	●

2. CHECKING FOR NORMALITY

To check for normality the CFCTP core programme data were considered to belong to eight different populations corresponding to each of the fatigue test conditions referred to above. In the first instance the data were plotted on probability paper and subjectively evaluated as discussed in section 2.1. Then the χ^2 test for goodness of fit (reference [illegible]) was used for statistical evaluation of the data. This is illustrated in section 2.2.

2.1 Graphical Procedure for Test of Normality

A set of forty fatigue life data was available for each of the eight fatigue test conditions. Each data set represented four specimens tested by each of the ten participants in the CFCTP core programme. The data sets were arranged in ascending order of fatigue lives, which were assigned median ranks for a sample size of n = 40. Tables of median ranks are compiled e.g. in reference [illegible]. Median ranks correspond to cumulative probabilities of failure and were plotted against the fatigue lives on arithmetic normal and logarithmic normal probability paper.

An example is given in table 1. A straight line fits the data when plotted on logarithmic normal probability paper, but not when plotted on arithmetic normal probability paper. This means that the data approximate to a log-normal distribution and may be treated in the same way as random variables in a normal distribution provided that the logarithm of each datum is used.

2.2 χ^2 Test for Goodness of Fit

The χ^2 test for goodness of fit involves testing the hypothesis that the distribution function F(x) of a sample approximates the distribution function F(x) of the population. To decide this it is necessary to know how much F(x) can differ from F(x) without invalidating the hypothesis. A summary of the procedure involved in the χ^2 test is given here:

(1) Subdivide the sample into K intervals such that each interval contains at least 5 values.

(2) Determine the number of sample values f_o in each interval.

(3) Using F(x) compute the number of sample values f_t theoretically expected in each interval if the hypothesis is true.

(4) Compute the deviation $\chi_o^2 = \sum \frac{(f_o - f_t)^2}{f_t}$.

(5) Choose a significance level α (e.g. 5 %, 1 %).

(6) Determine the solution c of the equation $P\ (\chi^2 \leq c) = 1-\alpha$ from the appropriate value of χ^2 in the table of the χ^2 distribution (included in most standard texts on statistics). The appropriate value of χ^2 is listed under the chosen value of α and for

- K-1 degrees of freedom if all parameters of F(x) are known
- K-r-1 degrees of freedom if r parameters of F(x) are unknown *and their maximum likelihood* estimates are used.

(7) If $\chi_o^2 \leq c$, *do not* reject the hypothesis. If $\chi_o^2 > c$, reject the hypothesis.

An example using CFCTP core programme data is given in table 2. This shows that the data approximate to a log-normal distribution and may be treated in the same way as random variables in a normal distribution provided that the logarithm of each datum is used.

3. TESTING FOR HOMOGENEITY OF VARIANCES

There are several methods of testing for homogeneity of variances. For the CFCTP core programme two tests were used, both of which are discussed in reference (4):

(1) Bartlett's test, which is used when the sample size is large.

(2) Box's test, which is a modified version of Bartlett's test and used when the number of degrees of freedom of any sample variance is less than 4.

The objective of these tests is to check the hypothesis that the variances σ^2 of k populations are equal. This is done by estimating the variances s^2 for each of the k samples and following the computational procedures outlined in table 3, which is almost self-explanatory. The two tests are quite similar. The statistic used in Bartlett's test is

$$\chi_o^2 = \frac{K}{1+L} \qquad \text{with } \nu_1 \text{ degrees of freedom}$$

or

$$F_o = \frac{\chi_o^2}{\nu_1} = \frac{K/\nu_1}{1+L} \qquad \text{with } \nu_1 \text{ and } \infty \text{ degrees of freedom.}$$

Box's test changes *the denominator of the statistic* F_o *as follows:*

$$F_o = \frac{K/\nu_1}{D/\nu_2} \qquad \text{with } \nu_1 \text{ and } \nu_2 \text{ degrees of freedom.}$$

Note that for large samples Bartlett's test and Box's test are consistent with each other.

The calculated values χ_o^2 and F_o are compared with appropriate values of χ^2 and F in tables of the χ^2 and F distribution (included in most standard texts on statistics). The appropriate values of χ^2 and F are listed under the chosen significance level α and for ν_1 and ν_1, ν_2 degrees of freedom respectively. If χ_o^2 and F_o are less than or equal to the respective χ^2 and F values, the hypothesis that the variances σ^2 of the k populations are equal is not rejected. If χ_o^2 and F_o are greater than the respective χ^2 and F values, the hypothesis is rejected.

Examples of the use of Bartlett's test and Box's test for the CFCTP core programme data are given in table 4. The logarithms of the fatigue lives were used for all calculations since both tests assume normality.

4. ANALYSIS OF VARIANCE

Analysis of variance is a statistical technique for comparing three or more sets of experimental data to determine the effect of various factors (experimental variables) on some characteristic of a product or specimen. The analysis is based on separating the total variation present in the data sets into parts, each of which measures variability attributable to a specific source.

Three-way analysis of variance was used for the CFCTP core programme. In a three-way analysis of variance, which evaluates the simultaneous effects of three factors, the sources of variation are variations due to each main factor, interacting factors, and residual (experimental) error. The parts of the variance are analysed (hence the name: analysis of variance) for significant differences between the data sets by comparing their means. Thus the hypothesis tested is that the means of k populations from which k samples are obtained are equal.

The procedure for testing this hypothesis is illustrated schematically in table 5 for a fairly simple three factor experiment. The three main factors are assigned to columns (c), rows (r) and groups (g). In the computations the sums of the squares and mean squares are determined for each main factor, the two-way interactions, the three-way interaction and the residual error term. The ratio of each mean square to the residual mean square provides values of the statistic F_o, which is then compared with appropriate F values from the F distribution table. When F_o is greater than F the influence of a factor or combination of factors on the data is considered significant. When F_o is less than or equal to F any differences in means are indicated to be due to chance or experimental error only.

Certain assumptions are necessary when analysis of variance is used. These are:

(1) The data represent random samples from normally distributed populations.

(2) The variances of these populations are equal.

Failure to meet these assumptions may affect the validity of the analysis. However, the F distribution is very robust, i.e. "forgiving", with respect to violation of the assumptions, so that moderate violations should not affect the outcome of the analysis. For the CFCTP core programme the data were found to be log-normal or to approximate log-normal distributions, and there were only a few slight-to-moderate violations of the criteria for homogeneity of variances (see sections 3.2.1 and 3.2.2 of Part II of this report). These results were considered sufficient for continuing the statistical treatment of the fatigue life data provided that the logarithms of the fatigue lives were used.

Table 6 gives a schematic of the three-way analysis of variance for the CFCTP core programme. The input data are much more extensive than the schematic three factor experiment plan in table 5. This is why the analysis was done using a computer program called "ANOVA", which is part of the well-known Statistical Package for the Social Sciences (reference 5).

5. "FINE TUNING" WITH THE LEAST SIGNIFICANT DIFFERENCE TEST

As shown in figure 1, significant effects indicated by analysis of variance were investigated in more detail ("fine tuning") using the least significant difference test (references 6,7). From table 6 the significant effects indicated by analysis of variance were

- laboratory
- stress
- environment
- stress: environment.

However, it was not necessary to analyse the effect of stress level in more detail. Since there were only two stress levels it is obvious that the significant difference is between them.

The least significant difference test locates the source or sources of the significant difference in the data. This is done by comparing all possible combinations of two means in the k samples in order to determine which of the ½k (k-1) comparisons are significant and which are not. The test is based on the statistic t, which can be expressed as

$$t = \frac{\bar{x}_i - \bar{x}_j}{\sqrt{MS_{residual}\left(\frac{1}{n_i} + \frac{1}{n_j}\right)}}$$

where $\bar{x}_i$ and $\bar{x}_j$ are the means of two samples of sizes n_i and n_j respectively, and $MS_{residual}$ is the residual mean square obtained from analysis of variance (see table 5). The procedure for the least significant difference test is given in table 7 for the usual case of equal sample sizes and in modified form for unequal sample sizes. Tabulated values of the t distribution for various significance levels and degrees of freedom are included in most standard texts on statistics. The criteria for indication of a significant difference between two means are

$$| \bar{x}_i - \bar{x}_j | > LSD_\alpha$$

or

$$| t | > t_{0.5\alpha;\nu_{residual}} .$$

Examples of the use of the least significant difference test to locate the source or sources of a significant effect indicated by analysis of variance are given in table 8. Note that omission of data for reassembled specimens resulted not only in unequal sample sizes, but also changed the values of $MS_{residual}$ and $\nu_{residual}$ obtained from analysis of variance. In other words, one cannot simply omit data in the "fine tuning" stage. A complete reanalysis of variance has to be done as well.

6. "FINE TUNING" WITH DUNCAN'S NEW MULTIPLE RANGE TEST

As shown in figure 1, Duncan's new multiple range test (references 8,9) was used to investigate in more detail the *experimental variables, or their interactions,* that were not found to be significant by analysis of variance. From table 6 these are

- laboratory: stress
- laboratory: environment
- laboratory: stress: environment.

However, it should be noted that Duncan's test can be used whether or not the analysis of variance indicates a significant *effect*. Like the least significant difference test, Duncan's new multiple range test locates the source or sources of the significant difference in the data by comparing all possible combinations of two means in the k samples in order to *determine* which of the $\frac{1}{2}k\ (k-1)$ comparisons are significant and which are not. The test is based on the range of the k means, i.e. the difference between the smallest and largest means of the samples involved in a comparison. The *difference between* any two ranked means is significant if it exceeds a shortest significant range (SSR).

The procedure *for Duncan's test is best illustrated* using actual examples from the CFCTP core programme. Table 9 gives an example for the usual case of equal sample sizes. As shown in the table, the procedure consists of the following steps:

(1) Rank the means and calculate the standard error of the mean $s_{\bar{x}}$ from the residual mean square $MS_{residual}$ (*obtained from analysis* of variance) and the sample size n.

(2) Choose a significance level α and determine the *significant* studentized ranges z for appropriate values of p, the number of means involved in a comparison, and $\nu_{residual}$ degrees of freedom. Tables of z values are available e.g. in references (8,9).

(3) Calculate the shortest significant ranges SSR from the products of $s_{\bar{x}}$ and the appropriate z values.

(4) Test the differences between means in the following order: largest minus the smallest, largest minus the second smallest, and so on, ending with the second smallest minus the smallest. With one exception each difference is declared significant if it exceeds the corresponding SSR, otherwise *it is declared insignificant. The exception* is that no difference between two means can be declared significant if they are both contained in a sub-set of means which has a non-significant range. Thus as soon as a non-significant *difference* between two means is found, the remaining differences between these means and all the intervening ones are insignificant and need not be tested against the SSR. However, this testing is shown for completeness in table 9.

Table 10 gives an example of Duncan's test for unequal sample sizes. The procedure is much the same as for equal sample sizes except that $s = \sqrt{MS_{residual}}$ is used *instead* of $s_{\bar{x}}$ and the difference between two means $\bar{x}_i$ and $\bar{x}_j$ is multiplied by $\sqrt{\frac{2n_i n_j}{n_i + n_j}}$, where n_i and n_j are the sample sizes for each mean. As was mentioned in section 5, it should be noted that omission of data for reassembled specimens resulted not only in unequal sample sizes, but *also* changed the values of $MS_{residual}$ and $\nu_{residual}$ obtained from analysis of variance.

7. LIPSON AND SHETH METHOD FOR ADEQUATE SAMPLE SIZE

Scatter in the CFCTP core programme fatigue life data was used to check for adequacy of sample size (four specimens per test condition per participant). The method used is *due to* Lipson and Sheth (reference 10) and involves selecting an acceptable error level, usually 5 % and 10 %, and finding the required sample size for a particular confidence level. The sample size check has two purposes:

(1) To find the combination of error and confidence levels for which the actual sample size was sufficient.

(2) To give an indication of differences in data scatter between participants and fatigue test *conditions*.

Table 11 illustrates the *Lipson and Sheth method* by using an actual example from the CFCTP core programme. The table is largely self-explanatory. On the basis of a log normal distribution for the population the percent coefficient of variation $\frac{s}{\bar{x}}$ is calculated. An error level is selected and the percent error divided by the percent coefficient of variation is used to graphically determine the nearest integer sample size *for a given confidence level. The curves in the graph are derived from the t distribution* according to the following expression:

$$\frac{\%\ \text{ERROR}}{\%\ \text{COEFFICIENT OF VARIATION}} = \pm \frac{t_{0.5\alpha;\nu}}{\sqrt{n}}$$

where α is the significance level and n and ν are the appropriate sample sizes and degrees of freedom ($\nu = n-1$).

To indicate differences in data scatter the required sample sizes for a given combination of error and confidence levels were determined for the complete set of CFCTP core programme *fatigue life data*, as shown in table 12. The shaded regions denote exceedance of the actual sample size, and a larger required sample size reflects greater scatter in the data.

8. χ^2 TEST OF INDEPENDENCE, YATES' CORRECTED χ^2 TEST AND FISHER'S EXACT TEST

As mentioned in the introduction to this Appendix and shown in figure 1, the χ^2 test of independence, Yates' corrected χ^2 test or Fisher's exact test were used, as appropriate, to analyse the primary fatigue origin data with respect to the influence of stress level and environment. In addition, these tests were used (as appropriate) to check whether there were significant correlations between fatigue lives and locations of primary fatigue origins for each of the eight combinations of fatigue stress levels and testing schedules.

8.1 χ^2 Test of Independence

The χ^2 test of independence (reference 1) involves testing the hypothesis that two variables or characteristics of a sample are independent of each other. Data for this test are arranged in a table which shows one characteristic and its r categories down the left side of the table, and the other characteristic and its c categories across the top. This table is known as a contingency table. It has r rows and c columns that form cells in the body of the table. Each cell contains the number of sample members observed to have each particular combination of the characteristics being examined.

8.1.1 Analysis of primary fatigue origin data

Construction of a contingency table and the procedure for the χ^2 test to analyse the primary fatigue origin data with respect to stress level and environment will be illustrated using table 13, which gives an example from the CFCTP core programme. The test compares the observed frequencies of occurrence f_o in each cell with the theoretically expected frequency f_t if the hypothesis of independence is true. The expected frequency for a cell is obtained from the product of the total of the row and total of the column in which the cell appears, divided by the total number of observations. The sum of the expected frequencies should equal the total number of observations.

Application of the χ^2 test is reliable only if every expected frequency is at least five. If this requirement is not satisfied the results of two or more categories must be combined to raise the expected frequency to the necessary level. The initial contingency table in table 13 does not contain enough B/N, C/O and D/P primary fatigue origins to give expected frequencies of five in each cell. Therefore the B/N, C/O and D/P categories were combined with the E/Q category in a modified contingency table.

The procedure is then as follows:

(1) Compute the deviation $\chi_o^2 = \Sigma \dfrac{(f_o - f_t)^2}{f_t}$.

(2) Choose a significance level α (e.g. 5 %, 1 %).

(3) Determine the solution c of the equation $P(\chi^2 \leq c) = 1-\alpha$ from the appropriate value of χ^2 in the table of the χ^2 distribution (included in most standard texts on statistics). The appropriate value of χ^2 is listed under the chosen value of α and for (r-1)(c-1) degrees of freedom.

(4) If $\chi_o^2 \leq c$, do not reject the hypothesis. If $\chi_o^2 > c$, reject the hypothesis.

For the example in table 13 the hypothesis is rejected, i.e. it is concluded that the locations of primary fatigue origins depend on the environments (fatigue testing schedules).

8.2 Yates' Corrected χ^2 Test

A slight modification of the χ^2 test is usually recommended for contingency tables with r=2 and c=2 (one degree of freedom). This modification is known as Yates' correction for continuity (reference 11). It is used to correct for the fact that the χ^2 distribution is continuous whereas the observed frequencies are discrete.

The only change is that the formula $\chi_o^2 = \Sigma\, (f_o - f_t)^2/f_t$ is modified to

$$\chi_c^2 = \Sigma \frac{(\mid f_o - f_t \mid - 0.5)^2}{f_t}$$

where $\mid f_o - f_t \mid$ is the absolute value of $(f_o - f_t)$. χ_c^2 is always smaller then χ_o^2. This means that the hypothesis of independence is more readily accepted, i.e. Yates' corrected χ^2 test is more conservative.

8.2.1 Correlation of fatigue lives and primary fatigue origins

Table 14 gives an example of using Yates' corrected χ^2 test to check an association between fatigue lives and primary fatigue origins. The fatigue life data were arranged in ascending order together with the corresponding primary fatigue origins. The median value of fatigue life was used to separate the data into two columns for the contingency table. The median value was used instead of the mean because the median is less affected by data scatter.

The hypothesis to be tested is that the locations of primary fatigue origins do not depend on fatigue life. The initial contingency table in table 14 does not contain enough F/R and G/S primary fatigue origins to give expected frequencies of five in each cell. Therefore the F/R and G/S categories were combined in a modified contingency table.

The results in table 14 indicate that the hypothesis should be accepted, i.e. it is concluded that for this fatigue test condition (fatigue in air at S_{max} = 210 MPa) the locations of primary fatigue origins do not depend on the fatigue lives.

8.3 Fisher's Exact Test

Fisher's exact test (reference 12) is used for contingency tables with r=2 and c=2 when the total sample size is ≤ 20 or when the sample size is between 20 and 40 and the smallest expected frequency is less than five. This is because Yates' corrected χ^2 test is inaccurate for small numbers. In Fisher's test a probability is calculated from the values in the contingency table and is compared to the actual value of a chosen significance level α. For a 2 X 2 contingency table containing four values a, b, c, d; marginal totals n_1, n_2, n_3, n_4; and a grand total N, thus:

a	b	n_1
c	d	n_2
n_3	n_4	N

The probability P is given by

$$P = \frac{n_1! \times n_2! \times n_3! \times n_4!}{N! \times a! \times b! \times c! \times d!}$$

An illustration of Fisher's exact test is given in table 15. The initial contingency table is modified by combining the E/Q and C/O categories and the F/R and G/S categories. The probability P is calculated from the modified contingency table.

The hypothesis to be tested is that the locations of primary fatigue origins do not depend on fatigue life. The hypothesis is accepted if the calculated probability is greater than α. The result in table 15 indicates that the hypothesis should be rejected, i.e. it is concluded that for this fatigue test condition (fatigue in salt spray at S_{max} = 144 MPa) the locations of primary fatigue origins depend on the fatigue lives.

9. REFERENCES

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TABLE 1: EXAMPLE OF GRAPHICAL PROCEDURE FOR TEST OF NORMALITY

● FATIGUE LIFE DATA ARRANGED IN ASCENDING ORDER AND ASSIGNED MEDIAN RANKS

PRE-EXPOSURE + FATIGUE IN SALT SPRAY AT S_{max} - 144 MPa							
FATIGUE LIFE (CYCLES)	MEDIAN RANKS (%)	FATIGUE LIFE (CYCLES)	MEDIAN RANKS (%)	FATIGUE LIFE (CYCLES)	MEDIAN RANKS (%)	FATIGUE LIFE (CYCLES)	MEDIAN RANKS (%)
15,160	1.73	39,572	26.48	67,798	51.23	93,692	75.99
22,608	4.20	41,320	28.96	67,940	53.71	104,817	78.46
28,139	6.68	41,557	31.43	71,021	56.18	106,209	80.94
31,116	9.15	45,500	33.91	73,840	58.66	114,147	83.41
31,200	11.63	46,550	36.38	76,442	61.13	121,927	85.89
31,762	14.10	48,291	38.86	79,830	63.61	125,357	88.36
33,693	16.58	56,478	41.33	85,956	66.08	139,690	90.84
36,553	19.05	56,574	43.81	86,655	68.56	143,841	93.31
37,012	21.53	60,019	46.28	88,720	71.03	144,344	95.79
38,512	24.01	65,121	48.76	90,392	73.51	154,293	98.26

● GRAPHICAL TEST FOR NORMALITY

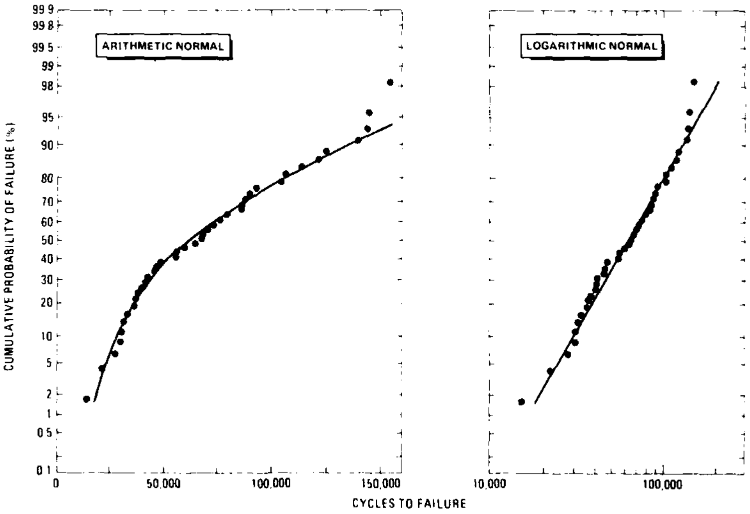


TABLE 2: EXAMPLE OF χ^2 TEST FOR GOODNESS OF FIT TO CHECK FOR NORMALITY

χ^2 TEST PROCEDURE FOR THE CFCTP CORE PROGRAMME

ASSUME F(x) IS THE *NORMAL DISTRIBUTION*. *DIVIDE* F(x) INTO $K = 4$ INTERVALS SUCH THAT EACH INTERVAL INCLUDES 1/4 OF THE POPULATION. THIS IS A CONVENIENT DIVISION BASED ON THE SAMPLE SIZE $n = 40$ FOR EACH OF THE EIGHT COMBINATIONS OF FATIGUE STRESS LEVELS AND TESTING *SCHEDULES. THIS DIVISION ALSO MEANS* THAT THE THEORETICAL FREQUENCY f_t IS 1/4 OF THE SAMPLE, I.E. $f_t = 10$.

ARRANGE THE SAMPLE IN ASCENDING ORDER OF FATIGUE LIVES AND CALCULATE

- THE MEAN $\dot{x}$
- THE STANDARD DEVIATION $s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \dot{x})^2}{n-1}}$

THESE ARE THE MAXIMUM LIKELIHOOD ESTIMATES FOR THE SAME (UNKNOWN) PARAMETERS FOR F(x), I.E. $r = 2$

- THE STANDARDIZED NORMAL VARIATE $z = \frac{(x_i - \dot{x})}{s}$ FOR EACH DATUM.

COMPARE THE *VALUES OF z FOR THE SAMPLE WITH THE z* VALUES BOUNDING THE K INTERVALS OF F(x). THIS ENABLES DIVIDING THE SAMPLE INTO THE K INTERVALS AND GIVES THE NUMBER OF SAMPLE VALUES f_o IN EACH INTERVAL.

CALCULATE $\chi_o^2 = \Sigma \frac{(f_o - f_t)^2}{f_t}$ AND COMPARE WITH $c = \chi^2$ LISTED UNDER $\alpha = 5\ \%$ AND FOR $K-r-1 = 4-2-1 = 1$ DEGREE OF FREEDOM

<table>
<tr><th colspan="8"><i>FATIGUE IN SALT SPRAY AT</i> $S_{max} = 210$ MPa</th></tr>
<tr><th colspan="4">TEST FOR NORMAL DISTRIBUTION</th><th colspan="4"><i>TEST FOR LOG-NORMAL DISTRIBUTION</i></th></tr>
<tr><th>FATIGUE LIFE x (CYCLES)</th><th>$z = \frac{(x-\dot{x})}{s}$</th><th>FATIGUE LIFE x (CYCLES)</th><th>$z = \frac{(x-\dot{x})}{s}$</th><th>FATIGUE LIFE x (LOG CYCLES)</th><th>$z = \frac{(x-\dot{x})}{s}$</th><th>FATIGUE LIFE x (LOG CYCLES)</th><th>$z = \frac{(x-\bar{x})}{s}$</th></tr>
<tr><td>4,933</td><td>- 1.38</td><td>11,370</td><td>- 0.18</td><td>3.693</td><td>- 2.00</td><td>4.056</td><td>0.02</td></tr>
<tr><td>5,957</td><td>- 1.19</td><td>11,386</td><td>- 0.17</td><td>3.775</td><td>- 1.54</td><td>4.056</td><td>0.02</td></tr>
<tr><td>6,373</td><td>- 1.11</td><td>11,524</td><td>- 0.15</td><td>3.804</td><td>- 1.38</td><td>4.062</td><td>0.05</td></tr>
<tr><td>6,442</td><td>- 1.10</td><td>11,737</td><td>- 0.11</td><td>3.809</td><td>- 1.36</td><td>4.070</td><td>0.09</td></tr>
<tr><td>6,830</td><td>- 1.02</td><td>11,940</td><td>- 0.07</td><td>3.834</td><td>- 1.22</td><td>4.077</td><td>0.13</td></tr>
<tr><td>7,163</td><td>- 0.96</td><td>12,047</td><td>- 0.05</td><td>3.855</td><td>- 1.10</td><td>4.081</td><td>0.16</td></tr>
<tr><td>7,310</td><td>- 0.93</td><td>12,626</td><td>0.06</td><td>3.864</td><td>- 1.05</td><td>4.101</td><td>0.27</td></tr>
<tr><td>7,460</td><td>- 0.91</td><td>12,848</td><td>0.10</td><td>3.873</td><td>- 1.00</td><td>4.109</td><td>0.31</td></tr>
<tr><td>7,563</td><td>- 0.89</td><td>13,520</td><td>0.23</td><td>3.879</td><td>- 0.97</td><td>4.131</td><td>0.43</td></tr>
<tr><td>7,586</td><td>- 0.88</td><td>13,626</td><td>0.25</td><td>3.880</td><td>- 0.96</td><td>4.134</td><td>0.45</td></tr>
<tr><td>7,935</td><td>- 0.82</td><td>14,670</td><td>0.44</td><td>3.900</td><td>- 0.85</td><td>4.166</td><td>0.63</td></tr>
<tr><td>9,060</td><td>- 0.61</td><td>17,549</td><td>0.98</td><td>3.957</td><td>- 0.53</td><td>4.244</td><td>1.06</td></tr>
<tr><td>9,106</td><td>- 0.60</td><td>17,893</td><td>1.04</td><td>3.959</td><td>- 0.52</td><td>4.253</td><td>1.11</td></tr>
<tr><td>9,570</td><td>- 0.51</td><td>18,577</td><td>1.17</td><td>3.981</td><td>- 0.40</td><td>4.269</td><td>1.20</td></tr>
<tr><td>10,137</td><td>- 0.41</td><td>18,970</td><td>1.24</td><td>4.006</td><td>- 0.26</td><td>4.278</td><td>1.25</td></tr>
<tr><td>10,298</td><td>- 0.38</td><td>19,523</td><td>1.35</td><td>4.013</td><td>- 0.22</td><td>4.291</td><td>1.32</td></tr>
<tr><td>10,820</td><td>- 0.28</td><td>20,470</td><td>1.52</td><td>4.034</td><td>- 0.11</td><td>4.311</td><td>1.43</td></tr>
<tr><td>11,026</td><td>- 0.24</td><td>22,546</td><td>1.91</td><td>4.042</td><td>- 0.06</td><td>4.353</td><td>1.67</td></tr>
<tr><td>11,105</td><td>- 0.22</td><td>24,680</td><td>2.31</td><td>4.046</td><td>- 0.04</td><td>4.391</td><td>1.88</td></tr>
<tr><td>11,360</td><td>- 0.18</td><td>26,799</td><td>2.71</td><td>4.055</td><td>0.01</td><td>4.428</td><td>2.08</td></tr>
<tr><td colspan="2">$\dot{x} = 12,308$</td><td colspan="2">$s = 5,353$</td><td colspan="2">$\dot{x} = 4.053$</td><td colspan="2">$s = 0.180$</td></tr>
<tr><th>VALUES OF z BOUNDING THE K=4 INTERVALS OF F(x)</th><th>THEORETICAL <i>FREQUENCY</i> f_t</th><th>OBSERVED <i>FREQUENCY</i> f_o</th><th>$\frac{(f_o - f_t)^2}{f_t}$</th><th>VALUES OF z BOUNDING THE K=4 INTERVALS OF F(x)</th><th>THEORETICAL FREQUENCY f_t</th><th>OBSERVED FREQUENCY f_o</th><th>$\frac{(f_o - f_t)^2}{f_t}$</th></tr>
<tr><td>$-\infty$ ... -0.68</td><td>10</td><td>11</td><td>0.100</td><td>$-\infty$ ... -0.68</td><td>10</td><td>11</td><td>0.100</td></tr>
<tr><td>-0.68 ... 0.00</td><td>10</td><td>15</td><td>2.500</td><td>-0.68 ... 0.00</td><td>10</td><td>8</td><td>0.400</td></tr>
<tr><td>0.00 ... 0.68</td><td>10</td><td>5</td><td>2.500</td><td>0.00 ... 0.68</td><td>10</td><td>12</td><td>0.400</td></tr>
<tr><td>0.68 ... ∞</td><td>10</td><td>9</td><td>0.100</td><td>0.68 ... ∞</td><td>10</td><td>9</td><td>0.100</td></tr>
<tr><td>TOTALS</td><td>40</td><td>40</td><td>$\chi_o^2 = 5.200$</td><td>TOTALS</td><td>40</td><td>40</td><td>$\chi_o^2 = 1.000$</td></tr>
<tr><td colspan="4">FOR $\alpha = 5\ \%$ AND $K-r-1 = 4-2-1 = 1$ DEGREE OF FREEDOM $\chi^2 = 3.841$.
SINCE $5.200 > 3.841$ THE POPULATION IS NOT NORMAL.</td><td colspan="4">FOR $\alpha = 5\ \%$ AND $K-r-1 = 4-2-1 = 1$ DEGREE OF FREEDOM $\chi^2 = 3.841$
SINCE $1.000 < 3.841$ THE POPULATION IS NORMAL</td></tr>
</table>

TABLE 3: BARTLETT AND BOX TEST PROCEDURES FOR TESTING THE HOMOGENEITY OF VARIANCES

SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - \bar{x})^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
1	n_1	SS_1	ν_1	$\frac{1}{\nu_1}$	s_1^2	$\log s_1^2$	$\nu_1 \log s_1^2$
2	n_2	SS_2	ν_2	$\frac{1}{\nu_2}$	s_2^2	$\log s_2^2$	$\nu_2 \log s_2^2$
...	...	...	.	..	...	...	.
k	n_k	SS_k	ν_k	$\frac{1}{\nu_k}$	s_k^2	$\log s_k^2$	$\nu_k \log s_k^2$
SUM	–	–	–	$\Sigma \frac{1}{\nu}$	–	–	$\Sigma(\nu \log s^2)$
POOLED	–	ΣSS	$\Sigma \nu$	$\frac{1}{\Sigma \nu}$	$s_p^2 = \frac{\Sigma SS}{\Sigma \nu}$	$\log s_p^2$	$(\Sigma \nu) \log s_p^2$
DIFFERENCE	–	–	–	$D_1 = \Sigma \frac{1}{\nu} - \frac{1}{\Sigma \nu}$	–	–	$D_2 = (\Sigma \nu) \log s_p^2 - \Sigma(\nu \log s^2)$

$K = 2.3026\ D_2$ $\quad L = D_1/3(k-1)$ $\quad \nu_1 = k - 1$

BARTLETT TEST

$\chi_o^2 = \frac{K}{1 + L}$ WITH ν_1 DEGREES OF FREEDOM.

CHOOSE A SIGNIFICANCE LEVEL α (E.G. 5 %)

COMPARE χ_o^2 WITH THE χ^2 LISTED UNDER
$\alpha = 5$ % AND FOR ν_1 DEGREES OF FREEDOM

BOX TEST

$\nu_2 = (k+1)/L^2$

$D = \frac{\nu_2}{1 - L + (2/\nu_2)} - K$

$F_o = \frac{K/\nu_1}{D/\nu_2}$ WITH ν_1 AND ν_2 DEGREES OF FREEDOM

CHOOSE A SIGNIFICANCE LEVEL α (E.G. 5 %).

COMPARE F_o WITH THE F LISTED UNDER $\alpha = 5$ % AND
FOR ν_1 AND ν_2 DEGREES OF FREEDOM.

TABLE 4: EXAMPLES OF BARTLETT'S TEST AND BOX'S TEST FOR HOMOGENEITY OF VARIANCES

BARTLETT TEST TO CHECK FOR DIFFERENCES BETWEEN FATIGUE TEST CONDITIONS

COMPARISON OF POPULATION VARIANCES FOR FATIGUE IN AIR AND FATIGUE IN SALT SPRAY AT $S_{max} = 210$ MPa

SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - \bar{x})^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
1 fatigue in air	40	1.292	39	0.026	0.033	−1.480	− 57.706
2 fatigue in salt spray	40	1.269	39	0.026	0.033	−1.487	− 58.012
$k = 2$							
SUM	–	–	–	0.052	–	–	− 115.718
POOLED	–	2.561	78	0.013	0.033	−1.484	− 115.727
DIFFERENCE	–	–	–	$D_1 = 0.039$	–	–	$D_2 = -0.009$

$K = 2.3026\ D_2 = -\ 0.021$ $\quad L = \frac{D_1}{3(k-1)} = 0.013$ $\quad \nu_1 = k - 1 = 1$

$\chi^2_o = \frac{K}{1+L} = -\ 0.021$ WITH $\nu_1 = 1$ DEGREE OF FREEDOM.

FOR $\alpha = 5$ % AND 1 DEGREE OF FREEDOM $\chi^2 = 3.841$. SINCE $-\ 0.021 < 3.841$ THE POPULATION VARIANCES ARE EQUAL

BOX TEST TO CHECK FOR INTER-LABORATORY DIFFERENCES

COMPARISON OF POPULATION VARIANCES FOR PRE-EXPOSURE + FATIGUE IN SALT SPRAY AT $S_{max} = 144$ MPa

SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - \bar{x})^2$	DEGREES OF FREEDOM $\nu = n - 1$	$\frac{1}{\nu}$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	$\log s^2$	$\nu \log s^2$
1 NADC	4	0.091	3	0.333	0.030	−1.517	− 4.550
2 SASKATCHEWAN	4	0.250	3	0.333	0.083	−1.079	− 3.237
3 VOUGHT	4	0.085	3	0.333	0.028	−1.548	− 4.644
4 AFWAL	4	0.060	3	0.333	0.020	−1.697	− 5.091
5 NLR	4	0.261	3	0.333	0.087	−1.061	− 3.182
6 DFVLR	4	0.157	3	0.333	0.052	−1.281	− 3.844
7 NDRE	4	0.333	3	0.333	0.111	−0.955	− 2.864
8 RAE	4	0.155	3	0.333	0.052	−1.287	− 3.861
9 SIFFRL	4	0.302	3	0.333	0.101	−0.998	− 2.993
10 PISA	4	0.017	3	0.333	0.006	−2.241	− 6.723
$k = 10$							
SUM	–	–	–	3.330	–	–	− 40.989
POOLED	–	1.711	30	0.033	0.057	−1.244	− 37.316
DIFFERENCE	–	–	–	$D_1 = 3.297$	–	–	$D_2 = 3.673$

$K = 2.3026\ D_2 = 8.457$ $\quad L = \frac{D_1}{3(k-1)} = 0.122$ $\quad \nu_1 = k - 1 = 9$ $\quad \nu_2 = \frac{k+1}{L^2} = 739$

$D = \frac{\nu_2}{1 - L + (2/\nu_2)} - K = 831$ $\quad F_o = \frac{K/\nu_1}{D/\nu_2} = 0.836$ WITH 9 AND 739 DEGREES OF FREEDOM

FOR $\alpha = 5$ % AND 9 AND 739 DEGREES OF FREEDOM $F = 1.880$. SINCE $0.836 < 1.880$ THE POPULATION VARIANCES ARE EQUAL.

TABLE 5. PROCEDURE FOR THREE-WAY ANALYSIS OF VARIANCE

THREE FACTOR EXPERIMENT PLAN

		GROUPS (g)	COLUMNS (c)	
			c_1	c_2
ROWS (r)	r_1	g_1	x_1 x_2	x_9 x_{10}
		g_2	x_3 x_4	x_{11} x_{12}
	r_2	g_1	x_5 x_6	x_{13} x_{14}
		g_2	x_7 x_8	x_{15} x_{16}

x = each datum

COMPUTATIONS FOR THREE FACTOR ANALYSIS OF VARIANCE

SOURCE OF VARIATION	SUM OF SQUARES SS	DEGREES OF FREEDOM	MEAN SQUARE $MS = \frac{SS}{f}$
among columns	$SS_c = \frac{\Sigma T_c^2}{nrg} - \frac{T^2}{N} = \frac{(x_1 + \dots + x_8)^2 + (x_9 + \dots + x_{16})^2}{2 \times 2 \times 2} - \frac{(x_1 + \dots + x_{16})^2}{16}$	$f_c = c - 1$	$\frac{SS_c}{f_c}$
among rows	$SS_r = \frac{\Sigma T_r^2}{ncg} - \frac{T^2}{N} = \frac{(x_1 + \dots + x_4 + x_9 + \dots + x_{12})^2 + (x_5 + \dots + x_8 + x_{13} + \dots + x_{16})^2}{2 \times 2 \times 2} - \frac{(x_1 + \dots + x_{16})^2}{16}$	$f_r = r - 1$	$\frac{SS_r}{f_r}$
among groups	$SS_g = \frac{\Sigma T_g^2}{ng} - \frac{T^2}{N} = \frac{(x_1 + x_2 + x_5 + x_6 + x_9 + x_{10} + x_{13} + x_{14})^2 + (x_3 + x_4 + x_7 + x_8 + x_{11} + x_{12} + x_{15} + x_{16})^2}{2 \times 2 \times 2} - \frac{(x_1 + \dots + x_{16})^2}{16}$	$f_g = g - 1$	$\frac{SS_g}{f_g}$
column row interaction	$SS_{cr} = \frac{\Sigma T_{cr}^2}{rg} - \frac{T^2}{N} - SS_c - SS_r$, where $\Sigma T_{cr}^2 = (x_1 + \dots + x_4)^2 + (x_9 + \dots + x_{12})^2 + (x_5 + \dots + x_8)^2 + (x_{13} + \dots + x_{16})^2$	$f_{cr} = (c - 1)(r - 1)$	$\frac{SS_{cr}}{f_{cr}}$
column group interaction	$SS_{cg} = \frac{\Sigma T_{cg}^2}{nr} - \frac{T^2}{N} - SS_c - SS_g$, where $\Sigma T_{cg}^2 = (x_1 + x_2 + x_5 + x_6)^2 + (x_9 + x_{10} + x_{13} + x_{14})^2 + (x_3 + x_4 + x_7 + x_8)^2 + (x_{11} + x_{12} + x_{15} + x_{16})^2$	$f_{cg} = (c - 1)(g - 1)$	$\frac{SS_{cg}}{f_{cg}}$
row group interaction	$SS_{rg} = \frac{\Sigma T_{rg}^2}{nc} - \frac{T^2}{N} - SS_r - SS_g$, where $\Sigma T_{rg}^2 = (x_1 + x_2 + x_9 + x_{10})^2 + (x_3 + x_4 + x_{11} + x_{12})^2 + (x_5 + x_6 + x_{13} + x_{14})^2 + (x_7 + x_8 + x_{15} + x_{16})^2$	$f_{rg} = (r - 1)(g - 1)$	$\frac{SS_{rg}}{f_{rg}}$
column row group interaction	$SS_{crg} = \frac{\Sigma T_{crg}^2}{n} - \frac{T^2}{N} - SS_c - SS_r - SS_g - SS_{cr} - SS_{cg} - SS_{rg}$, where $\Sigma T_{crg}^2 = (x_1 + x_2)^2 + (x_9 + x_{10})^2 + (x_3 + x_4)^2 + (x_{11} + x_{12})^2$ $+ (x_5 + x_6)^2 + (x_{13} + x_{14})^2 + (x_7 + x_8)^2 + (x_{15} + x_{16})^2$	$f_{crg} = (c - 1)(r - 1)(g - 1)$	$\frac{SS_{crg}}{f_{crg}}$
total	$SS_{total} = \Sigma x^2 - \frac{T^2}{N} = (x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 + x_6^2 + x_7^2 + x_8^2 + x_9^2 + x_{10}^2 + x_{11}^2 + x_{12}^2 + x_{13}^2 + x_{14}^2 + x_{15}^2 + x_{16}^2) - \frac{(x_1 + \dots + x_{16})^2}{16}$	$f_{total} = N - 1$	$\frac{SS_{total}}{f_{total}}$
residual	$SS_{residual} = SS_{total} - SS_c - SS_r - SS_g - SS_{cr} - SS_{cg} - SS_{rg} - SS_{crg}$	$f_{residual} = f_{total} - f_c - f_r - f_g - f_{cr} - f_{cg} - f_{rg} - f_{crg}$	$\frac{SS_{residual}}{f_{residual}}$

x = each datum

n = number of replications

N = total number of data

T = total for all data

c = number of columns

r = number of rows

g = number of groups

T_c = total for each column

T_r = total for each row

T_g = total for each group

T_{cr} = total for each column row combination

T_{cg} = total for each column group combination

T_{rg} = total for each row-group combination

T_{crg} = total for each column-row-group combination

ANALYSIS OF VARIANCE TABLE FOR THREE FACTOR EXPERIMENT

SOURCE OF VARIATION		MEAN SQUARE $MS = \frac{SS}{f}$	MEAN SQUARE RATIO $MSR = \frac{MS}{MS_{residual}} = F_o$	MINIMUM MEAN SQUARE RATIO MSR REQUIRED FOR FACTORS TO BE SIGNIFICANT AT A GIVEN LEVEL α (F DISTRIBUTION VALUE)
MAIN FACTORS	among columns	$MS_c = \frac{SS_c}{f_c}$	$\frac{MS_c}{MS_{residual}}$	$F_{\alpha}(f_c, f_{residual})$
	among rows	$MS_r = \frac{SS_r}{f_r}$	$\frac{MS_r}{MS_{residual}}$	$F_{\alpha}(f_r, f_{residual})$
	among groups	$MS_g = \frac{SS_g}{f_g}$	$\frac{MS_g}{MS_{residual}}$	$F_{\alpha}(f_g, f_{residual})$
INTERACTING FACTORS	column row interaction	$MS_{cr} = \frac{SS_{cr}}{f_{cr}}$	$\frac{MS_{cr}}{MS_{residual}}$	$F_{\alpha}(f_{cr}, f_{residual})$
	column group interaction	$MS_{cg} = \frac{SS_{cg}}{f_{cg}}$	$\frac{MS_{cg}}{MS_{residual}}$	$F_{\alpha}(f_{cg}, f_{residual})$
	row group interaction	$MS_{rg} = \frac{SS_{rg}}{f_{rg}}$	$\frac{MS_{rg}}{MS_{residual}}$	$F_{\alpha}(f_{rg}, f_{residual})$
	column row group interaction	$MS_{crg} = \frac{SS_{crg}}{f_{crg}}$	$\frac{MS_{crg}}{MS_{residual}}$	$F_{\alpha}(f_{crg}, f_{residual})$
	residual	$MS_{residual} = \frac{SS_{residual}}{f_{residual}}$	-	

TABLE 6: SCHEMATIC OF THREE-WAY ANALYSIS OF VARIANCE FOR THE CFCTP CORE PROGRAMME

INPUT DATA

			FATIGUE LIFE TO FAILURE (LOG CYCLES)									
			COLUMNS (LABORATORIES)									
		GROUPS (ENVIRONMENTS)	NADC	SASK.	VOUGHT	AFWAL	NLR	DFVLR	NDRE	RAE	SIFFRL	PISA
ROWS (STRESSES)	S_{max} = 210 MPa	fatigue in air	4.272 4.408 4.413 4.449	3.963 4.140 4.339 4.431	4.085 4.412 4.312 4.384	4.348 4.513 4.531 4.561	4.375 4.395 4.427 4.509	4.389 4.404 4.412 4.536	4.403 4.407 4.284 4.341	4.312 4.418 4.430 4.472	4.582 3.976 4.159 3.919	3.950 4.239 4.059 3.992
		pre-exposure + fatigue in air	3.699 3.802 4.040 4.216	4.263 3.902 4.004 4.115	4.456 4.305 3.922 4.308	4.090 4.196 4.193 4.279	4.298 4.314 4.394 4.517	3.732 4.211 3.797 3.928	4.390 4.271 4.086 3.594	4.161 4.268 3.659 3.943	4.012 4.058 3.903 4.087	3.492 3.524 3.630 4.106
		fatigue in salt spray	4.070 4.055 3.900 3.879	4.101 4.269 4.253 4.013	3.855 3.693 3.804 3.809	4.131 3.873 3.957 4.391	4.034 4.062 4.056 3.775	4.056 4.278 4.353 4.291	4.134 3.959 4.042 4.006	4.0[illegible] 4.046 4.081 4.428	3.981 3.864 3.834 4.166	4.244 4.311 4.109 3.880
		pre-exposure + fatigue in salt spray	4.225 3.3[illegible] 3.663 3.922	3.947 3.729 3.699 3.910	3.575 3.892 3.973 3.979	3.787 3.641 3.995 3.880	3.717 4.001 4.057 4.209	3.752 4.198 3.762 3.839	4.004 4.058 3.851 3.994	4.012 3.801 4.291 4.055	3.894 3.914 3.949 4.059	3.910 3.925 3.954 4.355
	S_{max} = 144 MPa	fatigue in air	4.682 5.126 5.168 5.301	5.623 4.776 5.039 5.030	5.246 5.231 5.264 5.243	5.184 5.388 5.018 5.468	5.060 5.090 5.212 5.295	5.016 5.049 5.259 5.038	5.244 4.909 5.047 5.165	5.187 4.984 4.834 5.133	5.048 4.205 5.063 4.841	4.927 5.258 4.836 4.876
		pre-exposure + fatigue in air	4.983 5.026 5.040 5.370	5.047 5.088 4.916 5.067	5.076 4.934 4.979 5.022	5.089 5.053 5.186 5.111	4.920 5.042 5.272 5.294	4.939 5.129 4.921 4.648	4.856 4.857 4.858 4.881	4.892 5.075 5.010 5.589	4.964 5.033 4.905 4.762	4.944 5.432 4.345 4.659
		fatigue in salt spray	5.157 5.178 5.087 4.869	4.893 5.017 4.663 5.164	5.088 4.777 5.281 4.548	4.834 5.348 4.895 5.239	4.743 5.105 4.914 4.670	4.734 5.296 4.847 4.975	4.968 4.917 4.656 5.085	5.194 5.146 4.757 5.437	4.733 4.847 4.690 4.885	4.519 4.659 4.423 4.545
		pre-exposure + fatigue in salt spray	4.752 5.057 4.938 5.158	4.972 4.502 4.814 5.188	4.934 4.753 4.684 4.528	5.145 4.902 4.868 4.832	4.586 4.728 4.493 5.159	4.494 4.658 4.851 5.020	5.026 4.754 4.883 5.086	5.098 4.563 4.956 4.831	4.948 4.181 4.668 4.616	4.597 4.449 4.568 4.619

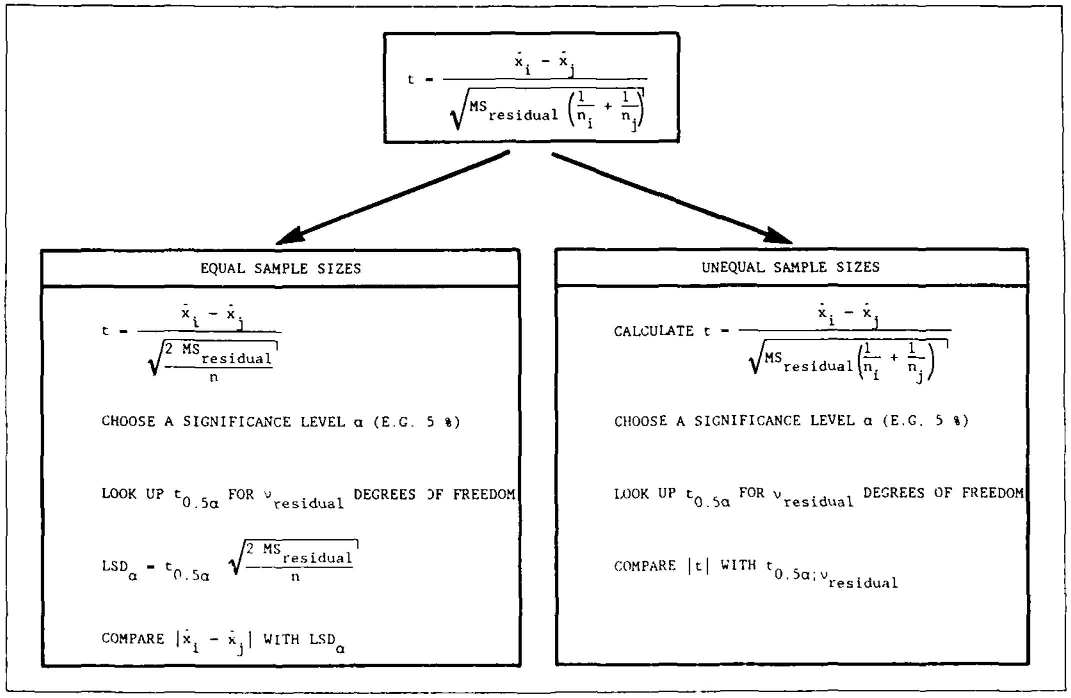
STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES

SUBPROGRAM ANOVA

ANALYSIS OF VARIANCE RESULTS (95 % CONFIDENCE . I E $\alpha = 5$ %)

SOURCE OF VARIATION		SUM OF SQUARES SS	DEGREES OF FREEDOM ν	MEAN SQUARES $MS = \frac{SS}{\nu}$	MEAN SQUARE RATIO $MSR = \frac{MS}{MS_{residual}} = F_o$	F DISTRIBUTION VALUE $F_{0.05,\nu;240}$	SIGNIFICANT EFFECTS OF EXPERIMENTAL VARIABLES $(F_o > F_{0.5,\nu,240})$
MAIN FACTORS	laboratory	1.962	9	0.218	5.763	1.93	yes
	stress	59.494	1	59.494	1572.877	3.89	yes
	environment	5.113	3	1.704	45.055	2.65	yes
INTERACTING FACTORS	laboratory:stress	0.557	9	0.062	1.637	1.93	no
	laboratory:environment	1.427	27	0.053	1.397	1.54	no
	stress:environment	0.302	3	0.101	2.662	2.65	yes
	laboratory:stress:environment	1.510	27	0.056	1.478	1.54	no
	residual	9.078	240	0.038	–	–	–

TABLE 7: PROCEDURE FOR THE LEAST SIGNIFICANT DIFFERENCE TEST



$$t = \frac{\bar{x}_i - \bar{x}_j}{\sqrt{MS_{residual}\left(\frac{1}{n_i} + \frac{1}{n_j}\right)}}$$

EQUAL SAMPLE SIZES

$$t = \frac{\bar{x}_i - \bar{x}_j}{\sqrt{\frac{2\ MS_{residual}}{n}}}$$

CHOOSE A SIGNIFICANCE LEVEL α (E.G. 5 %)

LOOK UP $t_{0.5\alpha}$ FOR $\nu_{residual}$ DEGREES OF FREEDOM

$$LSD_{\alpha} = t_{0.5\alpha} \sqrt{\frac{2\ MS_{residual}}{n}}$$

COMPARE $|\bar{x}_i - \bar{x}_j|$ WITH LSD_{α}

UNEQUAL SAMPLE SIZES

CALCULATE $t = \frac{\bar{x}_i - \bar{x}_j}{\sqrt{MS_{residual}\left(\frac{1}{n_i} + \frac{1}{n_j}\right)}}$

CHOOSE A SIGNIFICANCE LEVEL α (E.G. 5 %)

LOOK UP $t_{0.5\alpha}$ FOR $\nu_{residual}$ DEGREES OF FREEDOM

COMPARE $|t|$ WITH $t_{0.5\alpha;\nu_{residual}}$

TABLE 8: EXAMPLES OF LEAST SIGNIFICANT DIFFERENCE TEST FOR LOCATING THE SOURCE OR SOURCES OF A SIGNIFICANT EFFECT OF STRESS VERSUS ENVIRONMENT (FATIGUE TESTING SCHEDULE) INDICATED BY ANALYSIS OF VARIANCE

EQUAL SAMPLE SIZES: COMPLETE DATA SETS FROM ALL TEN [illegible] CORE PROGRAMME PARTICIPANTS

STRESS LEVEL	S_{max} = 210 MPa				S_{max} = [illegible] MPa			
FATIGUE TESTING SCHEDULE	fatigue in air	pre exposure + fatigue in air	fatigue in salt spray	pre exposure + fatigue in salt spray	fatigue in air	pre exposure + fatigue in air	fatigue in salt spray	pre exposure + fatigue in salt spray
LOG MEAN FATIGUE LIFE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LSD [illegible] = [illegible] $\sqrt{\frac{M_{residual}}{[illegible]}}$ = [illegible] × 2 $\sqrt{[illegible]}$ = [illegible]

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	S_{max} = 210 MPa		S_{max} = [illegible] MPa	
	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SIGNIFICANT DIFFERENCE [illegible]	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES	SIGNIFICANT DIFFERENCE
fatigue in air/pre exposure + fatigue in air	[illegible]	[illegible]	[illegible]	[illegible]
fatigue in air/fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
fatigue in air/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
pre exposure + fatigue in air/fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
fatigue in salt spray/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]

UNEQUAL SAMPLE SIZES: [illegible]

STRESS LEVEL	S_{max} = [illegible] MPa				S_{max} = [illegible] MPa			
FATIGUE TESTING SCHEDULE	fatigue in air	pre exposure + fatigue in air	fatigue in salt spray	pre exposure + fatigue in salt spray	fatigue in air	pre exposure + fatigue in air	fatigue in salt spray	pre exposure + fatigue in salt spray
LOG MEAN FATIGUE LIFE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SAMPLE SIZE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible] = [illegible] $M_{residual}$ = [illegible]

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	S_{max} = [illegible] MPa		S_{max} = [illegible] MPa	
	[illegible]	SIGNIFICANT DIFFERENCE [illegible]	[illegible]	SIGNIFICANT DIFFERENCE
fatigue in air/pre exposure + fatigue in air	[illegible]	[illegible]	[illegible]	[illegible]
fatigue in air/fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
fatigue in air/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
pre exposure + fatigue in air/fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
pre exposure + fatigue in air/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]
fatigue in salt spray/pre exposure + fatigue in salt spray	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 9: EXAMPLE OF DUNCAN'S NEW MULTIPLE RANGE TEST FOR EQUAL SAMPLE SIZES AND FOR ONE OF THE LABORATORY VERSUS ENVIRONMENT (FATIGUE TESTING SCHEDULE) INTERACTIONS

● RANKING [illegible] AND [illegible] THE STANDARD [illegible] THE MEAN [illegible]

EQUAL SAMPLE SIZES: COMPLETE DATA SETS FROM ALL TEN [illegible] PROGRAMME [illegible]
[illegible] MEAN FATIGUE LIVES RANKED IN ORDER FOR [illegible] IN AIR
[illegible]

● [illegible]

●

● [illegible]

TABLE 10: EXAMPLE OF DUNCAN'S NEW MULTIPLE RANGE TEST FOR UNEQUAL SAMPLE SIZES AND FOR ONE OF THE LABORATORY VERSUS STRESS VERSUS ENVIRONMENT (FATIGUE TESTING SCHEDULE) INTERACTIONS

- ● RANKING FATIGUE LIVES AND CALCULATION OF THE RESIDUAL MEAN s

UNEQUAL SAMPLE SIZES: OMISSION OF DATA FOR REASSEMBLED SPECIMENS (SEE SECTION 3.2.5 OF PART II OF THIS REPORT)

RESULTS FROM SIFFRL

STRESS LEVEL	S_{max} = 210 MPa				S_{max} = 144 MPa			
FATIGUE TESTING SCHEDULE	pre-exposure + fatigue in salt spray	fatigue in salt spray	pre-exposure + fatigue in air	fatigue in air	pre-exposure + fatigue in salt spray	fatigue in salt spray	fatigue in air	pre-exposure + fatigue in air
LOG MEAN FATIGUE LIVES RANKED IN ORDER	3.954	3.961	4.035	4.159	4.599	4.789	[illegible]	4.998
SAMPLE SIZE n	4	4	2	4	3	4	3	[illegible]

$$s = \sqrt{MS_{residual}} = \sqrt{0.036} = 0.190$$

- ● CHOOSE A SIGNIFICANCE LEVEL α AND LOOK UP THE SIGNIFICANT STUDENTIZED RANGES FOR APPROPRIATE VALUES OF p AND $\nu_{residual}$ DEGREES OF FREEDOM

SIGNIFICANT STUDENTIZED RANGES (z) FOR α = 5% AND $\nu_{residual}$ = 210

NUMBER OF MEANS p INVOLVED IN A SET OF COMPARISONS	2	3	4
$z_{0.05,p,210}$	2.772	2.918	[illegible]

- ● CALCULATE THE SHORTEST SIGNIFICANT RANGES

SHORTEST SIGNIFICANT RANGES SSR

NUMBER OF MEANS p INVOLVED IN A SET OF COMPARISONS	2	3	4
$SSR = sz_{0.05,p,210}$	0.527	[illegible]	[illegible]

- ● TEST THE DIFFERENCES

	p	COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	DIFFERENCE BETWEEN LOG MEAN FATIGUE LIVES X $\sqrt{\frac{2n_i n_j}{n_i+n_j}}$	SSR	SIGNIFICANT DIFFERENCE $\bar{x}_i - \bar{x}_j \sqrt{\frac{2n_i n_j}{n_i+n_j}} > SSR$
S_{max} = 210 MPa	4	fatigue in air/pre-exposure + fatigue in salt spray	0.410	[illegible]	no
	3	fatigue in air/fatigue in salt spray	0.396	0.554	no
	2	fatigue in air/pre-exposure + fatigue in air	0.202	0.527	no
	3	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	0.132	0.554	no
	2	pre-exposure + fatigue in air/fatigue in salt spray	0.121	0.527	no
	2	fatigue in salt spray/pre-exposure + fatigue in salt spray	0.014	0.527	no
S_{max} = 144 MPa	4	pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	0.618	[illegible]	yes
	3	pre-exposure + fatigue in air/fatigue in salt spray	0.341	0.554	no
	2	pre-exposure + fatigue in air/fatigue in air	0.063	0.527	no
	3	fatigue in air/pre-exposure + fatigue in salt spray	0.617	0.554	yes
	2	fatigue in air/fatigue in salt spray	0.307	0.527	no
	2	fatigue in salt spray/pre-exposure + fatigue in salt spray	0.352	0.527	no

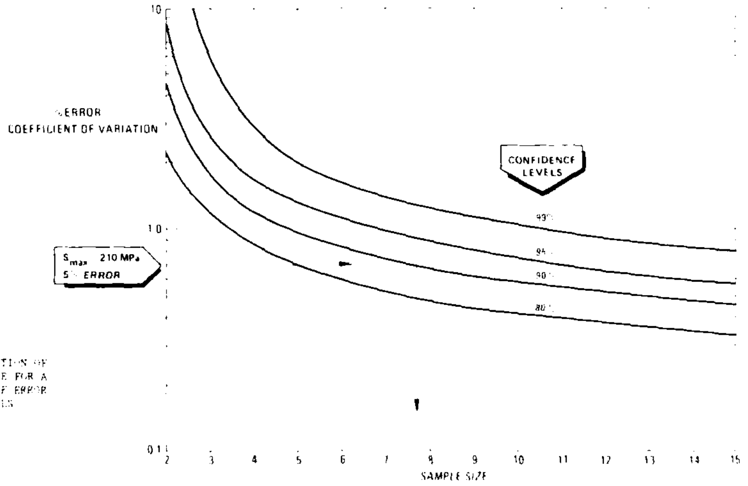
TABLE 11: THE LIPSON AND SHETH METHOD OF SAMPLE SIZE DETERMINATION

RESULTS FROM SIFFRL FOR FATIGUE IN AIR								
S_{max} (MPa)	LOG FATIGUE LIFE x	LOG MEAN FATIGUE LIFE $\bar{x}$	SAMPLE SIZE n	SUM OF SQUARES $SS = \Sigma(x_i - \bar{x})^2$	DEGREES OF FREEDOM $\nu = n - 1$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	STANDARD DEVIATION s	% COEFFICIENT OF VARIATION $\frac{s}{\bar{x}}$
210	3.919 3.976 4.159 4.582	4.159	4	0.270	3	[illegible]	0.300	[illegible]
144	4.205 4.841 5.063 5.[illegible]78	4.927	4	0.104	3	[illegible]	[illegible]	[illegible]

- ● SELECTION OF ERROR LEVELS

% ERROR	% ERROR / % COEFFICIENT OF VARIATION	
	S_{max} = 210 MPa	S_{max} = 144 MPa
5	[illegible]	[illegible]
10	1.386	[illegible]

- ● ILLUSTRATION OF THE GRAPHICAL DETERMINATION OF REQUIRED SAMPLE SIZE FOR A GIVEN COMBINATION OF ERROR AND CONFIDENCE LEVELS



- ● EXAMPLE OF REQUIRED SAMPLE SIZES

% ERROR	REQUIRED SAMPLE SIZE FOR [illegible] % CONFIDENCE LEVEL	
	S_{max} = 210 MPa	S_{max} = 144 MPa
5	8	[illegible]
10	[illegible]	3

TABLE 12: REQUIRED SAMPLE SIZES FOR 5 % ERROR AND 90 % CONFIDENCE LEVELS

S_{max} (MPa)	FATIGUE TESTING SCHEDULE	NADC	SASK	VOUGHT	AFWAL	SLR	DFVLR	NORE	RAE	SIFFRL	FISA
210	fatigue in air	3	5	[illegible]	3	3	3	3	3	8	3
	pre-exposure + fatigue in air	6	[illegible]	5	3	3	5	10	7	3	8
	fatigue in salt spray	3	3	2	5	[illegible]	[illegible]	3	5	4	4
	pre-exposure + fatigue in salt spray	6	4	5	[illegible]	5	5	3	5	3	5
144	fatigue in air	[illegible]	7	2	4	3	3	3	3	4	4
	pre-exposure + fatigue in air	[illegible]	2	2	2	[illegible]	4	2	6	3	12
	fatigue in salt spray	3	4	6	5	4	5	[illegible]	5	3	3
	pre-exposure + fatigue in salt spray	4	6	[illegible]	3	6	5	7	5	7	2

TABLE 13: EXAMPLE OF χ^2 TEST OF INDEPENDENCE FOR ANALYSING THE PRIMARY FATIGUE ORIGIN DATA (ORIGINAL EIGHT CFCTP PARTICIPANTS AND SIFFRL)

- ● CONSTRUCTION OF INITIAL CONTINGENCY TABLE

PRIMARY FATIGUE ORIGINS VERSUS ENVIRONMENT: S_{max} = 144 MPa

ROWS, r (LOCATIONS OF PRIMARY FATIGUE ORIGINS)	COLUMNS, c (FATIGUE TESTING SCHEDULES)				ROW TOTALS, R
	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	
E/Q	0	4	7	9	20
F/R	11	11	16	15	53
G/S	25	14	10	6	55
B/N	0	5	0	4	9
C/O	0	1	1	1	3
D/P	0	1	0	1	2
COLUMN TOTALS, C	36	36	34	36	142 = N

- ● MODIFICATION OF THE CONTINGENCY TABLE (SEE TEXT)

PRIMARY FATIGUE ORIGINS VERSUS ENVIRONMENT S_{max} = 144 MPa

ROWS, r (LOCATIONS OF PRIMARY FATIGUE ORIGINS)	COLUMNS, c (FATIGUE TESTING SCHEDULES)				ROW TOTALS, R
	fatigue in air	pre-exposure + fatigue in air	fatigue in salt spray	pre-exposure + fatigue in salt spray	
E/Q, B/N, C/O, OR D/P	0	11	8	15	34
F/R	11	11	16	15	53
G/S	25	14	10	6	55
COLUMN TOTALS, C	36	36	34	36	142 = N

- ● CALCULATION OF χ_o^2 AND COMPARISON WITH χ^2 LISTED UNDER α = 5 % AND FOR (r-1)(c-1) DEGREES OF FREEDOM

THEORETICAL (EXPECTED) FREQUENCY $f_t = \frac{RC}{N}$	OBSERVED FREQUENCY f_o	$\frac{(f_o - f_t)^2}{f_t}$	THEORETICAL (EXPECTED) FREQUENCY $f_t = \frac{RC}{N}$	OBSERVED FREQUENCY f_o	$\frac{(f_o - f_t)^2}{f_t}$
$\frac{34 \times 36}{142} = 8.620$	0	8.620	$\frac{53 \times 34}{142} = 12.690$	16	0.863
$\frac{34 \times 36}{142} = 8.620$	11	0.657	$\frac{53 \times 36}{142} = 13.437$	15	0.182
$\frac{34 \times 34}{142} = 8.141$	8	0.002	$\frac{55 \times 36}{142} = 13.944$	25	8.766
$\frac{34 \times 36}{142} = 8.620$	15	4.722	$\frac{55 \times 36}{142} = 13.944$	14	0.001
$\frac{53 \times 36}{142} = 13.437$	11	0.442	$\frac{55 \times 34}{142} = 13.169$	10	0.763
$\frac{53 \times 36}{142} = 13.437$	11	0.442	$\frac{55 \times 36}{142} = 13.944$	6	4.526

$\Sigma f_t = \Sigma f_o = N = 142$ $\chi_o^2 = \sum \frac{(f_o - f_t)^2}{f_t} = 29.986$

FOR α = 5 % AND (r-1)(c-1) = (3-1)(4-1) = 6 DEGREES OF FREEDOM χ^2 = 12.597. SINCE 29.986 > 12.597 IT MAY BE CONCLUDED WITH 95 % CONFIDENCE THAT THERE IS A SIGNIFICANT ASSOCIATION BETWEEN PRIMARY FATIGUE ORIGINS AND ENVIRONMENTS (FATIGUE TESTING SCHEDULES).

TABLE 14: EXAMPLE OF YATES' CORRECTED χ^2 TEST FOR CHECKING THE ASSOCIATION OF FATIGUE LIVES AND PRIMARY FATIGUE ORIGINS (ORIGINAL EIGHT CFCTP PARTICIPANTS)

- PRIMARY FATIGUE ORIGINS CORRELATED WITH FATIGUE LIVES ARRANGED IN ASCENDING ORDER

FATIGUE IN AIR AT S_{max} = 210 MPa							
FATIGUE LIFE (CYCLES)	LOCATIONS OF PRIMARY FATIGUE ORIGINS	FATIGUE LIFE (CYCLES)	LOCATIONS OF PRIMARY FATIGUE ORIGINS	FATIGUE LIFE (CYCLES)	LOCATIONS OF PRIMARY FATIGUE ORIGINS	FATIGUE LIFE (CYCLES)	LOCATIONS OF PRIMARY FATIGUE ORIGINS
9,180	Q	21,850	R	25,500	Q	26,894	S
12,165	R	21,940	Q	25,500	R	26,950	R
13,800	Q	22,300	Q	25,606	F	28,114	S
13,800	R	23,713	Q	25,841	Q	29,677	Q
18,705	Q	24,235	E	25,841	F	32,312	F
19,217	E	24,429	Q	25,841	Q	32,600	F
20,494	E	24,822	E	25,894	Q	34,000	G
20,499	R	25,310	E	26,177	G	34,350	S
21,850	Q	25,373	F	26,714	G	36,400	S
MEDIAN VALUE OF FATIGUE LIFE = 25,437 CYCLES							

- CONSTRUCTION OF INITIAL CONTINGENCY TABLE

ROWS, r (LOCATIONS OF PRIMARY FATIGUE ORIGINS)	COLUMNS, c (FATIGUE LIVES)		ROW TOTALS, R
	BELOW 25,437 CYCLES	ABOVE 25,437 CYCLES	
E/Q	13	7	20
F/R	5	4	9
G/S	0	7	
COLUMN TOTALS, C	18	18	36 = N

- MODIFICATION OF THE CONTINGENCY TABLE (SEE TEXT)

ROWS, r (LOCATIONS OF PRIMARY FATIGUE ORIGINS)	COLUMNS, c (FATIGUE LIVES)		ROW TOTALS, R
	BELOW 25,437 CYCLES	ABOVE 25,437 CYCLES	
E/Q	13	7	20
F/R or G/S	5	11	16
COLUMN TOTALS, C	18	18	36 = N

- CALCULATION OF χ^2_c AND COMPARISON WITH χ^2 LISTED UNDER α = 5 % AND FOR (r−1)(c−1) DEGREES OF FREEDOM

THEORETICAL (EXPECTED) FREQUENCY $f_t = \frac{RC}{N}$	OBSERVED FREQUENCY f_o	$\frac{(\lvert f_o - f_t \rvert - 0.5)^2}{f_t}$	THEORETICAL (EXPECTED) FREQUENCY $f_t = \frac{RC}{N}$	OBSERVED FREQUENCY f_o	$\frac{(\lvert f_o - f_t \rvert - 0.5)^2}{f_t}$
$\frac{20 \times 18}{36} = 10.0$	13	0.625	$\frac{16 \times 18}{36} = 8.0$	5	0.781
$\frac{20 \times 18}{36} = 10.0$	7	0.625	$\frac{16 \times 18}{36} = 8.0$	11	0.781

$$\Sigma f_t = \Sigma f_o = N = 36 \qquad \chi^2_c = \sum \frac{(\lvert f_o - f_t \rvert - 0.5)^2}{f_t} = 2.812$$

FOR α = 5 % AND (r−1)(c−1) = (2−1)(2−1) = 1 DEGREE OF FREEDOM χ^2 = 3.841. SINCE 2.812 < 3.841 IT MAY BE CONCLUDED WITH 95 % CONFIDENCE THAT THERE IS NO SIGNIFICANT ASSOCIATION BETWEEN FATIGUE LIVES AND PRIMARY ORIGINS OF FATIGUE FOR THIS TEST CONDITION.

TABLE 15: EXAMPLE OF FISHER'S EXACT TEST FOR CHECKING THE ASSOCIATION OF FATIGUE LIVES AND PRIMARY FATIGUE ORIGINS (ORIGINAL EIGHT CFCTP PARTICIPANTS)

- ● PRIMARY FATIGUE ORIGINS CORRELATED WITH FATIGUE LIVES ARRANGED IN ASCENDING ORDER

FATIGUE IN SALT SPRAY AT S_{max} = 144 MPa							
FATIGUE LIFE (CYCLES)	LOCATIONS OF PRIMARY FATIGUE ORIGINS	FATIGUE LIFE (CYCLES)	LOCATIONS OF PRIMARY FATIGUE ORIGINS	FATIGUE LIFE (CYCLES)	LOCATIONS OF PRIMARY FATIGUE ORIGINS	FATIGUE LIFE (CYCLES)	LOCATIONS OF PRIMARY FATIGUE ORIGINS
35,331	R	69,170	G	94,341	R	142,815	R
45,240	G	70,228	R	104,040	E	[illegible] 663	G
46,046	F	73,974	R	121,584	–	156,1[illegible]	S
46,824	R	78,088	G	122,092	G	173,2[illegible]	[illegible]
54,165	R	78,530	Q	122,468	Q	[illegible]	[illegible]
55,317	F	82,098	F	127,344	E	[illegible]	[illegible]
57,088	R	82,561	G	139,186	[illegible]	222,[illegible]	S
59,900	R	92,929	F	143,634	G	273,[illegible]	–
MEDIAN VALUE OF FATIGUE LIFE = 93,635 CYCLES							

- ● CONSTRUCTION OF INITIAL CONTINGENCY TABLE

ROWS, r (LOCATIONS OF PRIMARY FATIGUE ORIGINS)	COLUMNS, c (FATIGUE LIVES)		ROW TOTALS, R
	BELOW 93,635 CYCLES	ABOVE 93,635 CYCLES	
E/Q	1	5	6
F/R	11	2	13
G/S	4	[illegible]	[illegible]
G/Q	0	[illegible]	[illegible]
COLUMN TOTALS, C	16	14	30 = N

- ● MODIFICATION OF THE CONTINGENCY TABLE (SEE TEXT)

ROWS, r (LOCATIONS OF PRIMARY FATIGUE ORIGINS)	COLUMNS, c (FATIGUE LIVES)		ROW TOTALS, R
	BELOW 93,635 CYCLES	ABOVE 93,635 CYCLES	
E/Q or G/Q	1	6	7
F/R or G/S	15	8	23
COLUMN TOTALS, C	16	14	30 = N

- ● CALCULATION OF P AND COMPARISON WITH α = 5 %

$$P = \frac{7! \ X \ 23! \ X \ 16! \ X \ 14!}{30! \ X \ 1! \ X \ 6! \ X \ 15! \ X \ 8!} = 0.0236$$

SINCE P = 0.0236 IS LESS THAN α = 0.05 IT MAY BE CONCLUDED WITH 95 % CONFIDENCE THAT THERE IS A SIGNIFICANT ASSOCIATION BETWEEN FATIGUE LIVES AND PRIMARY ORIGINS OF FATIGUE FOR THIS TEST CONDITION

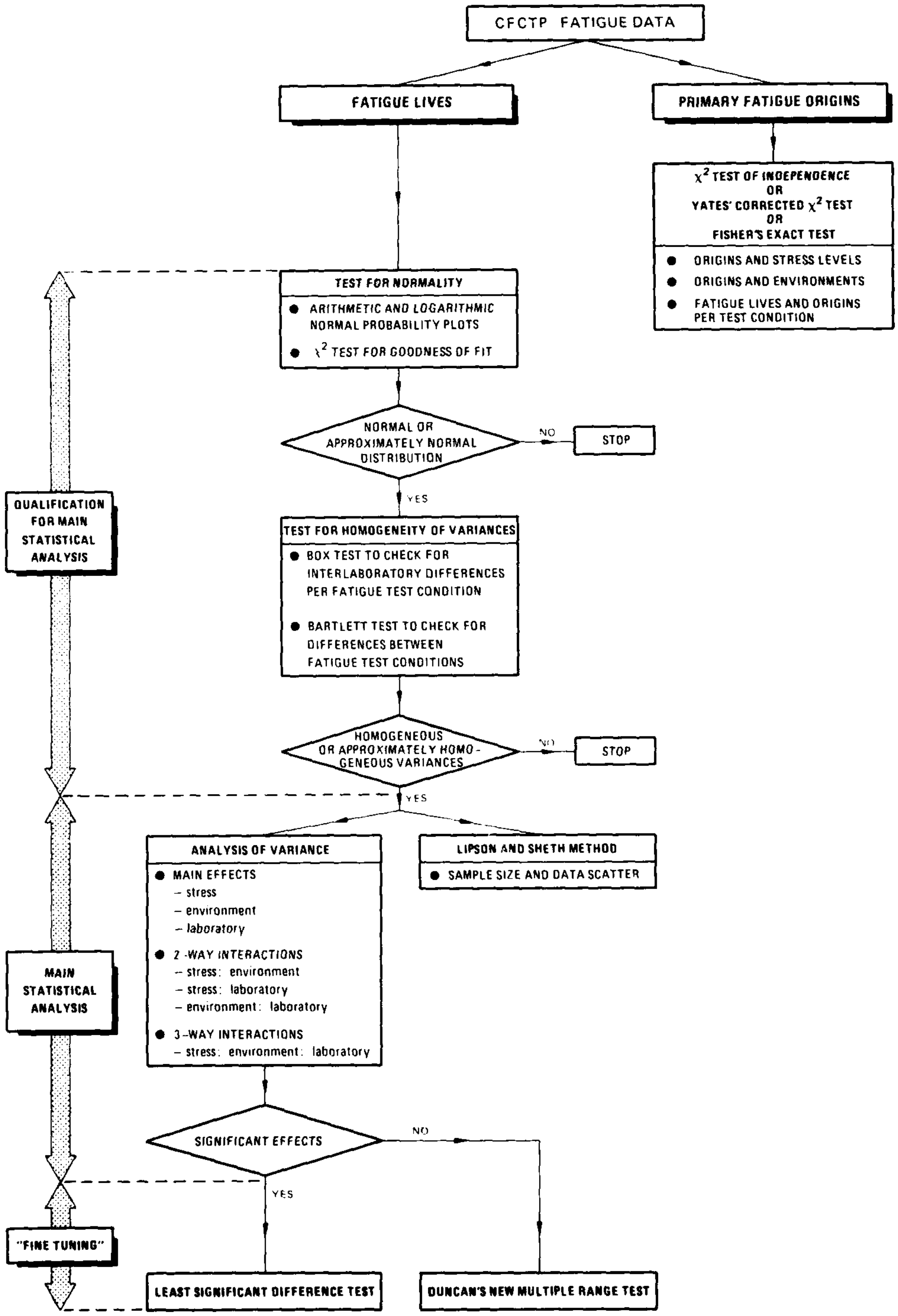


Fig. 1 Survey of statistical methods for analysing the CFCTP fatigue life and primary fatigue origin data

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14. Abstract

In accordance with the mission of AGARD the Structures and Materials Panel (SMP) has always kept an open eye for the possibilities to sponsor collaborative programmes of research. AGARD is unique in its ability to realise the cooperation of laboratories in up to sixteen nations. In this way AGARD distinguishes itself from other international scientific and technical organisations.

In the 1970s the SMP decided to embark on collaborative research activities in the area of fatigue. One of the first activities was the Corrosion Fatigue Cooperative Testing Programme (CFCTP), the precursor to the Fatigue in Aircraft Corrosion Testing (FACT) programme. Both programmes are described in this report.

Failure by fatigue and degradation by corrosion continue to be major considerations in aircraft design. Environmental effects influence both initiation and propagation of fatigue cracks, and dynamic loading may cause more rapid deterioration of corrosion protection systems. Therefore the conjoint action of dynamic loading and environmental attack, i.e. corrosion fatigue, requires special attention.

Many corrosion fatigue tests have been done on aluminium alloys. However, few included critical structural details like joints, under realistic cyclic load histories and in service-like environments. Even fewer used practical corrosion protection systems. These aspects are specifically addressed by the ~~CFCTP and~~FACT programmes, The results provide a significant contribution to the understanding of aircraft corrosion fatigue and should encourage further investigation in this difficult and challenging area of aerospace technology.

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