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An AGARD-Coordinated Corrosion Fatigue Cooperative Testing Programme

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.695

AN AGARD-COORDINATED CORROSION FATIGUE COOPERATIVE TESTING PROGRAMME

by

R.J.H.Wanhill
National Aerospace Laboratory – NLR
Amsterdam
The Netherlands

and

J.J. De Luccia
Naval Air Development Center
Warminster, PA
USA

This Programme was sponsored by the Structures and Materials Panel of AGARD.

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PREFACE

Failure by fatigue and degradation by corrosion continue to be major considerations in aircraft design. Environmental effects are known to influence both the initiation and propagation of fatigue cracks whereas dynamic loading may cause a more rapid deterioration of a corrosion protection scheme. 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 details, like joints, under realistic cyclic load histories and in service-like environments. Even fewer used practical corrosion protection systems. Consequently, in 1977 the AGARD Structures and Materials Panel appointed Dr R.J.H.Wanhill and Dr J.J.De Luccia as coordinators for a Corrosion Fatigue Cooperative Testing Programme (CFCTP). The CFCTP was a programme of round-robin testing in which eight laboratories from Europe and North America participated.

The present report is in two parts. Part 1 consists of a manual in which all technical requirements and test details for the CFCTP are specified. Part 2 presents the results of the CFCTP, which was completed in mid-1981.

Successful completion of the CFCTP has led to the establishment of a more extensive programme designated Aircraft Environment Simulation Fatigue Testing (AESFT). This programme is scheduled to be completed in 1984.

H.P. VAN LEEUWEN
Chairman, Sub-Committee on
Corrosion Fatigue

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PART 1

MANUAL FOR THE AGARD-COORDINATED CORROSION FATIGUE COOPERATIVE TESTING PROGRAMME (CFCTP)

1. INTRODUCTION

In 1976 the Structures and Materials Panel (SMP) of the Advisory Group for Aerospace Research and Development (AGARD) in NATO formed an ad hoc group for the subject of corrosion fatigue in aerospace structural materials. Authors from several NATO countries were invited to present pilot papers on this subject at the 44th Meeting of the SMP in Lisbon, Portugal, in April 1977. At that meeting it was decided to form an AGARD Sub-Committee and to appoint European and North American coordinators for a cooperative programme on corrosion fatigue of aerospace materials of particular interest to the NATO countries.

The incentive for such a programme came from the fact that:

- many fatigue failures in aerospace structures are facilitated by environmental effects
- there were few available data for fatigue life reductions owing to corrosion in aerospace environments
- there were even fewer data concerning the effectiveness of modern corrosion protection systems: these systems are degraded by long time exposure and cyclic loads and can be damaged by corrosion or by impact of foreign objects.

The objectives of this cooperative programme were:

- to assess the effectiveness of state-of-the-art protection schemes for aluminium alloys with respect to corrosion fatigue and corrosion + fatigue
- to stimulate the development of new protection products, procedures and techniques
- to bring researchers on both sides of the Atlantic together 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
- to enable participating laboratories to add to their fatigue testing capabilities by using a controlled atmospheric corrosion environment.

2. PROGRAMME OVERVIEW

As originally envisaged the AGARD-coordinated corrosion fatigue cooperative testing programme (CFCTP) consisted of participation in a two-phase core programme of round-robin testing and additional programmes of supplemental testing directed to the requirements of individual laboratories, with the entire programme scheduled to finish in 1980. However, during the course of the programme it became clear that its scope and complexity would prevent meeting this target date, although the core programme would be finished. In order to allow timely reporting of the core programme results it was decided to present them in Part 2 of this report. Supplemental testing programme results will be subsequently reported.

2.1 Core Programme

In any cooperative programme there are a number of parameters requiring consideration. For the CFCTP the main variables were:

- material and heat treatment
- specimen configuration
- protective systems and specimen treatment
- mechanical test conditions (static prestressing and fatigue)
- environmental conditions (pre-exposure and corrosion fatigue).

The core programme specified identical conditions for all of the foregoing parameters, as follows:

- **material and heat treatment**: 3.2 mm 7075-T76 bare aluminium alloy sheet supplied especially by ALCOA from one heat.
- **specimen configuration**: 1½ dogbone mechanically fastened by cadmium plated steel Hi-Loks from a single batch of fasteners. All prior-to-assembly aluminium alloy parts of specimens manufactured by the U.S. Air Force Materials Laboratory (AFML).
- **protective systems and specimen treatment**: Applied by the U.S. Naval Air Development Centre (NADC) as follows (see also section 3.4):
  - after machining by the AFML the specimen parts were treated with a chromate conversion coating
  - an inhibited epoxy polyamide primer was applied except to fastener areas
  - specimen assembly using aircraft quality cadmium plated steel Hi-Loks and re-priming
  - an aliphatic polyurethane topcoat was applied to the specimen exterior surfaces
  - specimens were individually wrapped and shipped in batches to participating laboratories
  - faying surface side edges and Hi-lok collars were to be sealed by participating laboratories.

- mechanical test conditions (static prestressing and fatigue): Before environmental exposure and fatigue testing all specimens were prestressed at 299 ± 10 K with two cycles to the maximum stress occurring in the subsequent fatigue test or 215 MPa, whichever was the greater, in order to crack the paint and primer layers in the fastener hole vicinities. Fatigue testing was with constant amplitude loading at a stress ratio R ($=S_{min}/S_{max}$) of 0.1. Cycle frequencies of 2 Hz in air and 0.5 Hz in salt spray.

- environmental conditions (pre-exposure and corrosion fatigue): After prestressing the faying surface side edges and Hi-Lok collars were sealed where necessary. Pre-exposure was in 5 % aqueous NaCℓ 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 kept at 315 ± 2K. Pre-exposure was for 72 hours. The corrosion fatigue environment was a 5 % aqueous NaCℓ salt spray acidified with H_2SO_4 to pH 4 and controlled to 295 ± 2K. All other fatigue tests occurred in laboratory air at 295 ± 5K, relative humidity 30 - 70 %.

2.1.1 Core programme phases

The core programme was in two phases:

- in phase I fatigue tests were carried out in laboratory air
- in phase II fatigue tests were carried out in acidified salt spray.

This phasing was intended to assist the scheduling for construction of a salt spray chamber for corrosion fatigue testing, while allowing early commencement of the programme by conducting fatigue tests in air.

2.1.2 Test schedules

The following table gives the testing schedules for the core programme. The stress levels (S_{max} and $S_{min} = 0.1\ S_{max}$) were determined from pilot tests at the National Aerospace Laboratory NLR of the Netherlands, see section 10.1.

CORE PROGRAMME TEST SCHEDULES

PHASE		NUMBER OF SPECIMENS	
		S_{max} for an uncorroded life ∿ 2×10^4 cycles	S_{max} for an uncorroded life ∿ 10^5 cycles
I	fatigue in air	4	4
I	Pre-exposure + fatigue in air	4	4
II	fatigue in salt spray	4	4
II	Pre-exposure + fatigue in salt spray	4	4

2.2 Supplemental Testing

A programme of supplemental testing was included so that individual laboratories could investigate the corrosion fatigue problems of particular relevance to them. However, it was emphasized that testing should be conducted with as much commonality as possible within the CFCTP.

It was recommended that:

- the same specimen configuration be used as for the core programme
- mechanical test conditions be identical (see section 2.2.1)
- environmental conditions (pre-exposure and corrosion fatigue) be identical to those for the core programme.

Further, it was advised that efforts should be made to obtain materials of mutual interest from one heat. Then the only variable would be the type of corrosion protection system applied. Via the programme coordinators several laboratories did in fact agree to test materials from a common source. Also, upwards of 200 specimens identical to those for the core programme were available to CFCTP participants for applying different corrosion protection systems.

2.2.1 Mechanical test conditions

Before environmental exposure and fatigue testing all specimens were prestressed at 209 ± 10K with two cycles to the maximum stress occurring in the subsequent fatigue test or 215 MPa, whichever was the greater, in order to crack any inflexible paint and primer layers in the fastener hole vicinities.

For fatigue testing the following table specifies the loading type and frequency.

FATIGUE TEST CONDITIONS FOR SUPPLEMENTAL TESTING

LOADING TYPE	CYCLE FREQUENCY
constant amplitude, R = 0.1	2 Hz in air 0.5 Hz in salt spray
manoeuvre spectrum FALSTAFF	15* Hz in air 2* Hz in salt spray
gust spectrum MINI-TWIST	15* Hz in air 5* Hz in salt spray

* nominal frequency based on total duration and number of load excursions for each flight block

2.2.2 Pilot tests

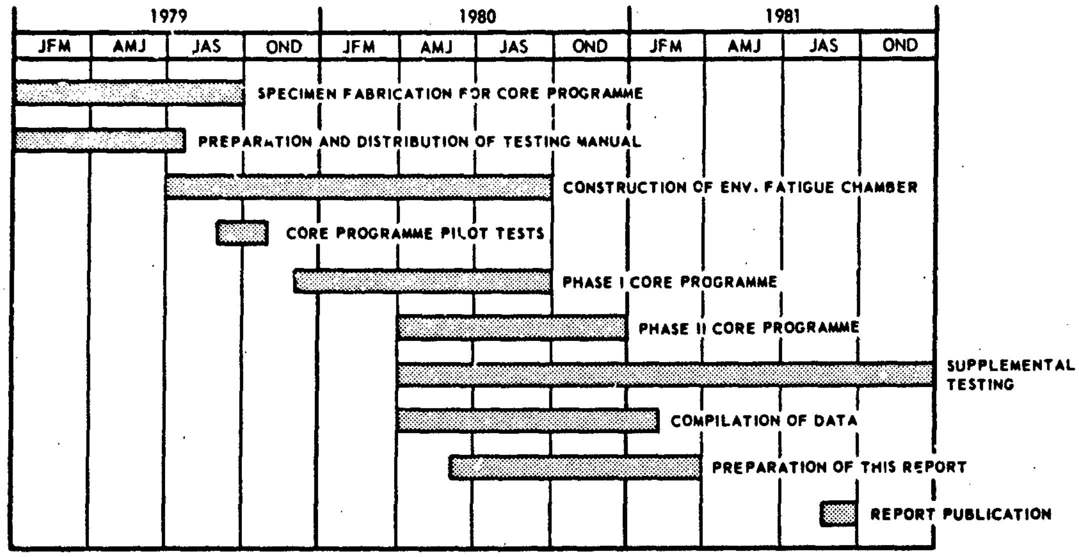
Pilot fatigue tests were conducted to determine the stress levels giving a desired uncorroded fatigue life. The following table is an example of pilot test requirements for supplemental testing at the NLR. More details are given in section 10.1.

EXAMPLE OF NLR PILOT TEST REQUIREMENTS FOR SUPPLEMENTAL TESTING

MATERIAL	LOADING TYPE	REQUIRED STRESS LEVELS FOR UNCORRODED SPECIMENS
7075-T6	constant amplitude, R = 0.1	S_{max} for a life $\sim 10^5$ cycles
	FALSTAFF	S_{max} for a life $\sim$ 4000 flights S_{max} for a life $\sim$ 10,000 flights
2024-T3	constant amplitude, R = 0.1	S_{mf} for a life $\sim 10^5$ cycles
	MINI-TWIST	S_{mf} for a life $\sim$ 10,000 flights S_{mf} for a life $\sim$ 40,000 flights

2.3 Milestones

The following milestone chart for the CFCTP is approximate. The most noteworthy feature is that owing to the number of laboratories participating (10-11) there was a fairly wide variation in "start-up" times for the various activities. Thus the planning of such cooperative programmes requires ample time allowance for data compilation and reporting.



3 SPECIMEN

The CFCTP core programme and recommended supplemental testing specimen was a 1½ dogbone containing a row of two countersunk Hi-Lok fasteners. The specimen simulates the load transfer and secondary bending characteristics of runouts of stiffeners attached to the outer skin, and was developed by the Laboratorium für Betreibsfestigkeit (LBF) West Germany.

The specimen has the following characteristics (see also figure 1):

- load transfer is $\Delta P/P \sim 40$ %
- secondary bending is $\varepsilon_b/\varepsilon_{ax} \sim 50$ %.

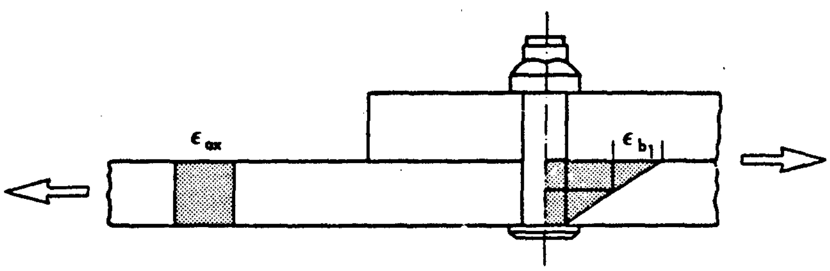


Fig. 1 Schematic definition of CFCTP specimen secondary bending

Additional points concerning these characteristics are:

- for a clearance fit and fastener without clamping force the load transfer will drop and become load dependent
- when load transfer drops the secondary bending decreases
- with fastener systems providing clamping force corresponding to Hi-Lok collars at torque-off the load transfer is not influenced by fastener fit (faying surfaces are coated with primer)
- secondary bending stress may shift location of crack initiation from hole surface to faying surface, notably for specimens without corrosion damage in the fastener areas
- tension limit load is $P \sim 40$ kN, based on static ultimate tensile strength of 7075-T6 alloy 3 mm thick sheet
- compression limit load is $P \sim -10$ kN, based on specimen stability, i.e. a specimen without anti-buckling support will not buckle when compression loads do not exceed -10 kN: this has been verified by load control tests at the NLR.

3.1 Configuration

Figure 2 shows the configuration of the CFCTP core programme and recommended supplemental testing specimen. The following table lists the component parts of the specimen.

SPECIMEN PARTS

NUMBER PER ASSEMBLY	PART NUMBER	NAME	STOCK
2	- 5	Hilok cellars	HL-70-8
2	- 4	Hilck pins	HL-19-PB-8-5
1*	- 3	Spacer	3.2x80x65
1	- 2	Half plate	3.2x80x185
1	- 1	Fatigue specimen	3.2x80x300

* see note (7) below

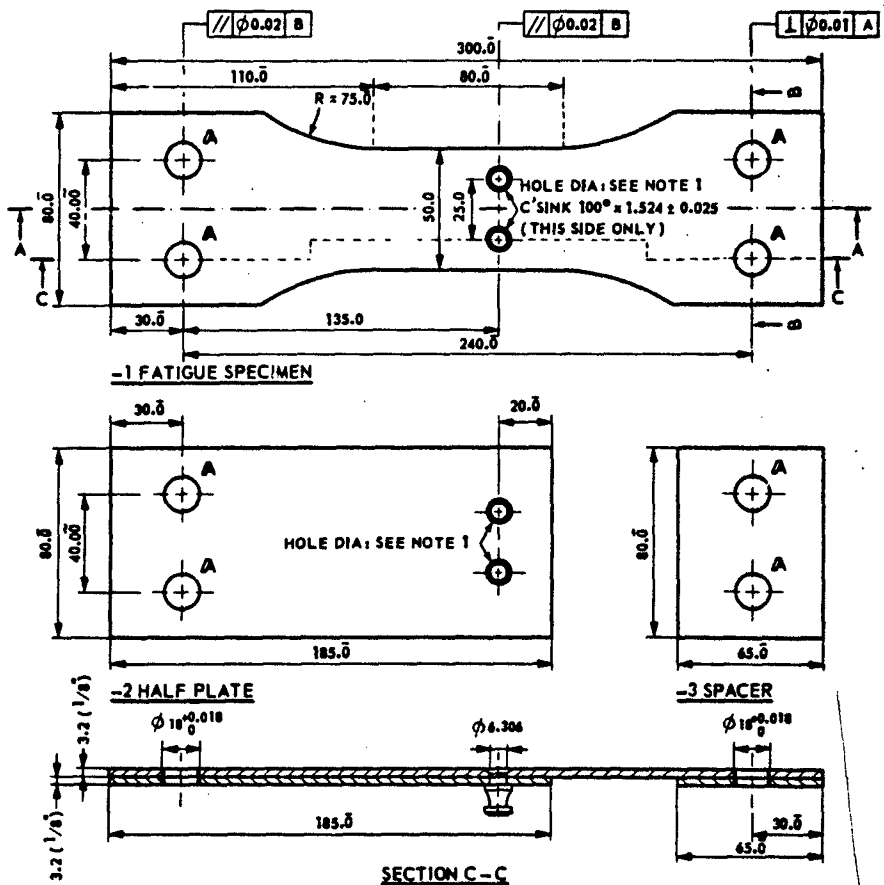


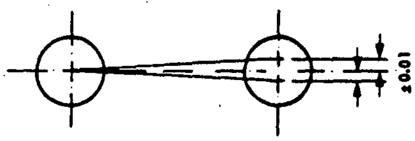
Fig. 2 The CFCTP core programme and recommended supplemental testing specimen. All dimensions are in millimetres.
Special tolerance indications are: 25 = 25 ± 0.5
25.0 = 25 ± 0.05
25.0̄ = 25 ± 0.1
25.0̃ = 25 ± 0.2

NOTES

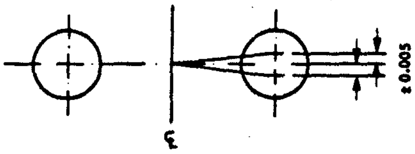
(1) Hole diameters 6.306 ± 0.044 mm for core programme specimens (slight press fit). Hole diameters 6.248 ± 0.0127 mm (interference fit) or 6.306 ± 0.044 mm (slight press fit) for supplemental testing specimens.

(2) All holes marked thus " **A** " are $18^{+0.018}_{+0}$ mm diameter.

(3) At the centre of each clamping hole the longitudinal tolerance with respect to the centre of its neighbouring clamping hole is ± 0.01 mm, i.e.



(4) At the centre of each clamping hole the longitudinal tolerance with respect to the junction of the centreline of the specimen and the line joining the centres of neighbouring clamping holes is ± 0.005 mm, i.e.



(5) Mill finish is retained on all surfaces without nicks, marks or scratches.

(6) Fasteners -4 and collars -5 are installed after treatment of parts but before topcoat application (see section 3.4.1).

(7) It is not necessary that a spacer -3 be made for each specimen.

3.2 Fastener Holes

The cylindrical parts of the Hi-Lok fastener holes in the fatigue specimen -1 and half plate -2 were drilled using special step drill combinations as illustrated in figure 3.

Fig. 3 Step drill combination for the fastener holes

The following table gives the nominal dimensions of the step drill combinations used for the CFCTP specimens.

STEP DRILL COMBINATION DIMENSIONS FOR THE CFCTP SPECIMENS

FASTENER FIT	STEP DRILL NOMINAL DIAMETER (mm)	DRILL NOMINAL DIAMETER (mm)	HOLE DIAMETERS (mm)	
			Minimum	Maximum
interference	4.8	6.248	6.235	6.261
slight press	4.8	6.306	6.262	6.350

Countersinking was done after drilling the cylindrical parts of the Hi-Lok fastener holes. Dimensions of the countersink are given in figure 4.

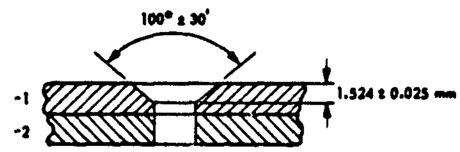


Fig. 4 CFCTP specimen countersink dimensions

After countersinking all hole edges EXCEPT the countersink were lightly deburred.

3.3 Fasteners

The VOI-SHAN Corporation supplied 4000 identical HL-19-PB-8-5 cadmium plated steel Hi-Loks, 2000 identical ion vapour deposited (IVD) aluminium coated Hi-Loks and 6000 identical HL-70-8 collars for use in the CFCTP. Of these about 1600 HL-PB-8-5 Hi-Loks and HL-70-8 collars were designated for the core programme and supplemental testing 7075-T76 specimens. The remaining Hi-Loks and collars were available to CFCTP participants for assembling supplemental testing specimens.

The coding -PB-8-5 refers to:

- PB: type II cadmium plate
- 8 : 6.35 mm pin diameter
- 5 : 6.35 mm to 7.94 mm grip length.

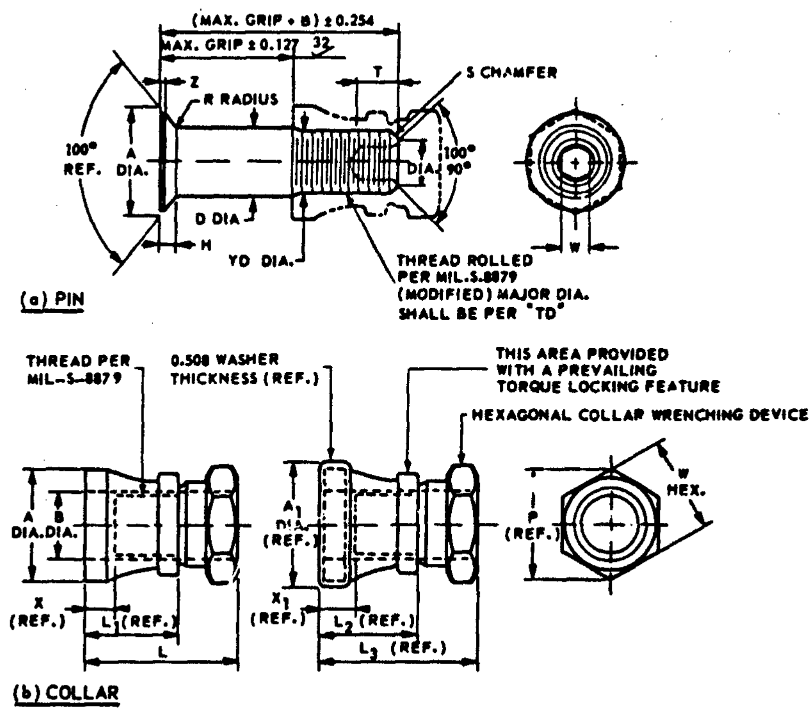


Fig. 5 Hi-Lok pin and collar

Figure 5 shows the Hi-Lok pin and collar with lettered indications of dimensions given in the following table.

CFCTP HI-LOK PIN AND COLLAR DIMENSIONS (MILLIMETRES)

LETTERED DIMENSIONS	A DIA.	B REF.	D DIA.	TD DIA.	F	H	R RAD.	∠ MAX.	SOCKET		
									W HEX.	T DEPTH	Y DIA.
PIN	10.03 9.90	10.03	6.337 6.312	6.198 6.121	0.152	1.549 1.499	0.762 0.508	0.381	2.456 2.405	3.810 3.302	3.607 3.009

LETTERED DIMENSIONS	A DIA.	A_1 DIA.	B DIA.	L	L_1 REF.	L_2 REF.	L_3 REF.	P REF.	W HEX.	X REF.	X_1 REF.
COLLAR	10.46 10.36	11.73	6.629 6.401	14.02 13.51	8.636	9.398	14.53	9.652	8.788 8.433	2.845	3.607

3.4 Corrosion Protection and Assembly

3.4.1 Core programme specimens

The corrosion protection scheme for the core programme specimens was applied as follows:

- chromate conversion coating on ALL surfaces
- inhibited epoxy polyamide primer EXCEPT in countersunk fastener holes
- assembly of fatigue specimen -1 and half plate -2 with Hi-Lok fasteners and collars and application of primer to the fastener area
- aliphatic polyurethane topcoat applied to all exterior surfaces
- specimens individually wrapped and shipped to CFCTP participants
- sealing of faying surface side edges and Hi-Lok collars for phase I specimens to be pre-exposed and for phase II specimens, in order to exclude corrosion attack except at fastener hole vicinities (see section 3.5).

NOTES

(1) Sealing of faying surface side edges and Hi-Lok collars was not done for phase I core programme specimens only to be tested in laboratory air (see section 2.1).

(2) For all other core programme specimens the sealing of faying surface side edges and Hi-Lok collars was done AFTER prestressing at 209 ± 10 K in a cold box (see sections 2.1 and 6).

For the core programme specimens the dimensions of the countersunk fastener holes resulted in a slight press fit of the Hi-Lok fasteners in the cylindrical parts of the fastener holes. Fastener installation was as follows:

- a large plastic retaining block was made with accurately parallel and flat surfaces, one of which was sculpted by drilling out two holes to easily accept the ends of the Hi-Lok fasteners as fully inserted in the fatigue specimen -1 and half plate -2
- the specimen, consisting of the fatigue specimen -1 and half plate -2, was supported by the sculpted block underneath the half plate -2 with the holes in the block aligned with the countersunk fastener holes in the specimen.
- the fasteners were then fully installed as lightly as possible using smooth flat plastic cylinders of diameter slightly less than the fastener head and mounted in a press
- the collars were installed using a special ratchet wrench* with provision for insertion of a hexagonal wrench, dimension W in figure 5a, that fitted into the end of the fastener: the hexagonal collar wrenching device, see figure 5b, automatically sheared off at the correct torque (6.78 - 9.04 Nm).

* These wrenches are usually available via aerospace companies. They are made by HI-SHEAR Corporation and when ordering them the fastener type and collar must be specified (see section 3.3). For the CFCTP a HLH 314-8 complete assembly was required.

3.4.2 Supplemental testing specimens

The procedures before Hi-Lok fastener and collar installation in supplemental testing programme specimens were recommended to be as in the following table.

PREPARATION OF SUPPLEMENTAL TESTING SPECIMENS BEFORE HI-LOK INSTALLATION

PROCESSING		WHEN TO DRILL COUNTERSUNK FASTENER HOLES TO FINAL DIMENSIONS	REQUIRED FASTENER HOLE CONDITION
MECHANICAL	CHEMICAL		
machine specimen; drill all holes marked **A** in figure 2; pre-bore countersunk fastener holes to a maximum of 4.8 mm diameter	anodizing and priming	after priming*	bare
		after anodizing and before priming*	primed
	chromate conversion coating and priming	after priming*	bare
		before conversion coating: mask off before priming	chromate conversion coated
		before conversion coating and priming	chromate conversion coated and primed

* care must be taken to prevent scratches in the protection schemes when drilling the countersunk fastener holes

It was suggested that masking off the countersunk fastener holes could be done either by using a rubber-based lacquer, e.g. SIKKENS Maskant and Process Coating 542/21, or by installing dummy fasteners accurately dimensioned to be an easy fit such that the holes would not be mechanically pre-conditioned before installing the actual fasteners.

After priming, the fatigue specimen -1 and half plate -2 were to be dry or wet assembled (i.e. with or without corrosion-inhibiting sealants in the countersunk fastener holes) with Hi-Lok fasteners and collars as described in section 3.4.1: less effort would be required to install the fasteners if a slight press fit were chosen instead of an interference fit (see NOTE (1) in section 3.1). The fastener area, including the fastener heads, was then to be re-primed and a topcoat applied to the specimen exterior surfaces. Sealing of faying surface side edges and Hi-Lok collars (section 3.5) was to be done AFTER prestressing at 209 ± 10 K in a cold box (see sections 2.1 and 6).

3.5 Sealing of Edges and Hi-Lok Collars

All specimens to be pre-exposed to 5 % aqueous $NaC\ell + SO_2$ and/or to be fatigued in a 5 % aqueous $NaC\ell$ salt spray environment, or any other environment except laboratory air, were to be sealed at the faying surface side edges and Hi-Lok collars of the assembled fatigue specimen -1 and half plate -2 in order to exclude corrosion attack except at the countersunk fastener holes. This sealing is shown schematically in figure 6: note that the faying surfaces around the sides of clamping holes were to be sealed.

The recommended sealant was PERMAGUM*, or its equivalent. PERMAGUM was made available to CFCTP participants by the NADC upon request.

NOTES

(1) Core programme specimens were supplied to CFCTP participants with the faying surface side edges and Hi-Lok collars unsealed. Sealing was done AFTER prestressing at 209 ± 10 K in a cold box (see section 2.1 and 6). Sealing was not necessary for phase I core programme specimens only to be tested in laboratory air (see section 2.1).

(2) The faying surface side edges and Hi-Lok collars of supplemental testing specimens were to be sealed after prestressing at 209 ± 10 K, excepting those specimens to be exposed and tested only in laboratory air, for which no sealing was necessary.

* PERMAGUM is the trade name for a non-hardening sealant made by VIRGINIA CHEMICALS, Portsmouth, Va., USA.

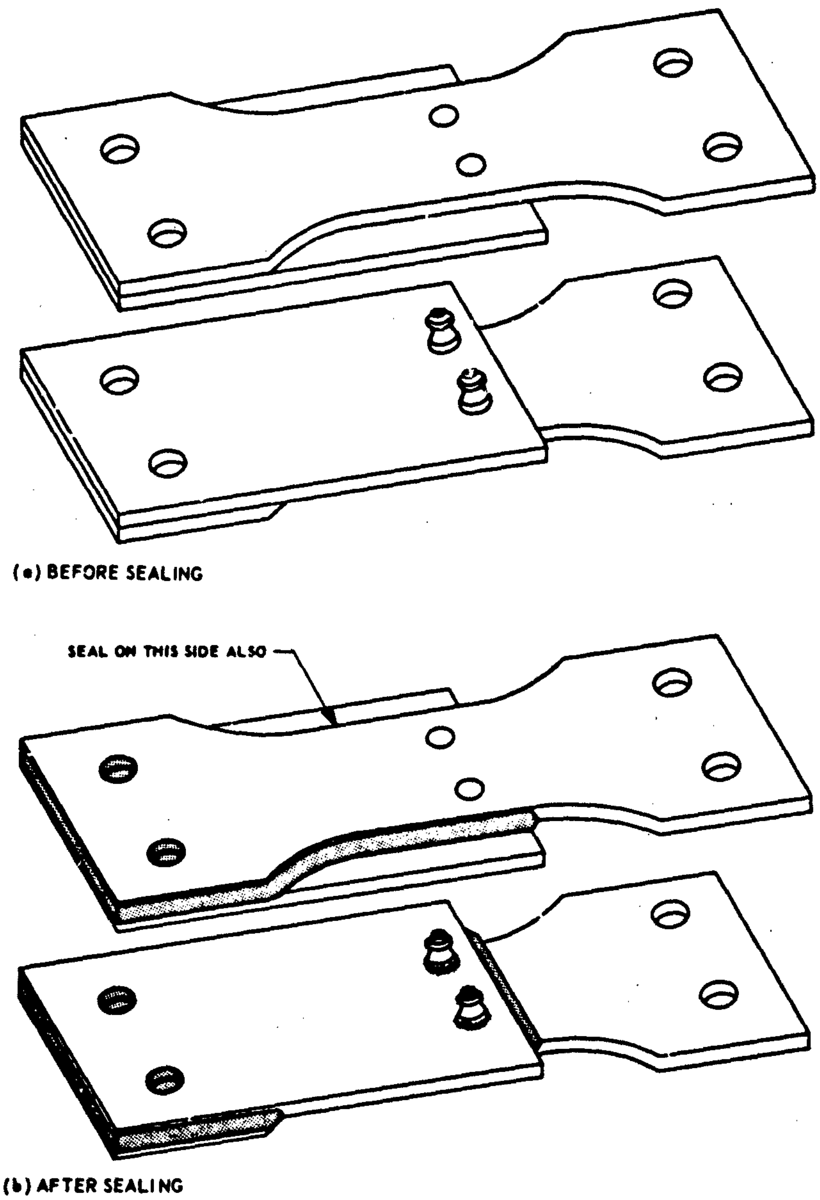


Fig. 6 Schematic of sealing faying surface side edges and Hi-lok collars

4 CLAMPING-IN

Clamping-in of the fatigue specimen assembly (fatigue specimen -1, half plate -2 and spacer -3) took place using bolted grips. With proper clamping-in procedure such grips minimise the introduction of additional secondary bending into the specimen assembly owing to misalignment.

4.1 Grips

Figure 7 shows the configuration of the CFCTP grip assembly (two required per specimen assembly).

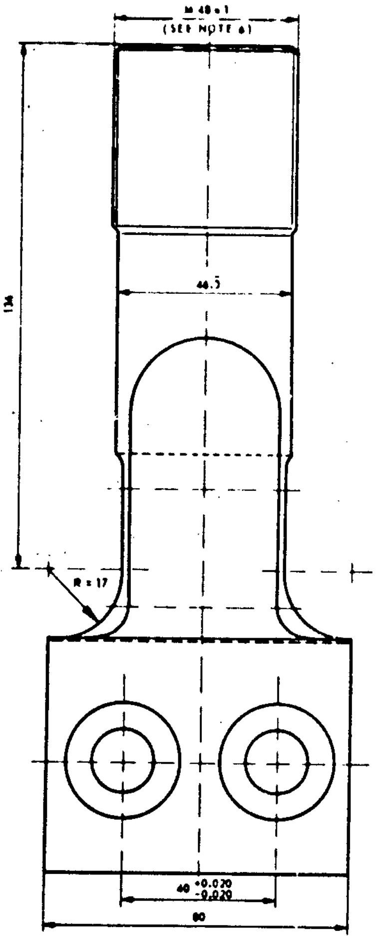


Fig. 7a Front view of grip assembly

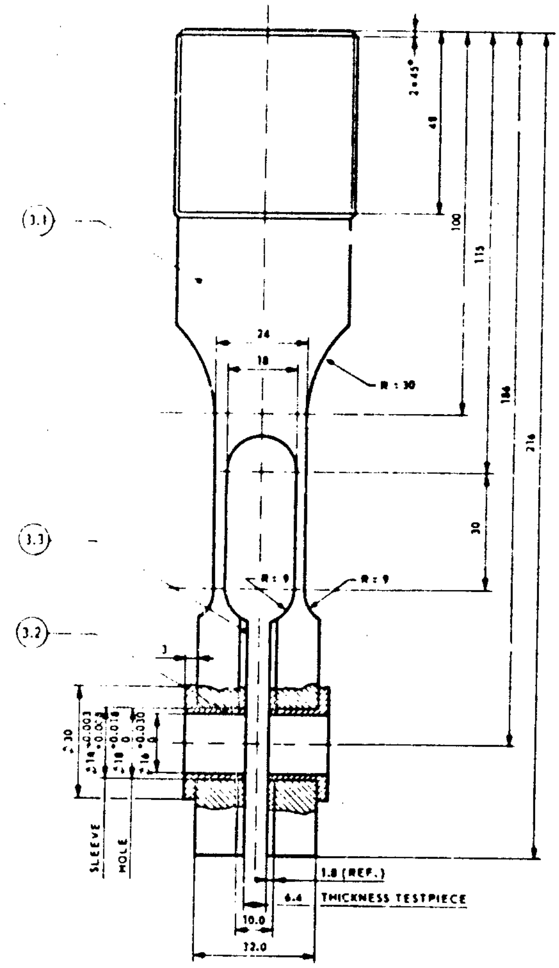


Fig. 7b Side view of grip assembly

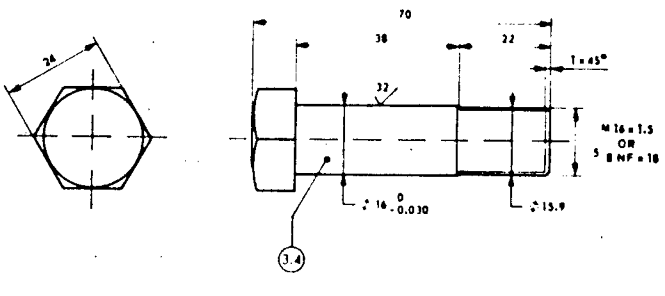


Fig. 7c Bolt

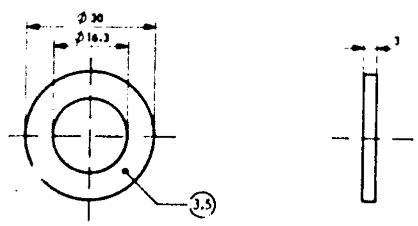


Fig. 7d Washer

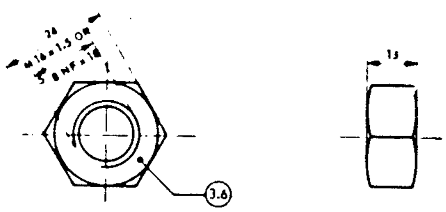


Fig. 7e Nut

The following table lists the component parts of the grip assembly.

GRIP PARTS

NUMBER PER SPECIMEN ASSEMBLY	PART NUMBER	NAME	STOCK
4	3.6	NUT	17-4 PH STEEL* , solution treated
4	3.5	WASHER	17-4 PH STEEL* , solution treated
4	3.4	BOLT	17-4 PH STEEL* , solution treated
4	3.3	PLATE	PHENOL-FORMALDEHYDE (TUFNOL or PERTINAX)
4	3.2	SLEEVE	PHENOL-FORMALDEHYDE (TUFNOL or PERTINAX)
2	3.1	CLAMPING HEAD	17-4 PH STEEL* , solution treated

* see note (3) below

NOTES

(1) All dimensions are in millimetres. Special tolerance indications are:

25 = 25 ± 0.5

25.0 = 25 ± 0.05

25.$\bar{0}$ = 25 ± 0.1

(2) Surface finish is √32 on all surfaces of parts 3.1, 3.2 and 3.3. Surface finish on part 3.4 is √125 except where otherwise specified (see figure 7c). Surface finish is √125 on all surfaces of parts 3.5 and 3.6.

(3) After finishing, parts 3.1, 3.4, 3.5 and 3.6 are heat treated in air at 755 ± 9 K for 1 hour followed by air cooling, resulting in a typical ultimate tensile strength of 1379 MPa in the longitudinal direction.

(4) There is a neat fit between parts 3.1 and 3.2.

(5) Part 3.3 is mechanically attached, i.e. not bonded, to part 3.1.

(6) The thread in the end of the clamping head must be adapted to individual requirements.

4.2 Bushings in Specimen Clamping Holes

Before clamping-in (see section 4.3) special polymeric material bushings were inserted into each clamping hole (**A** in figure 2) in the COMPLETE specimen assembly. These bushings were supplied to CFCTP participants by the NLR and NADC. The bushings had a nominal wall thickness of 1 mm and made a neat fit in the clamping holes, i.e. they could be inserted by hand. The bushings could be used for more than one test, depending on their post-test condition.

4.3 Clamping-in Procedure

The COMPLETE specimen assembly with bushings in each clamping hole is clamped in with the half plate -2 in the UPPER clamping head. As discussed in section 8.3, there are additional requirements for fatigue testing in a salt spray cabinet. These are:

- a clamping head extension
- the clamping heads are connected to the salt spray cabinet by soft plastic (PVC) bellows: this is a recommended arrangement
- the countersunk fastener heads on the fatigue specimen -1 must face a side wall of the salt spray cabinet.

The clamping-in procedure depends on whether the servohydraulic actuator is in the LOWER or UPPER crosshead. With the actuator in the LOWER crosshead, as is usual, the procedure is:

(1) Clamp the specimen assembly in the UPPER clamping head using the bolt/washer/nut assembly described in section 4.1. The fork of the clamping head is pressed against the specimen by torqueing each bolt to a prescribed value (see note (4) below). Rotation of the clamping head during torqueing must be restrained.

(2) Bring the LOWER clamping head to the correct height by moving the actuator.

(3) Insert the clamping bolts through the LOWER clamping head and specimen assembly (fatigue specimen -1 and spacer -3) and loosely attach the washers and nuts.

(4) Move the actuator down so that the fatigue specimen is pretensioned to the mean stress to be applied in the fatigue test.

(5) Clamp the specimen assembly in the LOWER clamping head by torqueing each bolt to a prescribed value (see note (4) below). Rotation of the clamping head during torqueing must be VERY CAREFULLY restrained.

With the actuator in the UPPER crosshead the procedure given in the following points (6)-(10) applies instead of points (1)-(5):

(6) Clamp the specimen assembly in the LOWER clamping head using the bolt/washer/nut assembly described in section 4.1. The fork of the clamping head is pressed against the specimen by torqueing each bolt to a prescribed value (see note (4) below). Rotation of the clamping head during torqueing must be restrained.

(7) Bring the UPPER clamping head to the correct height by moving the actuator.

(8) Insert the clamping bolts through the UPPER clamping head and specimen assembly (fatigue specimen -1 and half plate -2) and loosely attach the washers and nuts.

(9) Move the actuator up so that the fatigue specimen is pretensioned to the mean stress to be applied in the fatigue test.

(10) Clamp the specimen assembly in the UPPER clamping head by torqueing each bolt to a prescribed value (see note (4) below). Rotation of the clamping head during torqueing must be VERY CAREFULLY restrained.

NOTES

(1) Pre-tensioning of the specimen before final clamping-in prevents slipping in the grips for fatigue load histories without compression loads, e.g. the core programme constant amplitude testing (see section 2.1).

(2) For the manoeuvre spectrum FALSTAFF it was recommended to pretension at load level 14 (see section 12.1).

(3) For the gust spectra TWIST and MINI-TWIST pre-tensioning should be at the mean stress in flight (see section 12.2).

(4) It is difficult to prescribe a torque value for which no slippage occurs whatever the load history, since the required torque depends on the stress levels imposed on the specimen.
An NLR calculation indicated that a torque on each clamping bolt of 88 Nm (= 65 ft.lbf.) would be adequate. However, all CFCTP participants were requested to check for slippage during the pilot fatigue tests on unexposed specimens subsequently fatigue tested in laboratory air (see sections 2.1.2, 2.2.2 and 10.1). ON NO ACCOUNT was checking for slippage to take place during fatigue testing in salt spray.

(5) After clamping-in the sealing of the faying surface side edges and Hi-Lok collars of those specimens to be fatigued in salt spray was to be checked and resealed where necessary.

(6) The entire grip assembly (but NOT the soft plastic (PVC) bellows) was to be protected during salt spray fatigue testing by the application of AMLGUARD, which was supplied to participants by the NADC on request. The AMLGUARD had to cure for 1 day before testing.

(7) It turned out that under the clamping bolt HEADS the sleeves (part 3.2 in figure 7b) had to be renewed after about 5 - 6 tests. Otherwise there was a risk of specimen failure at the clamping holes.

4.4 Alignment Guidelines for Electrohydraulic Machines

Besides using grips that minimise the introduction of supplementary bending, the alignment quality of electrohydraulic fatigue machines should be checked. In what now follows the alignment specifications maintained by the NLR are discussed. These specifications were intended as guidelines for CFCTP participants.

The alignment specifications of the NLR are:

(1) Using a round and relatively short specimen at maximum load in the load range equal to 0.1 of the maximum capacity, the difference due to bending between the specimen surface stresses and the average axial stress shall not be higher than 3 %.

(2) After moving up and/or down, the differences in translation between the left and right hand sides of the moving cross head shall not be more than 0.02 mm.

(3) The eccentricity of the moving crosshead axis with respect to the axis of the fixed crosshead shall be not more than 0.02 mm.

These specifications were adopted by the NLR notably for minimising supplementary bending during axial load tests, and for high cycle fatigue tests, especially flight simulation with its numerous small load excursions.

The reason for the percentage in specification (1) is that long term experience has shown that exceeding a 3 % stress contribution from bending will result in a significant decrease in fatigue life for axial stress levels near the fatigue limit. As shown in figure 8 this specification covers the combination of two types of alignment error: rotation through an angle α and translation (eccentricity) over a distance e. The maximum bending stress can be determined by rotating a round specimen, with strain gauges attached as shown schematically in figure 8, around its longitudinal axis. Disadvantages of this method are that the dimensional accuracy of the specimen, especially at the ends, must be very high and perfectly adapted to the testing machine, and that only one location of the moving crosshead can be checked. To overcome this second disadvantage specification (2) was adopted.

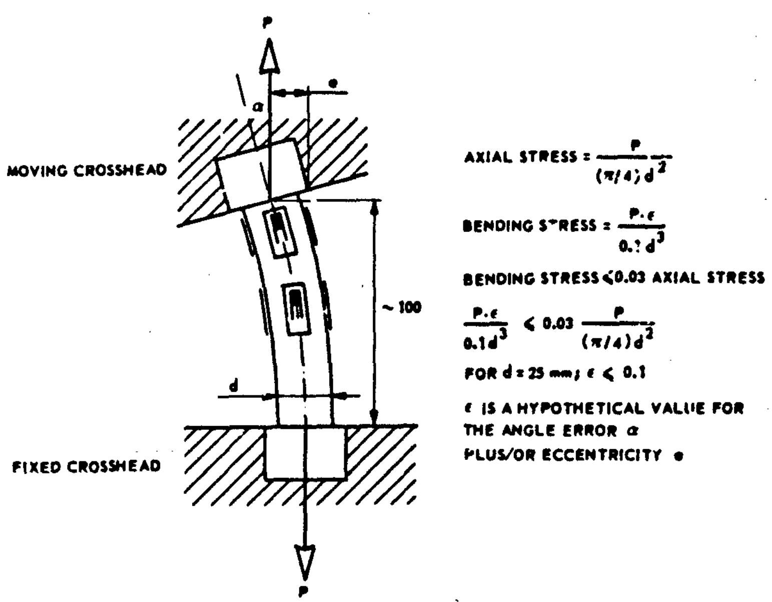


Fig. 8 Alignment errors covered by specification (1)

Specification (2) is based more or less on accepted manufacturing accuracy for a 670 mm wide crosshead. Figure 9 shows that the difference in translation (wobbling) between right and left hand sides of the moving crosshead results in a rotation α, which for a crosshead 670 mm wide is 6" (seconds of arc). As an example, if a 100 mm long x 25 mm diameter specimen is forced to follow this rotation, the difference in strain is 0.0008 %. From Hooke's Law it follows that for an aluminium alloy specimen there is a surface stress difference of 0.55 MPa. This does not seem impressive, but if it is to be ≤ 3 % of the lowest applied axial stress, then the lowest axial stress must be 18 MPa: this is significant, especially for flight simulation loading. Thus specification (2) is maintained by the NLR, and crosshead wobbling is measured using dial gauges or LVDTs.

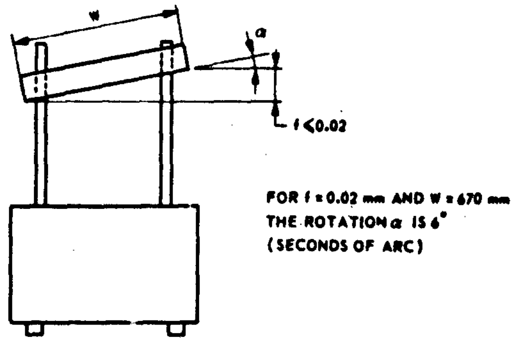


Fig. 9 Translation differences (wobbling) for the moving crosshead

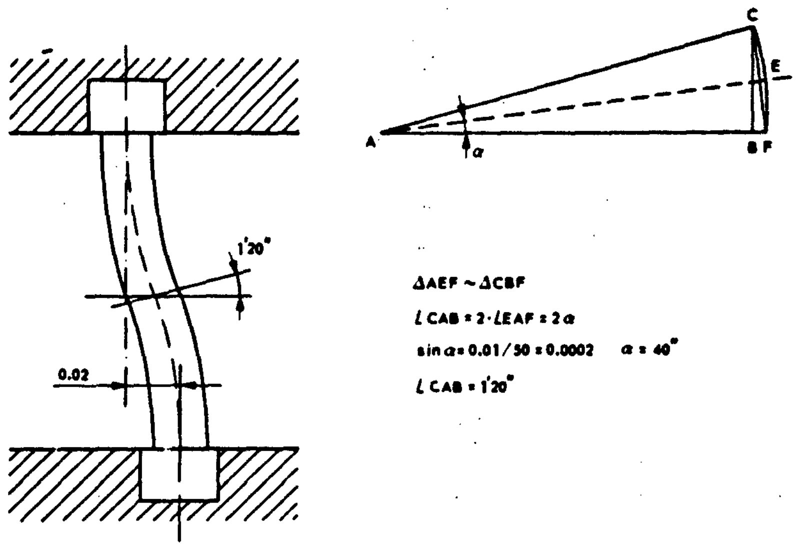


Fig. 10 Eccentricity of moving crosshead with respect to the axis of the fixed crosshead

Specification (3) permits a similar calculation of the bending stresses. Figure 10 shows for the same round specimen as before that eccentricity of the moving crosshead with respect to the axis of the fixed crosshead forces the specimen to assume an S-shape. For a 100 mm long x 25 mm diameter specimen the difference in strain is 25 sin 1'20" = 0.01 %. Again from Hooke's Law, it follows that for an aluminium alloy specimen there is a surface stress difference of 7 MPa. This stress difference appears fatal, in view of specification (1). However, in practice the machine frame is not infinitely stiff, and any play in the clamping will drastically reduce the bending forces. Nevertheless, specification (3) is important and will tend to dominate in attempts to meet specification (1).

In developing alignment specifications at the NLR, due attention was paid to the feasibility of testing machines meeting the specifications. In fact, the last two frames received at the NLR could meet specifications (1), (2) and (3). Thus it was recommended that CFCTP participants establish similar or identical alignment specifications for their testing machines.

5 ADDITIONAL GUIDELINES FOR ELECTROHYDRAULIC MACHINES

The NLR has developed additional specifications concerning the quality of electrohydraulic fatigue machines. These specifications are quoted here since they were given as guidelines for CFCTP participants.

5.1 Performance

There is a self-evident specification that the powerpack-machine frame-electronics assembly shall demonstrate the performance curve given by the manufacturer.

5.2 Static Calibration

The errors shown by the static calibration of stroke and load shall not exceed 1 %.

5.3 Dynamic Calibration

The errors shown by the dynamic calibration of stroke and load shall not exceed 3 %.

5.4 Hydraulic Shut-off Effects

Overloads due to hydraulic shut-off shall not exceed 5 % and shall preferably not exceed 3 %. A storage oscilloscope can show exactly what happens to the load on a specimen when the power pack is shut off, either manually or unexpectedly by the error trip. NLR experience is that overloads of 25 % can occur, and these are sufficient to vitiate a test result in some cases.

As yet there is no requirement that electrohydraulic fatigue machines meet similar or identical specifications to that of the NLR. Hence, whenever shut-off is done manually at the NLR the load is first zeroed and the specimen unclamped. However, the problem of unexpected shut-offs remains.

5.5 Electromagnetic Interference Effects

Overloads due to electromagnetic interference (EMI) effects shall not exceed 3 %. For example, a storage oscilloscope reveals impressive spikes when a simple low voltage soldering device is used in the vicinity of the testing machine, figure 11.

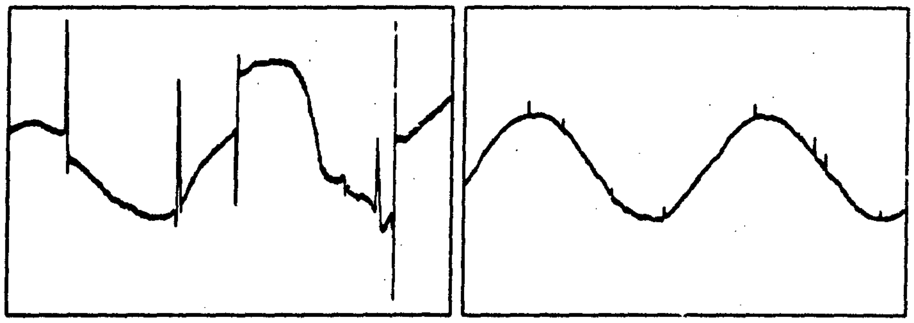


Fig. 11 Electromagnetic interference by a soldering iron and measured on the load cell output

Fortunately, the spikes have a high frequency so that the inertia of the actuator will dampen their effect. Also, the stiffness (or lack of it) of a specimen has an influence: a compliant specimen will further reduce the effect of a spike. Nevertheless, EMI should not be ignored, and MIL Standards 461A and 462 can be helpful in reducing these effects.

6 COLD BOX

Before environmental exposure and fatigue testing all specimens were to be prestressed at low temperature with two cycles to the maximum stress occurring in the subsequent fatigue test or 215 MPa, whichever was the greater. The purpose of this low temperature prestressing was to simulate service cracking of conventional paint and primer layers in the countersunk fastener hole vicinities: such paints and primers possess a glass transition temperature (∿250-260K) below which they are brittle. Prestressing took place at 209 ± 10 K, which allowed a generous margin for temperature control while not exceeding the glass transition temperature. The specimen assemblies were then stored in a desiccator at room temperature to await further testing (see also section 9).

In what follows a cold box for low temperature prestressing will be discussed. This description was intended as a guideline for CFCTP participants: any alternative solution was acceptable provided that the temperature control of the specimen was adequate (209 ± 10 K in the location containing the countersunk fastener holes).

6.1 Schematic of NLR Cold Box

A simple circuit diagram of the essential equipment for the NLR cold box is given in figure 12, and a photograph of the original equipment is shown as figure 13. This equipment was modified to be better suited to the dimensions of the CFCTP specimen, as discussed in section 6.2.

6.2 Configuration for the CFCTP Specimen

Three views of the modified cold box for testing the CFCTP specimen are shown in figure 14. Note that the liquid air supply tube is copper and is perforated only on the side facing AWAY from the specimen. Further, the opening for specimen insertion is smaller than in the original NLR cold box.

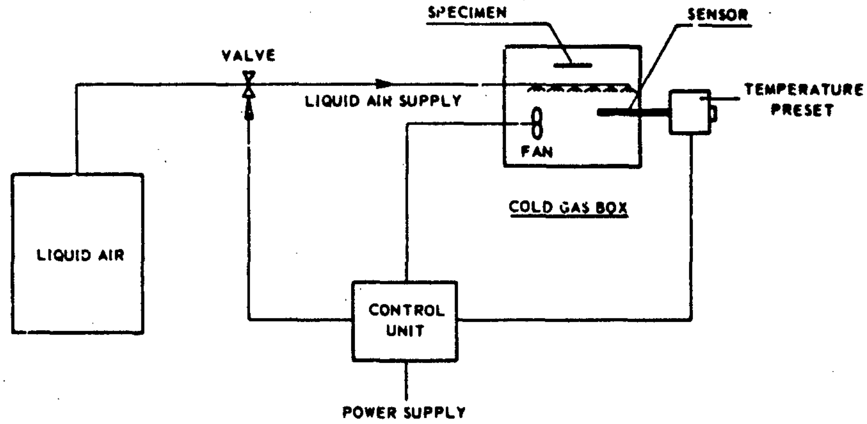


Fig. 12 Schematic of the NLR cold box

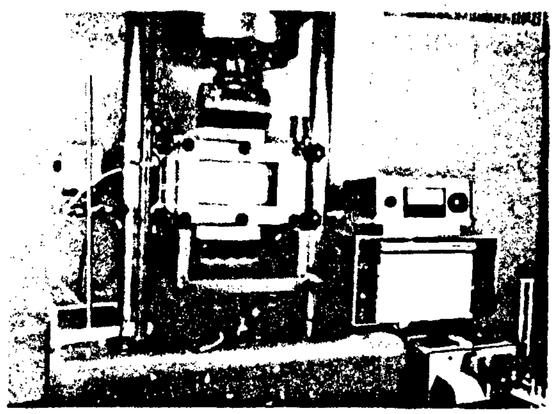


Fig. 13 NLR cold box for fatigue crack propagation tests at low temperatures

6.3 Calibration of Cold Boxes

For cold box calibration the NADC supplied each CFCTP participant with a dummy fatigue assembly. A thermocouple was then to be securely attached to the fatigue specimen -1 midway between the two countersunk Hi-Lok fasteners. A straightforward and satisfactory method used by the NLR was to drill a hole slightly larger than the thermocouple sheath to about halfway through the specimen thickness. The thermocouple was then inserted and the hole diameter was decreased by indenting the specimen close to and around the hole, using a hard punch. In this way the thermocouple was securely clamped in and made good contact with the specimen.

The thermocouple for temperature measurement within the NLR cold box, figure 14c, was inserted in a block of aluminium and clamped in a similar manner as described for the fatigue specimen.

Calibration proceeded as follows:

- the dummy specimen was clamped in and the cold box assembled round it
- the temperature sensor (figure 14c) was adjusted so that regulation of the liquid air supply resulted in a specimen thermocouple reading corresponding to an average* temperature of 209 K
- for the aluminium block the thermocouple reading and hence the temperature were recorded.

Use of the NLR cold box during prestressing the actual specimens for fatigue testing took place WITHOUT thermocouples on the specimens but using the aluminium block temperature as monitor. This procedure avoided damage to the corrosion protection system other than the simulated service cracking of conventional paint and primer layers in the vicinities of the countersunk fastener holes.

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* A very steady temperature is not possible with the NLR cold box system, but control within the specified range of ± 10 K (see the beginning of section 6) was easily obtainable.

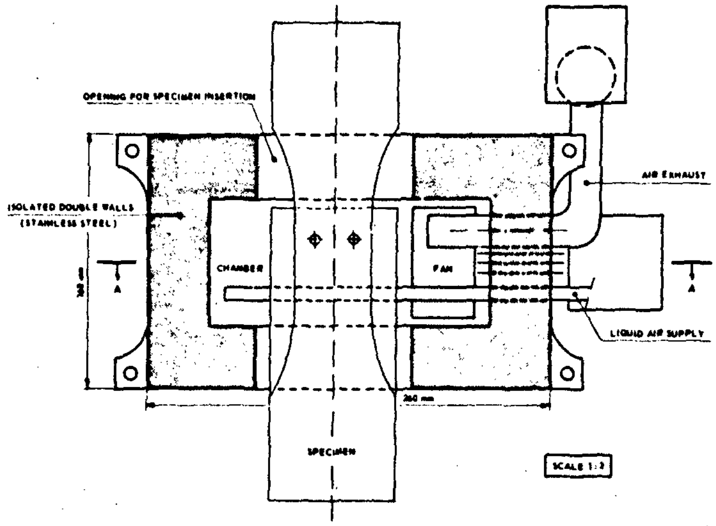


Fig. 14a Front view of the box (front panel removed)

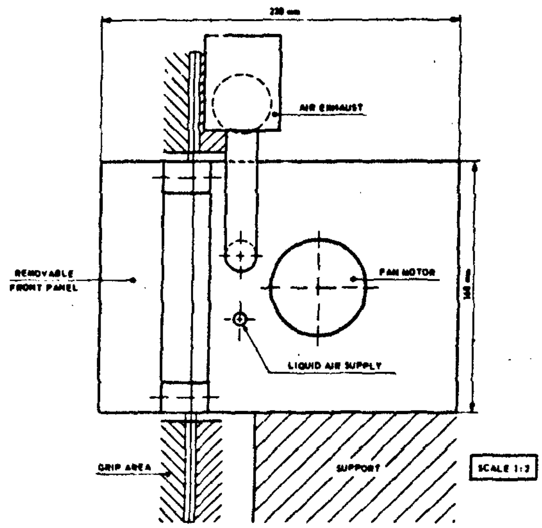


Fig. 14b Side view of the box

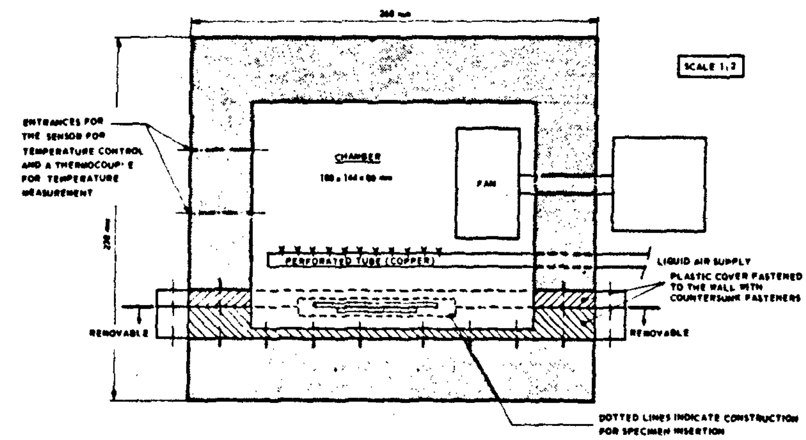


Fig. 14c Section A-A

7 PRE-EXPOSURE CHAMBERS AND PROCEDURE

The CFCTP schedules (see sections 2.1.2 and 2.2) included some tests with pre-exposure to a corrosive environment before fatigue testing. GENERAL requirements for the core programme and recommended supplemental testing pre-exposure conditions were and are:

- solution : 5 % aqueous NaCℓ + dissolved SO_2 generated by reaction of Na_2SO_3 with H_2SO_4
- $NaCℓ/SO_2$ ratio : for 3 litres of 5 % aqueous NaCℓ, 5.6 ± 0.8 g Na_2SO_3 mixed with not less than 16 mℓ of 50 % concentrated H_2SO_4
- test temperature : 315 ± 2K
- test duration : 72 hours.

This test was originally developed to simulate the flight deck environment of an aircraft carrier (sea spray and stack emissions containing sulphur). It is reported in "Localized Corrosion-Cause of Metal Failure", ASTM Special Technical Publication 516, pp. 273-302 (1972). In this reference there is a test requirement that the ratio of solution volume to specimen surface area be 7.75-15 $mℓ/cm^2$. This requirement was included because unprotected specimens were exposed, and it is then necessary to prevent premature cessation of the corrosion reaction by ensuring an adequate supply of solution. Since only a very small unprotected area, if any, of the CFCTP specimens was accessible to the environment (i.e. around and in the countersunk fastener holes) this volume/area requirement was OMITTED from the CFCTP. However, other requirements concerning volume of solution to number of specimens were specified, see section 7.1 and 7.3.

7.1 Core Programme Chamber

A schematic of the core programme pre-exposure chamber is given in figure 15. In addition to the GENERAL requirements listed at the beginning of section 7, the PARTICULAR requirements for core programme pre-exposure testing were:

- each specimen was individually exposed
- the specimen assembly consisting of fatigue specimen -1 and half plate -2 was immersed horizontally with the fatigue specimen -1 uppermost: it was NOT necessary to pre-expose spacers -3
- the specimen was held up by plastic supports (without sharp edges) such that the sealing of the Hi-Lok collars could not be damaged by contact with the bottom of the chamber
- the volume of 5 % aqueous NaCℓ for each specimen was 3 litres
- the ratio of volume of solution to the volume of air/gas above it was approximately 1:4.

NOTE

(1) For the fairly small core programme pre-exposure chamber the regulation of the test temperature of 315 ± 2 K was possible by using a hotplate. An immersion heater was, however, recommended.

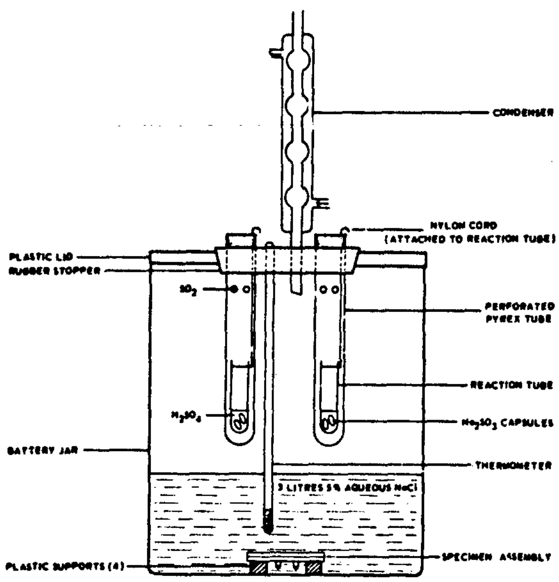


Fig. 15 Core programme pre-exposure chamber for the NaCℓ + SO_2 immersion test

7.2 Core Programme Pre-exposure Procedure

The procedure for commencing the core programme NaCℓ + SO_2 immersion test was as follows:

- the specimen assembly was immersed in 3 litres of 5 % aqueous NaCℓ which was already at a nominal temperature of 315 K
- the plastic lid containing the condenser and perforated pyrex tubes but MINUS the reaction tubes was sealed onto the chamber using silicone sealant
- the temperature of the 5 % aqueous NaCℓ was regulated to 315 ± 2 K
- the required amounts of H_2SO_4 were added to the reaction tubes which were then suspended just inside the perforated pyrex tubes
- gelatine capsules containing the required amounts of Na_2SO_3 powder or pellets were added to the reaction tubes
- the reaction tubes were quickly lowered to the bottoms of the perforated pyrex tubes, which were then sealed with rubber stoppers
- the beginning of the test was taken to be when vigorous gaseous emission from the gelatine capsules commenced(about 10 minutes after the capsules were added to the reaction tubes).

After 72 hours of testing the specimen assembly was removed from the NaCℓ + SO_2 solution and cleaned in the following way (see also section 9):

- 30 minutes rinse in copious amounts of tap water at 291-298 K
- final rinse in distilled water at 291-298 K for not less than 1 minute
- air dry at 323 K for 30 minutes.

As soon as possible thereafter, preferably IMMEDIATELY, the entire specimen assembly was clamped in and fatigue tested. If delay was unavoidable, the specimen assembly was stored in a desiccator at room temperature until fatigue testing could begin, care being taken not to damage the sealing of faying surface side edges and Hi-Lok collars (see also section 9).

Incidental spot checks of the solution pH after testing were recommended.

7.3 Supplemental Testing Programme Chamber

A schematic of the supplemental testing programme pre-exposure chamber is given in figure 16. Besides the GENERAL requirements listed at the beginning of section 7, the PARTICULAR requirements were and are:

- specimens could be exposed in batches of up to 20
- directly before exposure it was OPTIONAL whether each specimen underwent pre-treatment with a cleansing agent (see note (1) below)
- the specimen assemblies consisting of fatigue specimens -1 and half plates -2 were to be immersed at about 45° to the horizontal with the fatigue specimens -1 uppermost: it was NOT necessary to pre-expose spacers -3
- the specimens were to be held by a plastic rack (without sharp edges) such that the sealing of faying surface side edges and Hi-Lok collars could not be damaged
- the volume of 5 % aqueous NaCℓ for each specimen was to be 1 litre.

NOTES

(1) Since aircraft are routinely washed a cleansing pre-treatment was and is allowed as an OPTION for CFCTP participants. The choice of pre-treatment is also optional. An example of a typical treatment is:

- 10 minutes in TURCO AIR TEC No. 10 at a dilution of 20 : 1 with tap water at 291-298 K
- rinse with copious amounts of tap water at 291-298 K for 1 minute
- drain for 5 minutes at room temperature.

(2) Regulation of the test temperature of 315 ± 2 K to be obtained by using an immersion heater.

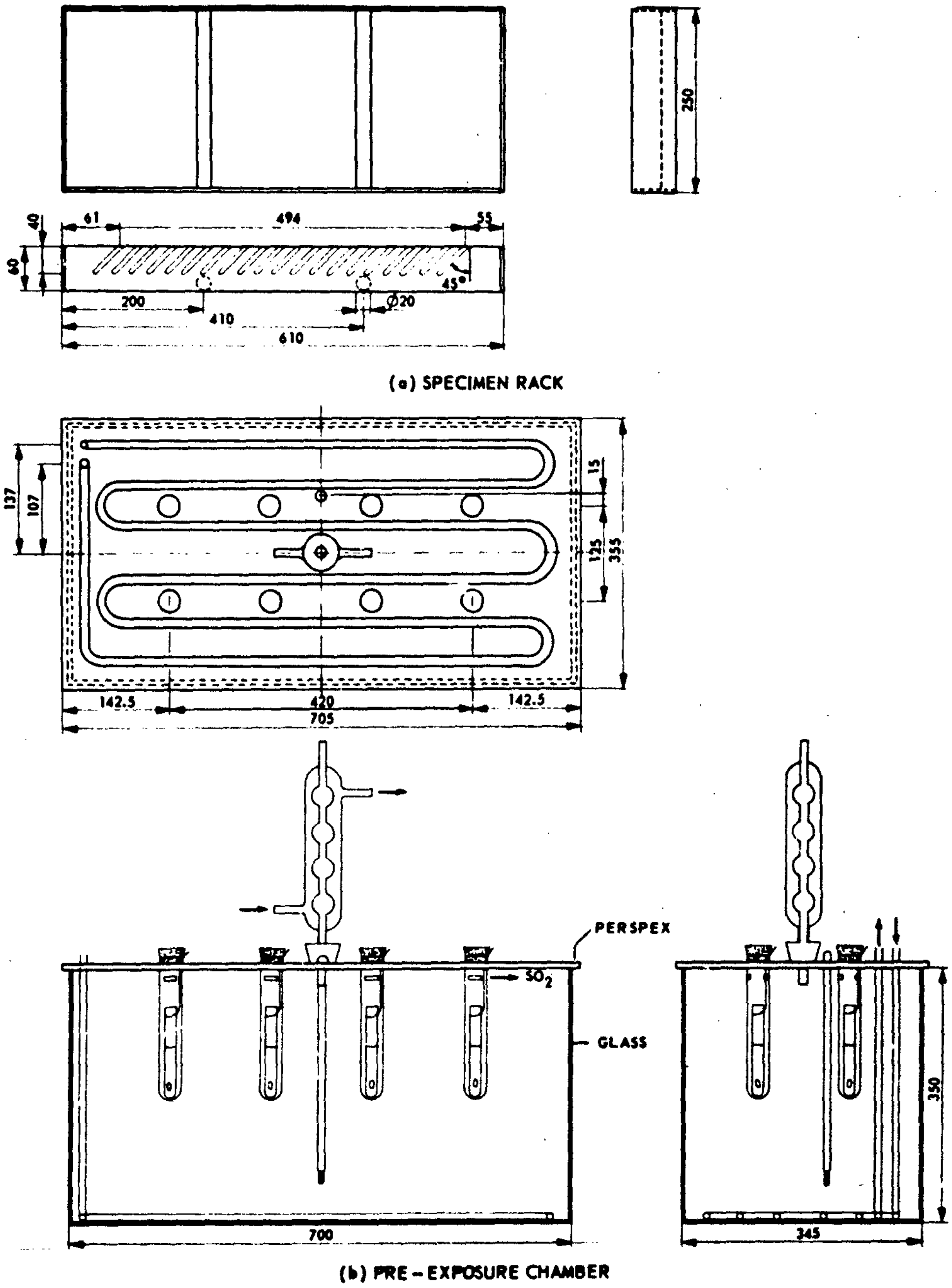


Fig. 16 Supplemental testing programme pre-exposure chamber for the NaCl + SO_2 immersion test

7.4 Supplemental Testing Programme Pre-exposure Procedure

The procedure for commencing the supplemental testing programme NaCℓ + SO_2 immersion test is as follows:

- the specimen assemblies are immersed in the required amount of 5 % aqueous NaCℓ, which is already at a nominal temperature of 315 K: if an optional pre-treatment has been done (see note (1) in section 7.3) the immersion in 5 % aqueous NaCℓ shall occur IMMEDIATELY after pre-treatment

- the plastic lid containing the condenser and perforated pyrex tubes but MINUS the reaction tubes is sealed onto the chamber using silicone sealant

- the temperature of the 5 % aqueous NaCl is regulated to 315 ± 2 K
- the required amounts of H_2SO_4 are added to the reaction tubes which are then suspended just inside the perforated pyrex tubes
- gelatine capsules containing the required amounts of Na_2SO_3 powder or pellets are added to the reaction tubes
- the reaction tubes are quickly lowered to the bottoms of the perforated pyrex tubes, which are then sealed with rubber stoppers
- the beginning of the test is taken to be when vigorous emission from the gelatine capsules commences (about 10 minutes after the capsules are added to the reaction tubes).

After 72 hours of testing the specimen assemblies are removed from the NaCl + SO_2 solution and cleaned in the following way (see also section 9):

- 30 minutes rinse in copious amounts of tap water at 291-298 K
- final rinse in distilled water at 291-298 K for not less than 1 minute
- air dry at 323 K for 30 minutes.

The specimen assemblies are then stored in a desiccator at room temperature to await fatigue testing, care being taken not to damage the sealing of faying surface side edges and Hi-Lok collars (see also section 9).

8 CORROSION FATIGUE SALT SPRAY CABINET

The CFCTP testing schedules (see sections 2.1.2 and 2.2) include fatigue tests in a salt spray environment. The environmental conditions are:

- solution : 5 % aqueous NaCl acidified with H_2SO_4 to a pH of 4 ± 0.1. Correction for TOO LOW a pH to be made by addition of 0.1 N NaOH
- test temperature : solution and humidified air (see section 8.1) at 295 ± 2 K
- test operation : continuous salt spray, solution pH to be checked daily. Atomization and quantity of salt spray checked according to paragraph 8.2 in ASTM STANDARD B 117.

8.1 Schematic of the Salt Spray Equipment for the CFCTP

A schematic diagram of the essential equipment for fatigue tests in salt spray is given in figure 17. Excepting the salt spray cabinet G and internal salt solution reservoir E, all items are obtainable from the GS/HARSHAW EQUIPMENT CO., which has representatives in Europe and North America. These items are:

(1) GS-9 gallon plastic distilled water storage tank with plastic tubing and necessary fittings for filling and automatic constant level control of humidifying tower.

(2) GS-20 gallon plastic external salt solution storage tank with plastic tubing, fittings and adapters for filling and automatic constant level control of inside salt solution reservoir.

(3) GS #43 stand for mounting GS level control reservoirs with storage shelf.

(4) Plexiglas saturator (humidifying) tower with heater, controls and gauges.

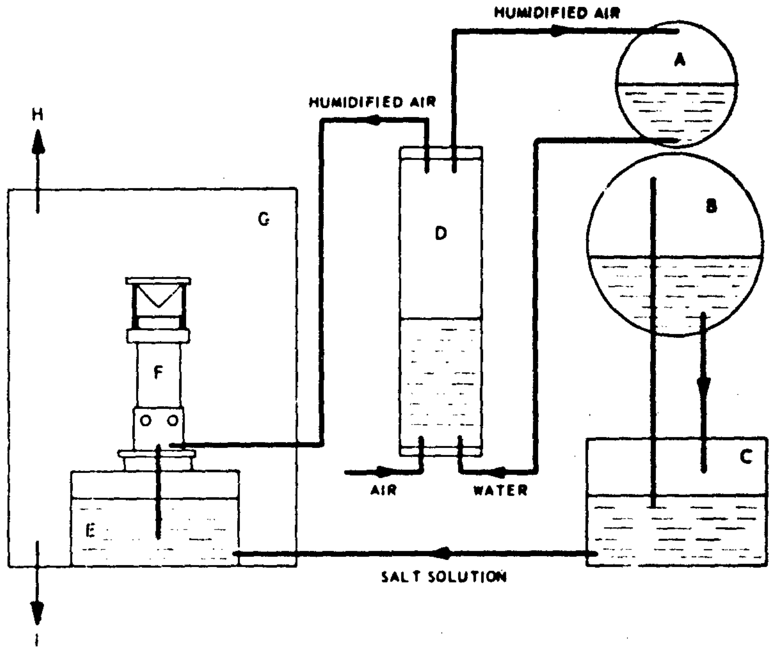
(5) GS "Uni-Fog" dispersion tower* complete with salt spray atomizer and fittings.

(6) #7009-10 combination GS jet exhaust and GS wet bottom drain.

(7) #7002 special air regulator for the saturator tower.

An optional item for the CFCTP was the #7003 special air gauge. Information on the installation of all these items of equipment is available from GS/HARSHAW.

* The "Uni-Fog" dispersion tower is normally supplied for a standard height and with an integral salt solution reservoir. For the CFCTP the tower was shortened to a total height of 320 ± 5 mm from the top of the integral reservoir to the lid of the tower. Furthermore, the integral reservoir was removed and the tower built onto a reservoir (E in figure 17) integral with the salt spray cabinet G, as described in section 8.2. The height of the cone above the cylindrical rim was to be about 25 mm (see figure 18a).



KEY

A	WATER CONTROL RESERVOIR FOR HUMIDIFYING TOWER	
B • C	SALT WATER LEVEL CONTROL RESERVOIRS	
D	HUMIDIFYING TOWER	
E	INTERNAL SALT SOLUTION RESERVOIR	
F	"UNI – FOG" DISPERSION TOWER	
G	CORROSION FATIGUE SALT SPRAY CABINET	
H	JET EXHAUST	COMBINATION ASSEMBLY
I	WET BOTTOM DRAIN	

Fig. 17 Schematic of the salt spray equipment for corrosion fatigue testing

8.2 Salt Spray Cabinet With Internal Reservoir

In what follows a salt spray cabinet for corrosion fatigue testing will be discussed. This description was intended as a RECOMMENDED guideline for CFCTP participants. Alternative designs were acceptable provided that the fatigue specimen and "Uni-Fog" tower were vertical during testing and that the internal volume of the cabinet, excluding the integral reservoir, was no less than 130 litres.

Four views of the salt spray cabinet are shown in figure 18. The construction material is 12.7 mm thick perspex adhesively bonded and then sealed at all internally exposed joints with silicone sealant. Also required are 16 6.35 mm diameter stainless steel or nylon bolts and wing nuts for fastening the access door to the cabinet. The heads of the bolts are silicone sealant bonded to the front frame and reinforcement.

There are six entrances to the salt spray cabinet and one entrance to the integral salt solution reservoir. The salt spray cabinet entrances are:

(1) At the front of the cabinet a large access port, closed by the door during testing.

(2) and (3) Circular ports for exit of the fatigue specimen clamping heads.

(4) and (5) Jet exhaust and wet bottom drain holes.

(6) A hole for access of the humidified air line to the "Uni-Fog" tower.

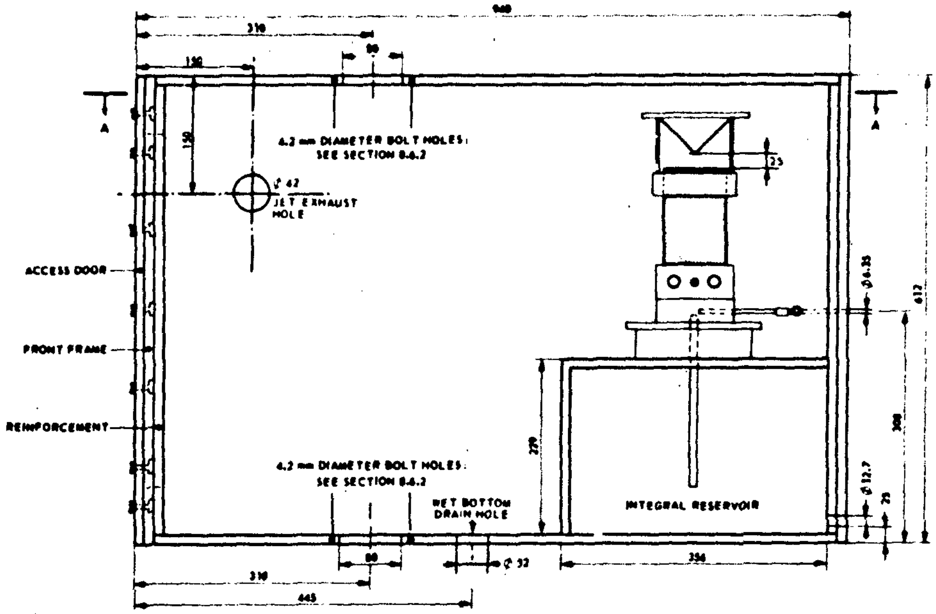


Fig. 18a Side view of salt spray cabinet

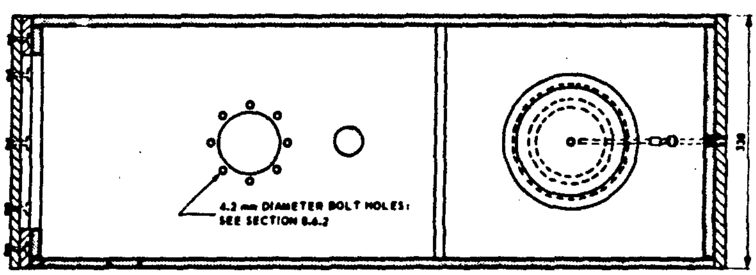


Fig. 18b Section A-A of salt spray cabinet

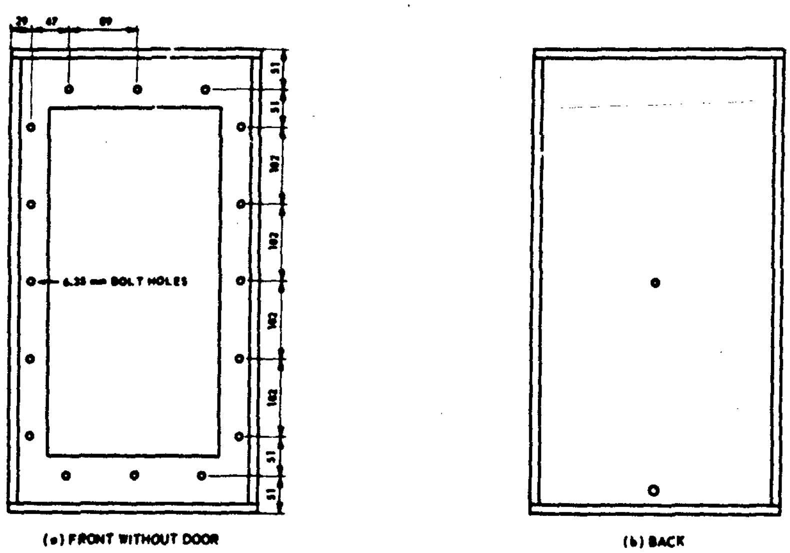


Fig. 18c Front and back views of salt spray cabinet

8.3 Attachment of Specimen + Grips Assembly

A schematic of the specimen + grips assembly attachment to the salt spray cabinet is shown in figure 19. The following GENERAL points are to be noted:

(1) The specimen is oriented with the half plate -2 gripped in the UPPER clamping head (see also section 4.3).

(2) The countersunk fastener heads on the fatigue specimen -1 must face a side wall of the salt spray cabinet. Tightening of the clamping head bolts and nuts then readily occurs via the front access port.

(3) A clamping head extension is required, see section 8.4.

(4) The clamping heads are connected to the salt spray cabinet by soft plastic (PVC) bellows, see section 8.5, with a total extension capability of at least 200 mm. These bellows were RECOMMENDED.

(5) Sealing arrangements are discussed in sections 8.6 and 8.7.

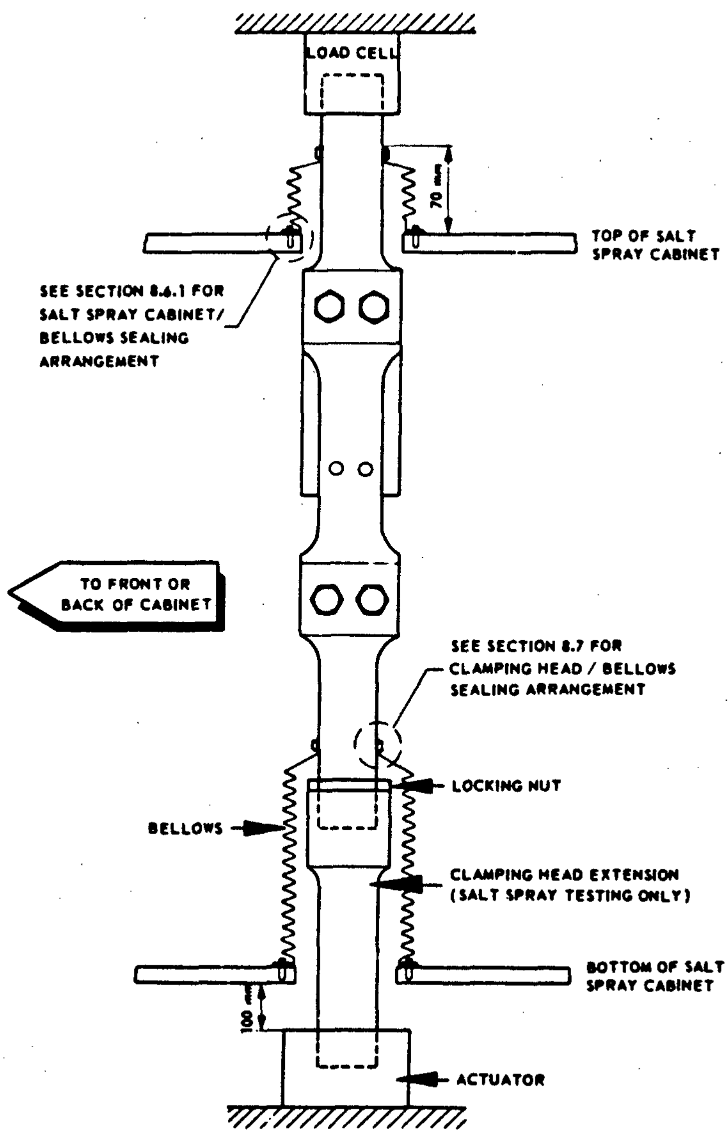


Fig. 19 Schematic of specimen + grips assembly in the salt spray cabinet: actuator in lower crosshead

The schematic in figure 19 has been given for the more usual case of the servohydraulic actuator being in the LOWER crosshead. For this case the following points apply:

(6) The upper bellows is OUTSIDE the salt spray cabinet and the lower bellows is INSIDE.

(7) Bolt holes for attaching the pair of bellows to the salt spray cabinet are drilled from the UPPER surfaces of the top and bottom of the cabinet.

(8) The clamping head extension is attached to the LOWER clamping head.

(9) With the upper bellows nearly fully compressed (length ∿ 70 mm) the lower bellows is halfway extended. This arrangement allows a ± 100 mm traverse for the actuator without damaging the lower bellows*.

(10) The bottom of the salt spray cabinet shall be not less than 100 mm from the top of the actuator if the actuator is greater in diameter than 80 mm (as is mostly the case). Otherwise the bottom of the salt spray cabinet shall be not less than 100 mm from any part of the actuator that projects beyond a diameter of 80 mm.

If the servohydraulic actuator is in the UPPER crosshead, the following points (11) - (15) apply instead of points (6) - (10):

(11) The upper bellows is INSIDE the salt spray cabinet and the lower bellows is OUTSIDE.

(12) Bolt holes attaching the pair of bellows to the salt spray cabinet are drilled from the LOWER surfaces of the top and bottom of the cabinet.

(13) The clamping head extension is attached to the UPPER clamping head.

(14) With the lower bellows nearly fully compressed (length ∿ 70 mm) the upper bellows is halfway extended. This arrangement allows a ± 100 mm traverse for the actuator without damaging the upper bellows.

(15) The top of the salt spray cabinet shall be not less than 100 mm from the bottom of the actuator if the actuator is greater in diameter than 80 mm. Otherwise the top of the salt spray cabinet shall be not less than 100 mm from any part of the actuator that projects beyond a diameter of 80 mm.

8.4 Clamping Head Extension for Salt Spray Fatigue Testing

For fatigue testing in the salt spray cabinet with the grip assembly described in section 4.1 it is necessary to use a clamping head extension + locking nut, as shown schematically in figure 19. An engineering drawing of the clamping head extension and locking nut is given in figure 20. In principle any fatigue-resistant steel heat treatable to a typical ultimate tensile strength ∿ 1400 MPa is suitable. The NLR chose 17-4 PH stainless steel, which is the same material as that used for the clamping heads.

NOTES

(1) All dimensions are in millimetres. Special tolerance indications are:

25 = 25 ± 0.5

25.0 = 25 ± 0.05

25.$\bar{0}$ = 25 ± 0.1

(2) The threads in the ends of the clamping head extension and locking nut must be adapted to individual requirements (compatibility with the clamping head and servohydraulic actuator).

(3) When the diameter of the servohydraulic actuator is GREATER than 80 mm the length of the centre section of the clamping head extension should be sufficient that when the clamping head is screwed into it to ∿ 30 mm and the extension is screwed into the servohydraulic actuator to ∿ 30 mm, the distance between the salt spray cabinet and the actuator is not less than 100 mm. A total length of 300 mm for the clamping head extension is sufficient for this purpose.

(4) When the diameter of the servohydraulic actuator is LESS than 80 mm the length of the centre section of the clamping head extension should be sufficient that when the clamping head is screwed into it to ∿ 30 mm and the extension is screwed into the servohydraulic actuator to ∿ 30 mm, the distance between the salt spray cabinet and any part of the actuator that projects beyond a diameter of 80 mm shall be not less than 100 mm.

(5) Surface finish is $\sqrt{125}$ on all surfaces.

(6) After finishing the clamping head extension and locking nut are heat treated to a typical ultimate tensile strength ∿ 1400 MPa. For 17-4 PH steel the heat treatment is in air at 755 ± 9 K for 1 hour followed by air cooling.

* Points (9) and (10) have been specified to allow for accidental movements of the actuator: the stroke on most, if not all, electrohydraulic fatigue machines is less than ± 100 mm.

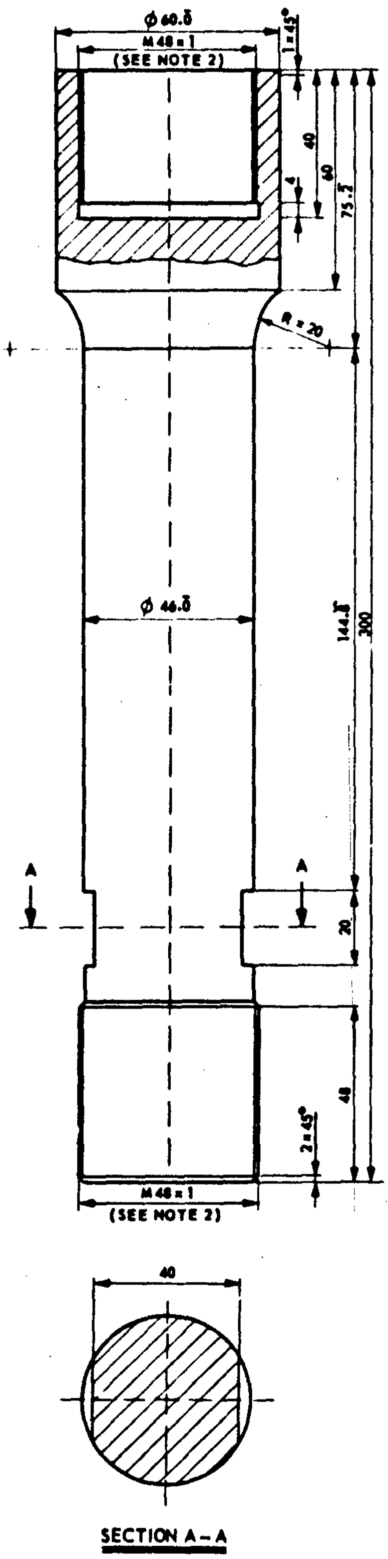


Fig. 20a The clamping head extension

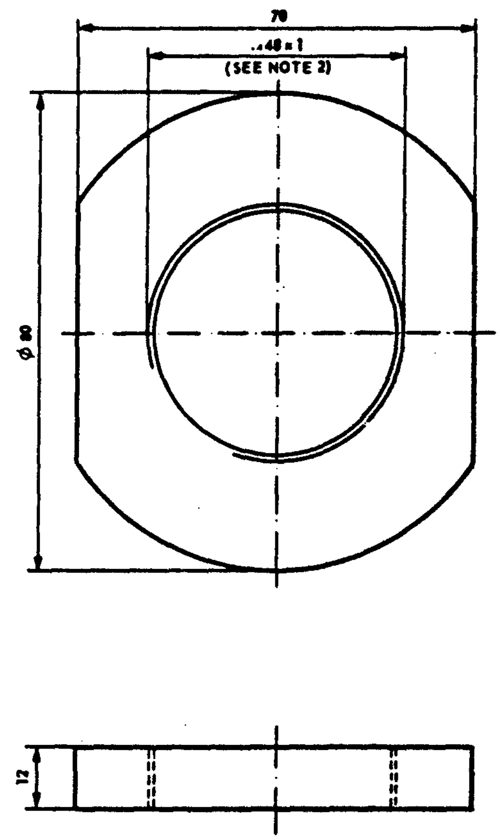


Fig. 20b The locking nut

8.5 Bellows

As mentioned in section 8.3, it was RECOMMENDED to connect the clamping heads to the salt spray cabinet using soft plastic (PVC) bellows. A schematic of the bellows is given in figure 21. The NLR ordered such bellows from ERIKS N.V., which has branches in the Netherlands, Belgium and the United Kingdom (ERIKS ALLIED POLYMER LTD). According to ERIKS such bellows are made only in the United States, so that relatively long delivery times should be anticipated in Europe.

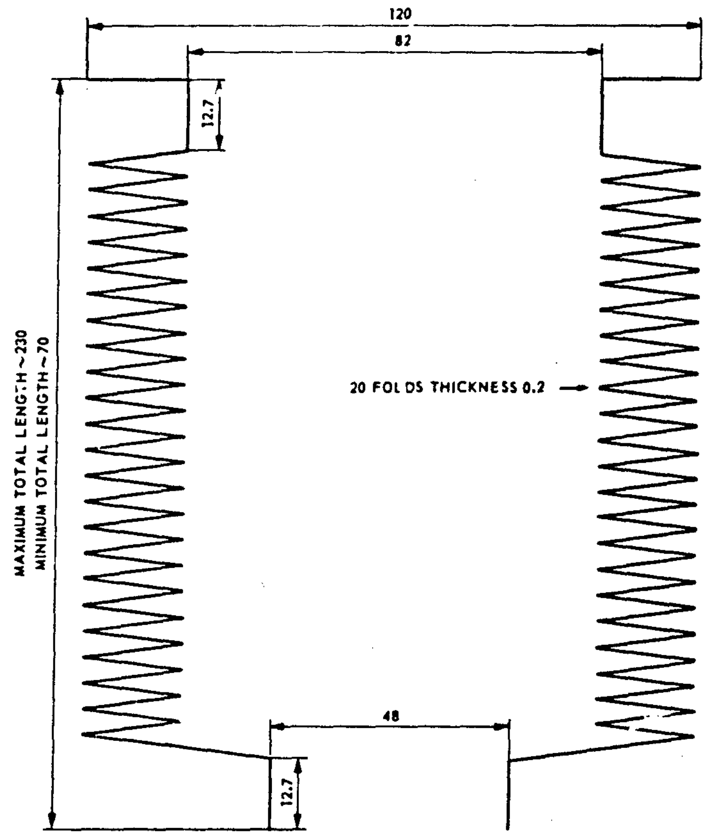


Fig. 21 Schematic of soft plastic (PVC) bellows, dimensions in millimetres

8.6 Sealing of the Salt Spray Cabinet

There are six entrances to the salt spray cabinet and one entrance to the integral salt solution reservoir, as mentioned in section 8.2. The salt spray cabinet entrances are:

(1) At the front of the cabinet a large access port, closed by the door during testing.

(2) and (3) Circular ports for exit of the fatigue specimen clamping heads.

(4) and (5) Jet exhaust and wet bottom drain holes.

(6) A hole for access of the humidified air line to the "Uni-Fog" tower .

The jet exhaust and wet bottom drain holes remain open. The humidified air line to the "Uni-Fog" tower and the salt solution line to the integral reservoir are simply sealed to the cabinet with adhesive and silicone sealant. There remain the sealing arrangements for the access and circular ports, discussed in sections 8.6.1 and 8.6.2.

8.6.1 Access door/front frame

As shown in figure 18, the access door is mechanically fastened to the front frame by 16 6.35 mm diameter stainless steel or nylon bolts and wing nuts. The bolt heads are silicone sealant bonded to the front frame and reinforcement. Before attaching the access door to the front frame, a layer of PERMAGUM, or its equivalent, is applied to the front frame according to figure 22. PERMAGUM was made available to CFCTP participants by the NADC upon request.

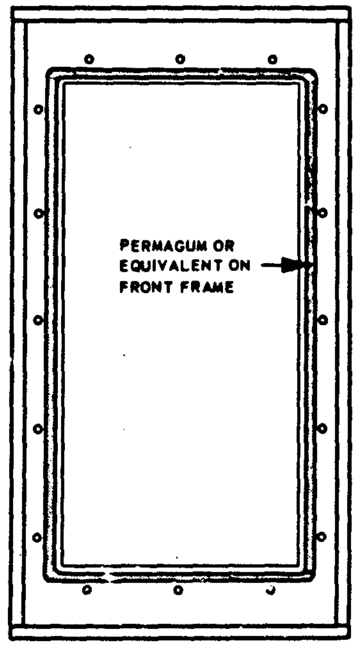


Fig. 22 Sealant on front frame of the salt spray cabinet before attaching the access door

8.6.2 Cabinet/bellows

It was RECOMMENDED to connect the salt spray cabinet to the clamping heads by soft plastic (PVC) bellows. Each bellows is mechanically fastened to the salt spray cabinet using a nylon collar and 8 4 mm diameter nylon bolts equally spaced on the circumference of a circle, diameter 100 mm and centred on the circular port. Figure 23 shows the mechanical fastening and sealing arrangements for the cabinet/bellows connection. These arrangements are identical except for attachment either to the upper or lower surfaces of the top and bottom of the salt spray cabinet according to whether the servohydraulic actuator is located in the lower or upper crosshead, respectively.

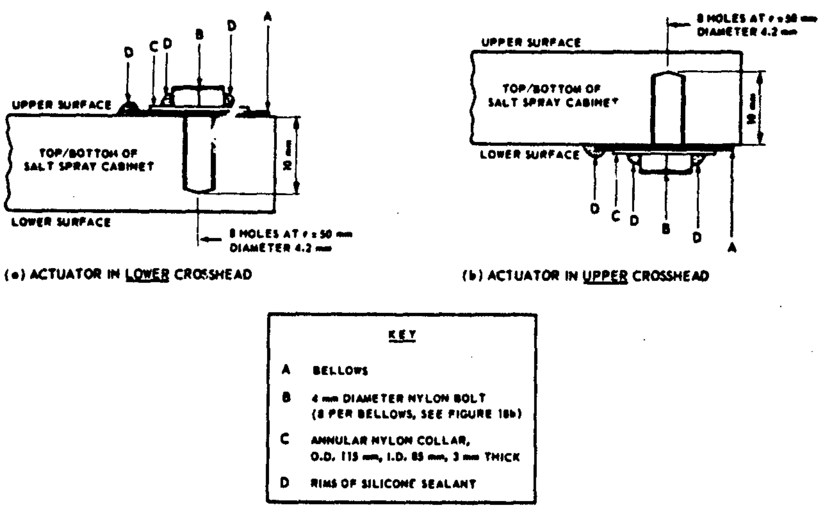


Fig. 23 Sealing of the salt spray cabinet to the bellows

8.7 Sealing of Clamping Heads to Bellows

Sealing of the clamping heads to the RECOMMENDED soft plastic (PVC) bellows is done using stainless steel circlips and rims of silicone sealant, as shown schematically in figure 24. Note that the sealing arrangements depend on whether the servohydraulic actuator is located in the lower or upper crosshead.

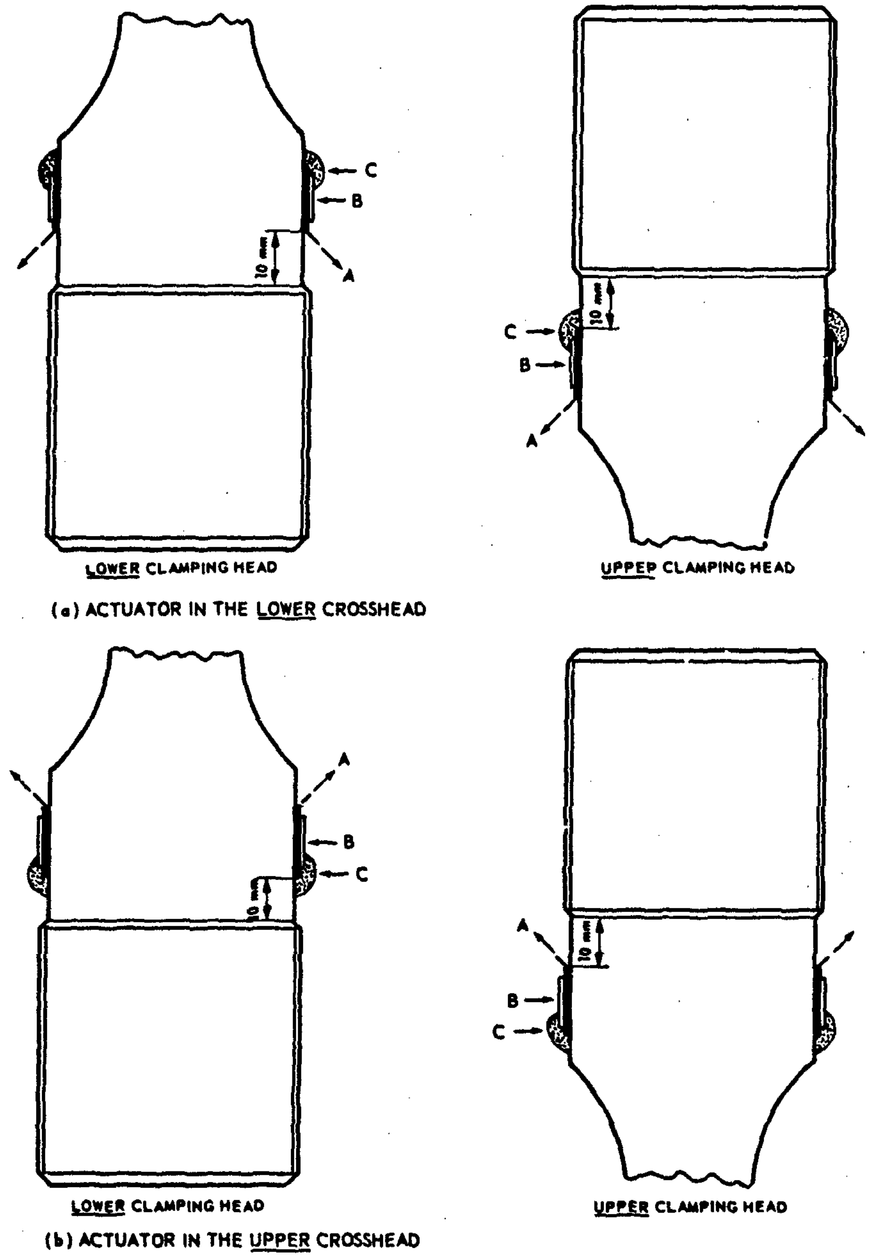
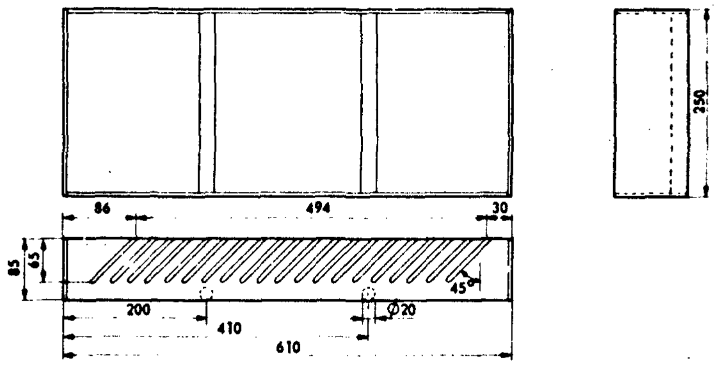


Fig. 24 Sealing of the clamping heads to the bellows: A-Bellows; B-stainless steel circlip 0.5 mm x 10 mm; C-rim of silicone sealant

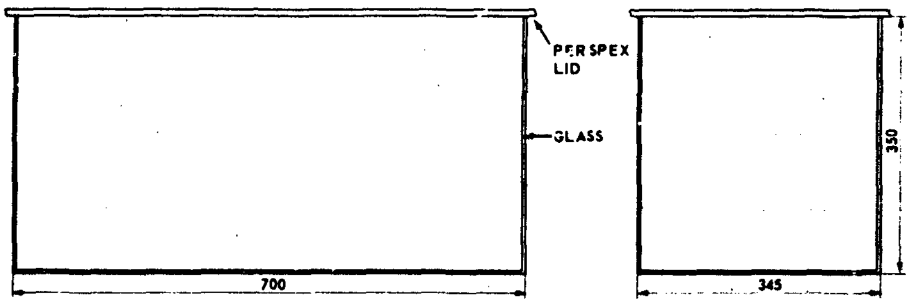
9 SPECIMEN STORAGE AND CLEANING

9.1 Storage

After prestressing at 209 ± 10 K (see the beginning of section 6) all specimen assemblies were to be stored in a desiccator at room temperature AT ALL TIMES except when immediately required for further testing (pre-exposure and fatigue). In storing the specimens care was taken not to damage the sealing of faying surface side edges and Hi-Lok collars of those specimens to be pre-exposed and/or fatigued in salt spray. A convenient way to do this is by mounting the specimen assemblies on racks inside a chamber containing desiccant (silicon gel). Figure 25 is a schematic example of a storage facility with a capacity of 60 specimen assemblies, i.e. three racks of 20 assemblies per storage chamber. The perspex lid is sealed onto the storage chamber using vaseline petroleum jelly, or its equivalent.



(a) STORAGE RACK; PERSPEX 5 mm THICK. 3 PER STORAGE CHAMBER



(b) STORAGE CHAMBER; GLASS 6 mm THICK, PERSPEX 5 mm THICK

Fig. 25 Facility for specimen storage: capacity 60 specimen assemblies

After pre-exposure the core programme specimens were IMMEDIATELY cleaned and then fatigue tested as soon as possible, preferably immediately. If delay before fatigue testing was unavoidable the cleaned specimens were stored in a desiccator as discussed above.

Supplemental testing programme specimens were to be IMMEDIATELY cleaned after pre-exposure and then stored in a desiccator, as discussed above, to await fatigue testing.

After fatigue testing in SALT SPRAY the separate parts of each failed specimen were to be cleaned, wrapped in tissue paper and stored in a desiccator, care being taken to avoid damage to the fracture surfaces. After fatigue testing in AIR the separate parts of each specimen were not to be cleaned, but were to stored in a similar manner.

Upon termination of the CFCTP, see section 2.3, the specimens were to be disposed of at the discretion of each participant unless there was a specific request to continue storing them or to send them to another laboratory.

9.2 Cleaning

Cleaning of the specimen assemblies was to done after pre-exposure and after fatigue testing in salt spray. The cleaning procedure (also mentioned in sections 7.2 and 7.4) is as follows:

- 30 minutes rinse in copious amounts of tap water at 291-298 K
- final rinse in distilled water at 291-298 K for not less than 1 minute
- air dry at 323 K for 30 minutes.

The cleaning procedure was to be commenced IMMEDIATELY after pre-exposure and as soon as possible after fatigue testing in salt spray (immediate cleaning after fatigue testing may often be impossible owing to failure at times outside personnel working hours).

10 TEST PROCEDURE

In section 2 an overview has been given of the mechanical and environmental test conditions for both core and supplemental testing programmes, and the core programme test schedules were defined (section 2.1.1). It was also mentioned that pilot tests were conducted to establish stress levels (sections 2.1.2 and 2.2.2).

In this section the requirements for establishment of stress levels by pilot testing will first be given, followed by a summary of the test procedure and the requirements for recording of data.

10.1 Establishment of Stress Levels

All stress levels were to be defined in terms of the GROSS SECTION STRESS in the fatigue specimen -1 at the location of the centreline between the countersunk Hi-Lok fasteners, i.e. including the fastener holes in the specimen area.

For the core programme it was required to test at maximum stress levels, S_{max}, giving nominal lives $\sim 2 \times 10^4$ cycles and 10^5 cycles for uncorroded specimens fatigue tested in laboratory air. The stress ratio R (= S_{min}/S_{max}) was 0.1. Figure 26 shows the result of pilot tests at the NLR for the purpose of establishing the core programme stress levels. From these tests the following stress levels were selected:

CORE PROGRAMME STRESS LEVELS

NOMINAL UNCORRODED LIFE (CYCLES)	S_{max} (MPa)	S_{min} (MPa)
2×10^4	210	21
10^5	144	14.4

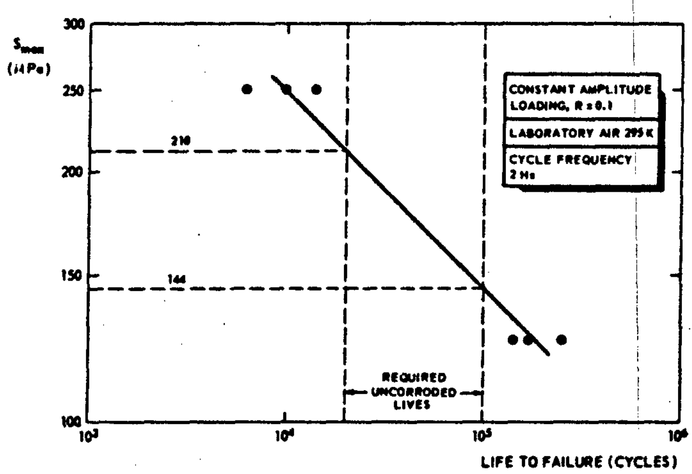


Fig. 26 Results of NLR pilot tests for the core programme

To establish supplemental testing programme stress levels the following pilot test procedure was and is required:

- select a minimum of TWO characteristic stress levels (S_{max} for constant amplitude loading ; S_{max} for FALSTAFF; S_{mf} for MINI-TWIST)
- test a minimum of THREE uncorroded specimens in laboratory air at each characteristic stress level (cycle frequency 2 Hz for constant amplitude loading, nominal 15 Hz for FALSTAFF and MINI-TWIST, see also section 2.2.1)
- if the results do not fully encompass the desired range in uncorroded fatigue lives for the actual test programme, select additional stress levels as necessary and test a minimum of THREE specimens per stress level
- plot the results on double logarithmic axes
- obtain the best straight line fit to the logarithmic mean lives
- read off from the straight line fit the characteristic stress levels corresponding to the desired uncorroded nominal fatigue lives.

NOTES

(1) Pilot tests DO NOT remove the necessity for testing uncorroded core programme and supplemental testing programme specimens in laboratory air at the ESTABLISHED stress levels.

(2) Examples of NLR pilot test requirements for supplemental testing are given in section 2.2.2 and may be helpful as guidelines for other CFCTP participants.

(3) If CLAD and BARE aluminium alloy sheet of the same TOTAL thickness are to be compared in the supplemental testing programme, the cladding layers are to be treated as if they do not contribute to the load-carrying capability. The thickness of the cladding layers must be determined and these thicknesses must be subtracted from the total sheet thickness when calculating the required LOADS on the fatigue specimen -1. These loads are defined by the established stress levels x the area of CORE material (including the cross-sectional area of the countersunk fastener holes). Thus the loads on a specimen made from clad material will be less than those for a specimen made from bare material.

10.2 Summary of Test Procedure

A schematic summary of the test procedure is given in figure 27.

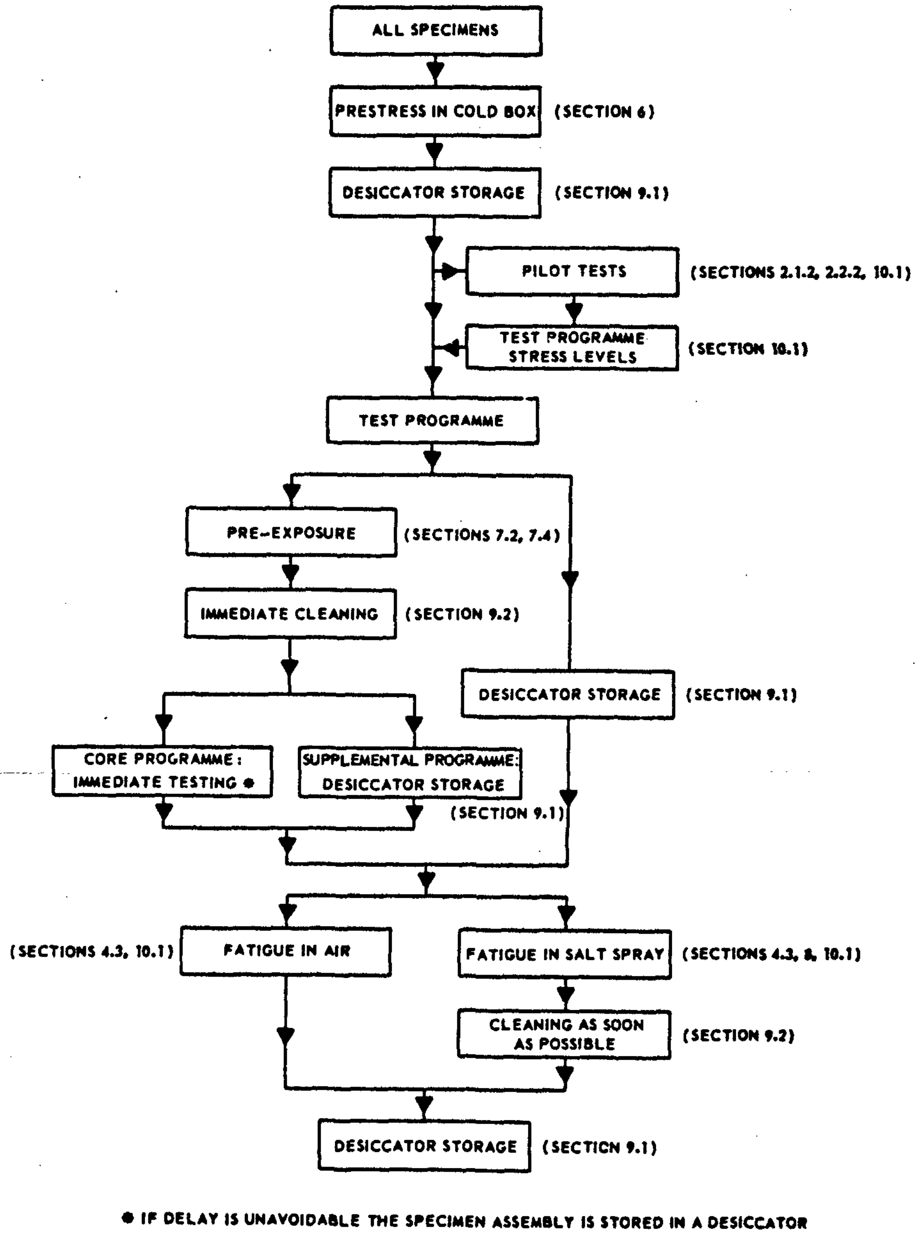


Fig. 27 Schematic summary of the test procedure

10.3 Data Recording

Individual data sheets must be completed for each CFCTP specimen, including pilot test specimens. An example of such a data sheet is given in figure 28. S.I. units will be used.

The failure origin or origins shall be determined using optical microscopy and, if necessary, electron microscopy. In the case of more than one origin the PRIMARY origin shall be determined and specified in the space labelled REMARKS. Additional comments are welcomed.

SPECIMEN NUMBER [ ]

DATE OF FATIGUE TESTING

DAY	MONTH	YEAR
		19

MATERIAL (THICKNESS, ALLOY, CLAD OR BARE) [ ]

CORROSION PROTECTION SYSTEM [ ]

HI-LOK FASTENER COATING [ ]

TEST PROGRAMME

CORE	SUPPLEMENTAL

PRE-EXPOSURE

YES	NO

FATIGUE TESTING CONDITIONS

ENVIRONMENT [ ]

TEMPERATURE [K]

LOADING TYPE [ ]

CYCLE FREQUENCY [Hz]

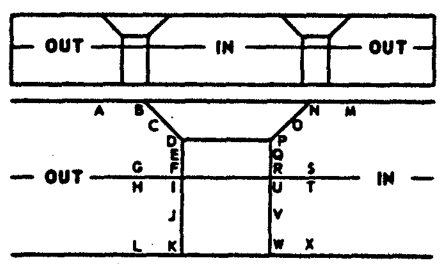
CHARACTERISTIC STRESS LEVEL

S_{max} (MPa)	S_{mf} (MPa)

FATIGUE LIFE

CYCLES	FLIGHTS

FAILURE ORIGIN(S)



REMARKS

Fig. 28 Example of CFCTP specimen individual data sheets

11 REPORTING

Copies of each data sheet shall be sent to BOTH coordinators.

11.1 Progress Reports

The following milestones for progress reporting of the CORE programme were specified (see also section 2.3).

CORE PROGRAMME PROGRESS REPORTS

AGARD STRUCTURES AND MATERIALS PANEL MEETING NUMBER	DATE	PROGRESS REPORTING
51	September 1980	comparison of phase I
52	April 1981	completion of programme

In order to meet these milestones it was requested that all data pertaining to the core programme phases be sent to both coordinators (by AIR MAIL if intercontinental) at least 30 days before the relevant meeting.

The following table gives the provisional milestones for progress reporting of the SUPPLEMENTAL TESTING programme (see also section 2.3).

SUPPLEMENTAL TESTING PROGRAMME PROGRESS REPORTS

AGARD STRUCTURES AND MATERIALS PANEL MEETING NUMBER	DATE	PROGRESS REPORTING
51	September 1980	supplemental programmes definition
52	April 1981	current status

CFCTP participants were to send overviews of their supplemental testing programmes as soon as possible to BOTH coordinators, and participants were encouraged to send data sheet copies as soon as each specific aspect of each programme had been investigated.

11.2 Final Reports

A final report covering the core programme (this document) has been prepared for presentation at the 52nd meeting, in April 1981, for approval by the Corrosion Fatigue Sub-Committee of the AGARD Structures and Materials Panel. The final report was prepered by the coordinators from the data provided by the CFCTP participants.

Final reporting of the supplemental testing programmes is to date unscheduled.

11.3 Specialists' Meeting

A Specialists' Meeting on Corrosion Fatigue was held at the 52nd meeting of the AGARD Structures and Materials Panel in April 1981. The Specialists' Meeting comprised invited papers by corrosion fatigue specialists together with two papers covering the final report of the CFCTP coordinators.

Publication of all contributions in an AGARD document was scheduled for the autumn of 1981.

12 APPENDIX: FLIGHT SIMULATION TESTING

12.1 The Manoeuvre Spectrum FALSTAFF

A microfiche facsimile of the complete report on FALSTAFF (Fighter Aircraft Loading STAndard For Fatigue) was sent to each CFCTP participant. This report was prepared as a joint effort by the Flugzeugwerke Emmen (F+W) Switzerland; the Laboratorium für Betriebsfestigkeit (LBF) Darmstadt, West Germany, the National Aerospace Laboratory (NLR) Amsterdam, the Netherlands, and the Industrieanlagen-Betriebsgesellschaft (IABG) Ottobrunn, West Germany.

12.2 The Gust Spectra TWIST and MINI-TWIST

Besides the facsimile of FALSTAFF a microfiche facsimile of the complete report on TWIST (Transport WIng STandard) was sent to each CFCTP participant. Modifications to generate MINI-TWIST (a shortened version) were also sent.

NOTE

(1) Hardcopies of the FALSTAFF, TWIST and MINI-TWIST reports are available on request to the abovementioned laboratories.

12.3 Verification of Flight Simulation Loading

In what follows a RECOMMENDED check of the accuracy with which flight simulation loads are applied to supplemental testing specimens is outlined. The purpose of such a check is to ascertain whether nominally correct load-exceedance profiles are obtained when testing with flight simulation spectra, particularly at higher cycle frequencies and stress levels.

In order to carry out the check it is necessary to use a calibration specimen/grip assembly with the same stiffness and secondary bending characteristics as actual test specimens. The check takes place in two stages:

(1) Comparison of the input (command) signal and the signal from the control load cell in the electrohydraulic machine.

(2) Characterization of the signal from the control load cell.

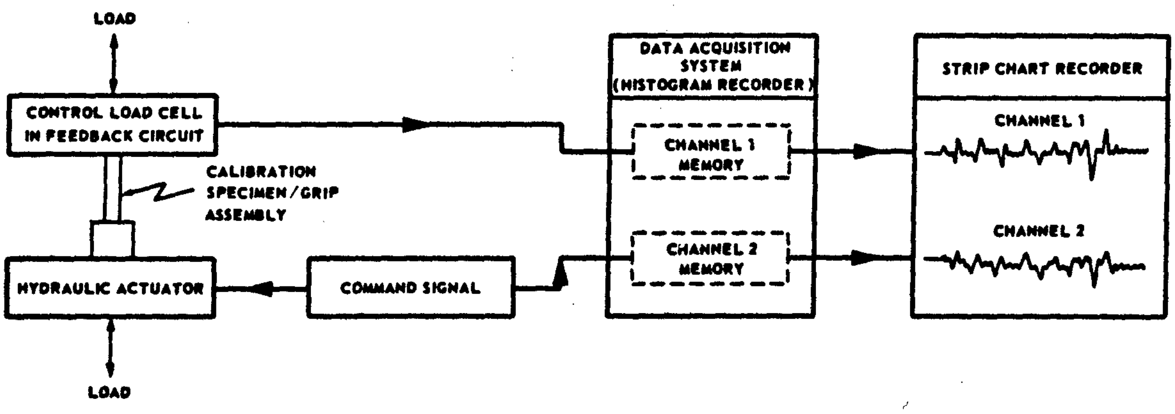


Fig. 29a Comparison of the command signal and load cell signal

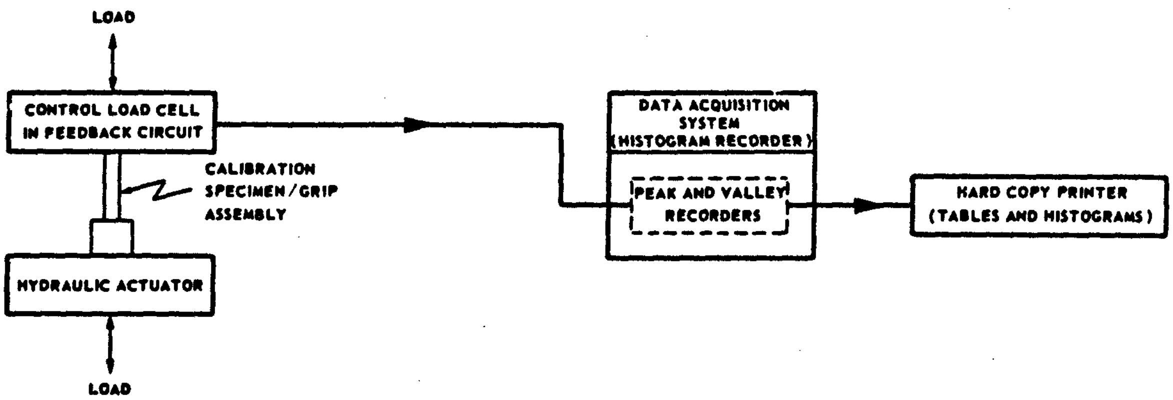


Fig. 29b Characterisation of the load cell signal

These stages are illustrated schematically in figure 29. For both stages the nominally applied stress levels and cycle frequencies are chosen to be representative of actual testing. In the first stage a particularly severe flight in the load history is selected and applied. The command and load cell signals are transmitted via separate channels to the memory of a data acquisition system (histogram recorder), figure 29a. The data so obtained are then transmitted to a multichannel strip chart recorder and traced out at relatively low speeds in terms of cycle frequency. The accuracy with which the load cell signal follows the command signal can then be ascertained. Several checks, including flights of different severity, can be made in this way.

Should there be a significant difference between the traces of the command and load cell signals, for example a difference of more than 3 % in the load maxima and minima (see also section 5.3 on dynamic calibration errors), then it is necessary to proceed to the second stage. In this stage the load cell signal is recorded for a complete block of flights (e.g. FALSTAFF consists of repetitions of blocks of 200 flights; TWIST and MINI-TWIST of repetitions of blocks of 4000 flights) using the data acquisition system to count signal and hence load reversals in terms of peaks and valleys, figure 29b. These counts are then compiled in a histogram and in tabular form for comparison with the originally defined flight simulation loading spectrum.

NOTE

(1) The foregoing procedure applies only when the testing conditions of stress levels and cycle frequency have been previously determined or specified. If this is not the case, then checking the accuracy with which flight simulation loads are applied can be done at various stress levels and cycle frequencies in order to find out the limiting conditions under which acceptable accuracy is still possible.

PART 2

RESULTS OF THE CFCTP CORE PROGRAMME

1. INTRODUCTION

As mentioned at the beginning of Part 1 of this report the objectives of the CFCTP were, and are:

- to assess the effectiveness of state-of-the-art protection schemes for aluminium alloys with respect to corrosion fatigue and corrosion + fatigue
- to stimulate the development of new protection products, procedures and techniques
- to bring researchers on both sides of the Atlantic together 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
- to enable participating laboratories to add to their fatigue testing capabilities by using a controlled atmospheric corrosion environment.

Within this context the CFCTP core programme was conceived as a two-phase programme of round-robin testing to establish whether participants could obtain confidence in one another's fatigue testing capabilities. At the same time the programme was designed to be sufficiently straightforward to encourage participation, particularly by those with relatively little experience of corrosion fatigue testing.

In this part of the report the scope and purpose of the CFCTP core programme are described, followed by presentation of the results, statistical analysis, discussion and conclusions.

2. SCOPE AND PURPOSE OF THE CFCTP CORE PROGRAMME

2.1 Scope

An overview of the scope of the CFCTP core programme is given in table 1. More details concerning the experimental part of the programme are to be found in Part 1 of this report. Engineering properties of the 7075-T76 aluminium alloy sheet were specified by ALCOA as follows:

0.2 % YIELD STRESS	UTS	ELONGATION	CONDUCTIVITY
479 MPa (max)	550 MPa (max)	11.0 %	38.0 % I.A.C.S.
455 MPa (min)	541 MPa (min)		

It was decided to plan the core programme testing schedules such that they could be carried out in two phases, corresponding to fatigue tests in laboratory air (phase I) and fatigue tests in acidified salt spray (phase II). This phasing was intended to assist participants in gaining testing experience as soon as possible, while in the meantime ordering and constructing equipment for fatigue testing in salt spray. It turned out that several participants did, in fact, make use of this flexibility in the programme.

Table 1 shows that there were nominally eight participants in the CFCTP core programme, four in North America and four in Europe. However, the Norwegian participation involved three institutions: the Norwegian Defence Research Establishment acted as coordinator; the Norwegian Army Material Command carried out the fatigue tests; and the Raufoss Ammunition Factory examined the specimen fracture surfaces. This examination was done in detail and is therefore included as Annex 1 to this report.

2.2 Purpose

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. 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 for the remaining laboratories.

In more detail there were several secondary aims, all but one of which were identifiable before testing. These prior-to-testing aims were to determine

- whether the effect of pre-exposure was significant on 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
- 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.

An additional aim was identified after testing. In the test procedure it had been specified that pre-exposed core programme specimens were to be cleaned and then fatigue tested as soon as possible, preferably immediately (see sections 7.2, 9.1, 9.2 and 10.2 of Part 1 of this report). However, some pre-exposed and cleaned specimens, notably those at the NLR and AFWAL, were stored for several days in a desiccator before fatigue testing. As will be discussed in section 3.4.1 of this Part of the report, the question arose whether the time delay between cleaning and fatigue testing had a significant influence on the results.

TABLE 1: SCOPE OF THE CFCTP CORE PROGRAMME

- MATERIAL : 3.2 mm thick 7075-T76 bare aluminium alloy sheet supplied especially by ALCOA from one heat.
- SPECIMEN : 1½ dogbone mechanically fastened by cadmium plated steel Hi-Loks from a single batch of fasteners supplied by the VOI-SHAN Corporation. All prior-to-assembly parts of specimens were manufactured by the U.S. Air Force Materials Laboratory (AFML).
- PROTECTIVE SYSTEM : chromate conversion coating + inhibited epoxy polyamide primer (except fastener holes) + aliphatic polyurethane topcoat, applied by the U.S. Naval Air Development Centre (NADC).
- PROTECTIVE SYSTEM DAMAGE : all specimens prestressed at 209 ± 10K with two cycles to a maximum stress of 215 MPa in order to crack the paint and primer layers in the fastener hole vicinities.
- FATIGUE LOADING : constant amplitude sinusoidal loading at a stress ratio $R(= S_{min}/S_{max})$ of 0.1 at two stress levels and frequencies, see below.
- FATIGUE ENVIRONMENTS : Laboratory air with relative humidity of 30 - 70 % and 5 % aqueous NaCl salt spray acidified with H_2SO_4 to pH 4; both environments at nominally 295K.
- STATIC PRE-EXPOSURE : 72 hours in 5 % aqueous NaCl with a predetermined amount of SO_2 gas added by reacting Na_2SO_3 pellets with H_2SO_4 in vented test tubes suspended above the salt solution, which was kept at 315 ± 2K.
- TEST PROGRAMME :

PHASE	FATIGUE TESTING SCHEDULES	NUMBER OF SPECIMENS		CYCLE FREQUENCY
		S_{max} = 210 MPa	S_{max} = 144 MPa	
I	fatigue in air	4	4	2 Hz
	pre-exposure + fatigue in air	4	4	
II	fatigue in salt spray	4	4	0.5 Hz
	pre-exposure + fatigue in salt spray	4	4	

- PARTICIPANTS :
  - Naval Air Development Centre NADC, Warminster, Pennsylvania, USA.
  - University of Saskatchewan, Saskatoon, Canada.
  - Vought Corporation, Dallas, Texas, USA.
  - Air Force Wright Aeronautical Laboratories AFWAL, Dayton, Ohio, USA.
  - National Aerospace Laboratory NLR, Amsterdam, The Netherlands.
  - Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt DFVLR, Cologne, Germany
  - Norwegian Defence Research Establishment NDRE, Kjeller, Norway.
  - Royal Aircraft Establishment RAE, Farnborough, United Kingdom.

3. RESULTS OF THE CFCTP CORE PROGRAMME

3.1 Presentation of the Fatigue Life Data

The complete set of fatigue life data for the CFCTP core programme is given in table 2, and log mean values in table 3. These tables are followed by figures 1 and 2, which compare the data in terms of log mean life and data range for each fatigue testing schedule and for each participant.

3.2 Statistical Methods for Analysing the Fatigue Life Data

In section 2.2 of this Part of the report the primary and secondary aims of the CFCTP core programme

TABLE 2: FATIGUE LIFE DATA FOR THE CFCTP CORE PROGRAMME

PARTICIPANTS	FATIGUE LIFE TO FAILURE (CYCLES)							
	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	18,705	4997	11,737	16,770	76,186	96,085	143,434	56,478
	25,606	6337	11,360	8015	133,611	106,206	150,663	114,147
	25,894	10,970	7935	4603	147,107	109,712	122,092	86,655
	28,134	16,458	7563	8354	199,893	234,427	73,974	143,841
UNIVERSITY OF SASKATCHEWAN	9180	18,310	12,626	8841	419,690	111,470	78,088	93,692
	13,800	7980	18,577	5352	59,710	122,390	104,090	31,762
	21,850	10,093	17,893	5006	109,340	82,483	46,046	65,121
	26,950	13,023	10,298	8129	107,050	116,596	145,818	154,293
VOUGHT	12,165	28,562	7163	3760	176,242	119,047	122,468	85,956
	25,841	20,168	4933	7791	170,330	85,912	59,900	56,574
	20,494	8353	6373	9395	183,450	95,243	191,035	48,291
	24,235	20,332	6442	9538	174,962	105,261	35,331	33,693
AFWAL	22,300	12,300	13,520	6120	152,700	122,800	68,170	139,690
	32,600	15,700	7460	4380	244,600	112,900	222,600	79,830
	34,000	15,600	9060	9890	104,200	153,600	78,530	73,840
	36,400	19,000	24,680	7590	293,800	129,100	173,270	67,940
NLR	23,713	19,873	10,820	5215	114,916	83,246	55,317	38,512
	24,822	20,628	11,524	10,030	123,105	110,280	127,344	60,019
	26,714	24,778	11,386	11,393	162,947	186,964	82,008	31,116
	32,312	32,887	5957	16,186	197,197	196,915	46,824	144,344
DFVLR	24,479	5393	11,370	5652	103,842	86,862	54,165	31,200
	25,373	16,254	18,970	15,777	111,862	134,522	197,748	45,500
	25,841	6268	22,546	5782	181,364	83,273	70,228	71,021
	34,340	8478	19,523	6898	109,060	44,498	94,341	104,817
NDRE	25,310	24,551	13,626	10,100	175,510	71,820	92,929	106,209
	25,500	18,670	9106	11,426	81,170	71,920	82,561	22,608
	19,210	12,200	11,026	7093	111,500	72,111	45,240	76,442
	21,940	3930	10,137	8794	146,240	76,120	121,584	121,927
RAE	20,499	14,492	11,940	10,272	153,788	78,828	156,170	125,357
	26,177	18,542	11,105	6330	96,362	118,805	139,186	36,553
	26,894	4565	12,047	19,523	68,216	102,326	57,088	90,392
	29,677	8768	26,799	11,345	135,889	387,955	273,635	67,798

TABLE 3: LOG MEAN VALUES OF THE FATIGUE LIFE DATA

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	24,304	8695	9457	8479	131,533	127,282	118,197	94,679
UNIVERSITY OF SASKATCHEWAN	15,527	11,772	14,418	6624	130,869	107,026	85,951	73,947
VOUGHT	19,878	17,686	6172	7158	176,184	100,628	83,884	53,036
AFWAL	30,798	15,468	12,254	6698	183,888	128,766	119,872	86,484
NLR	26,698	24,041	9590	9910	146,016	135,589	72,117	56,763
DFVLR	27,247	8261	17,553	7722	123,117	81,118	91,783	57,016
NDRE	22,838	12,176	10,852	9211	123,455	72,971	80,599	68,780
RAE	25,582	10,184	14,384	10,955	108,262	138,858	135,746	72,796

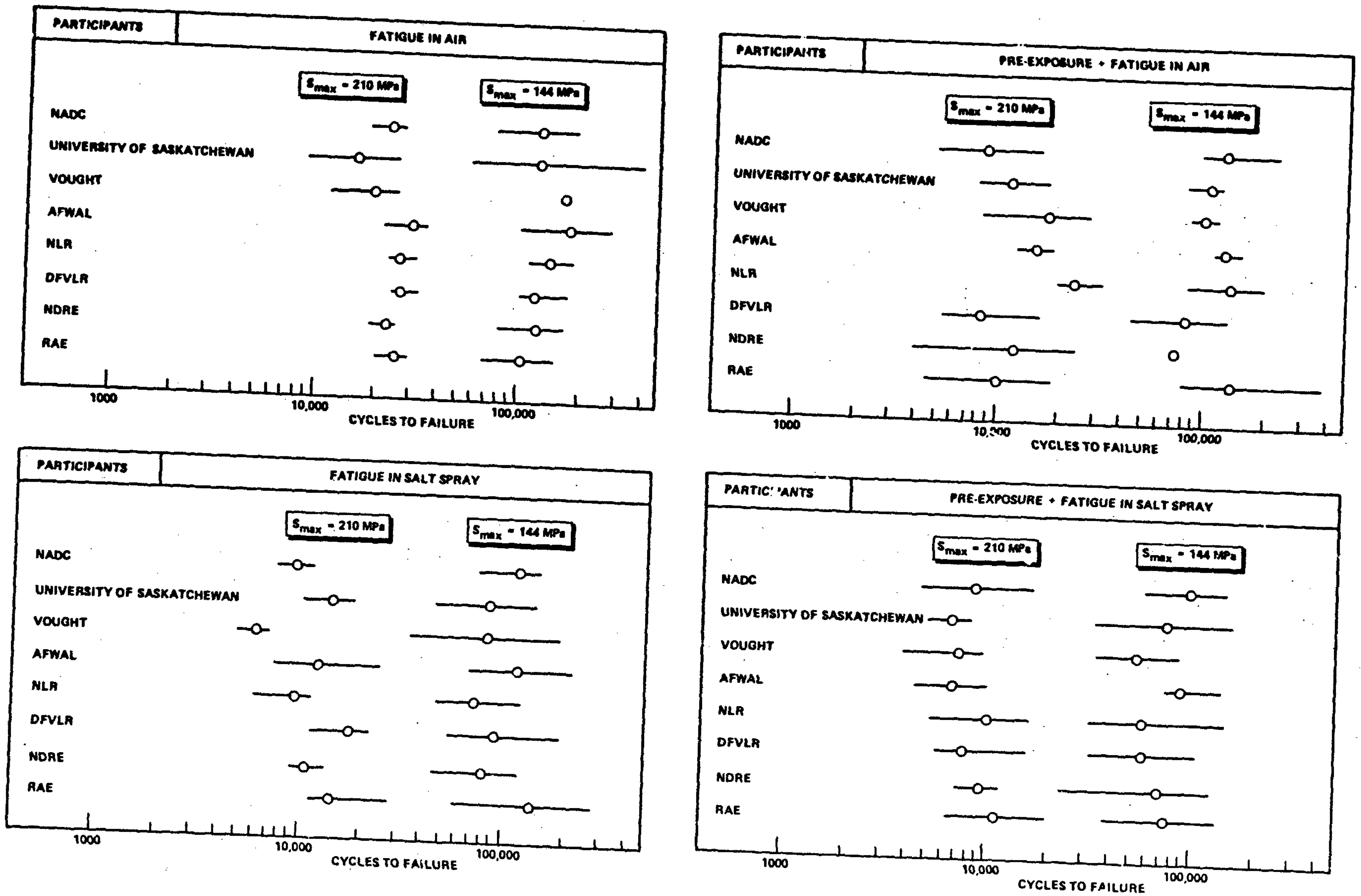


Fig. 1 CFCTP core programme fatigue life data per test schedule and participant

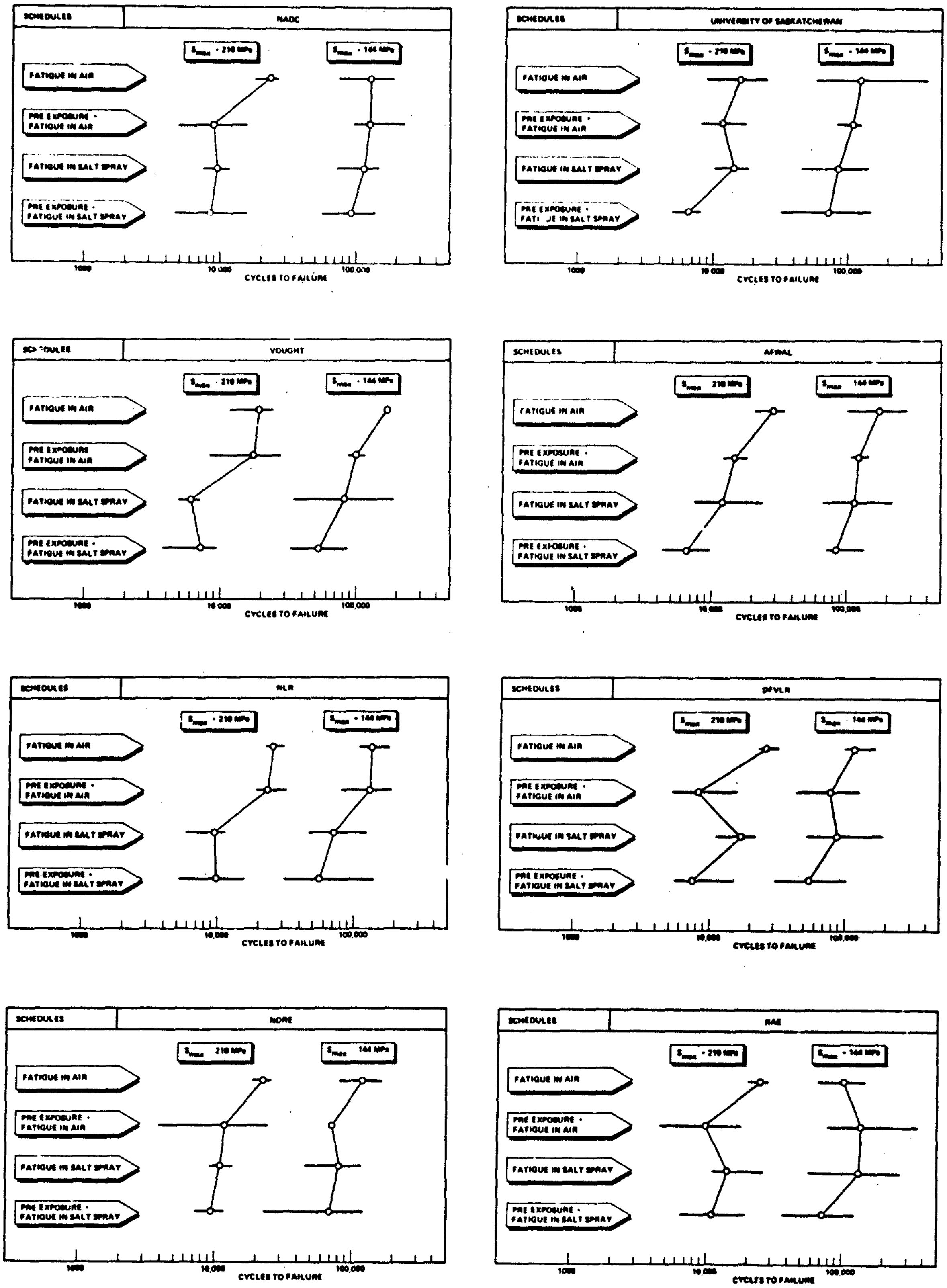


Fig. 2 CFCTP core programme fatigue life data per participant and test schedule

are listed. To accomplish the prior-to-testing aims the data were statistically treated using the methods listed in table 4. These methods are illustrated in Annex 2 to this report.

The tests for normality and for homogeneity of variances are prerequisites to the other, more detailed, statistical methods. First it should be known whether the data may be treated as random variables in a normal distribution, i.e. whether the data are from normally distributed populations. Then the choice of more detailed statistical treatment depends on whether the variances of the populations are equal (homogeneous).

3.3 Fatigue Life Analysis Results

3.3.1 Checking for normal distribution

In checking for normal distribution 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, table 1. It was found that the data for each population closely approximate to a log-normal distribution, see Annex 2.1. This means that the data may be treated in the same way as random variables in a normal distribution.

TABLE 4: STATISTICAL METHODS USED TO ANALYSE THE CFCTP CORE PROGRAMME DATA

PURPOSE OF ANALYSIS	TEST FOR NORMALITY [1]	BOX TEST FOR HOMOGENEITY OF VARIANCES [2]	BARTLETT TEST FOR HOMOGENEITY OF VARIANCES [3]	SINGLE FACTOR ANALYSIS OF VARIANCE [4]	SCHEFFE TEST FOR INDIVIDUAL COMPARISONS [5]	t-STATISTIC EVALUATION [6]	LIPSON AND SHETH METHOD [7]
CHECK FOR DIFFERENCES BETWEEN LABORATORIES	•	•		•	•		
CHECK FOR ENVIRONMENTAL EFFECTS	•		•			•	
CHECK SUFFICIENCY OF SAMPLE SIZE							•

[1] Checking for normal distribution of the fatigue life data was done in two ways. See Annex 2.1.

[2] The Box test was applied for each fatigue testing schedule at each stress level. The data from different laboratories were treated as coming from different populations, i.e. the sample size was 4. See Annex 2.2.

[3] The Bartlett test was applied for comparison of fatigue testing schedules at each stress level. The data from different laboratories were treated as coming from the same population, i.e. the sample size was 32. See Annex 2.3.

[4] Analysis of variance checked for significant differences in the data from different laboratories for each fatigue testing schedule at each stress level, i.e. the sample size was 4. See Annex 2.4.

[5] The Scheffé test of significance for a difference between any two means was used to determine the source, or sources, of significant differences indicated by the single factor analysis of variance. See Annex 2.5.

[6] The t-statistic evaluation checked for significant differences in the data for different fatigue testing schedules at each stress level (six comparisons per stress level). The data from different laboratories were treated as coming from the same population, i.e. the sample size was 32. See Annex 2.6.

[7] Checking for sufficiency of sample size (4 specimens per test condition per participant) was done according to a method described in Statistical Design and Analysis of Engineering Experiments, C. Lipson and N.J. Sheth, McGraw-Hill Book Company, p. 267 (1973): New York. See Annex 2.7.

TABLE 5: SUMMARY OF BARTLETT TEST RESULTS

COMPARISONS OF DATA FROM DIFFERENT FATIGUE TESTING SCHEDULES	HOMOGENEITY OF VARIANCES	
	S_{max} = 210 MPa	S_{max} = 144 MPa
fatigue in air/pre-exposure + fatigue in air	no	yes
fatigue in air/fatigue in salt spray	no	yes
fatigue in air/pre-exposure + fatigue in salt spray	yes	no
pre-exposure + fatigue in air/fatigue in salt spray	yes	no
pre-exposure + fatigue in air/pre-exposure + fatigue in salt spray	yes	no
fatigue in salt spray/pre-exposure + fatigue in salt spray	yes	yes

3.3.2 Checking for inter-laboratory differences

To achieve this primary aim the data from different laboratories were considered to come from different populations, so that there were sixty-four populations corresponding to data from each of the eight participants for each of the four fatigue testing schedules in combination with each of the two stress levels.

The data were first checked for homogeneity of variances using the Box test, see Annex 2.2. For a confidence level of 95 % it was found that two suspect outliers should be excluded. These were the University of Saskatchewan datum of 419,690 cycles for fatigue in air and the RAE datum of 387,955 cycles for pre-exposure + fatigue in air at a maximum stress level of 144 MPa, table 2. With these exclusions the Box test showed that the population variances were equal at the 95 % confidence level except for a moderate violation in the case of comparison of the eight populations for pre-exposure + fatigue in air at a maximum stress level of 144 MPa.

This result enabled proceeding to single factor analysis of variance, which is illustrated in Annex 2.4. The analysis was done with and without the two suspect outlying data. A significant inter-laboratory difference was indicated with 95 % confidence for fatigue in salt spray at a maximum stress level of 210 MPa. Otherwise there were no significant inter-laboratory differences.

The Scheffé test, Annex 2.5, was applied to the data for fatigue in salt spray at a maximum stress level of 210 MPa in order to locate the source, or sources, of the significant inter-laboratory difference. This test showed that there was a single source, namely the difference between results from Vought Corporation and the DFVLR (see also tables 2 and 3 and figure 1).

3.3.3 Checking for environmental effects

The three prior-to-testing secondary aims involving environmental effects have already been listed in section 2.2 of this Part of the report. However, for convenience they are given here also. These aims were to determine

- whether the effect of pre-exposure was significant on subsequent fatigue life in air or salt spray
- whether the effect of fatiguing 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.

An unforeseeable result of checking for inter-laboratory differences is that the third secondary aim has effectively been achieved without the necessity for further analysis. Thus a single source of significant inter-laboratory difference means that there was only one significant difference in the relative effects of environmental testing, namely the difference in the relative effect of fatigue in salt spray at a maximum stress level of 210 MPa as carried out by Vought Corporation and the DFVLR.

For further analysis with respect to the first two secondary aims it was desirable to treat the data for each fatigue testing schedule and stress level as coming from the same population. Thus no distinction was made between the data from different laboratories. This was not strictly correct, but was considered justified since only one significant inter-laboratory difference had been found.

The data were checked for homogeneity of variances using the Bartlett test, see Annex 2.3. The results are summarised in table 5. Several of the comparisons of data from different fatigue testing schedules showed that population variances were not equal. Because of this the data were analysed further using the t-statistic evaluation rather than the more orthodox two factor analysis of variance.

The t-statistic evaluation procedure was standard for comparisons of data with equal variance and modified for comparisons of data with unequal variance, see Annex 2.6. The following results were obtained for both stress levels with a confidence level of 95 %:

- pre-exposure significantly reduced the subsequent fatigue lives in air and salt spray
- fatigue lives in salt spray were significantly less than those in air
- there was no significant difference between fatigue lives for pre-exposure + fatigue in air and fatigue in salt spray, i.e. the reductions in fatigue life owing to pre-exposure or fatigue in salt spray were similar
- pre-exposure + fatigue in salt spray significantly reduced the fatigue lives as compared to the other testing schedules.

A general impression of these results is provided by figure 3, which shows the log mean fatigue life values of all thirty-two data for each fatigue testing schedule and stress level. The data trends for both stress levels are consistent and indicate relatively little difference between results for pre-exposure + fatigue in air and fatigue in salt spray. Also it is seen that environmental effects were relatively greater for the higher maximum stress level.

It is worth comparing the trends in figure 3 with the less orderly ones in figure 2, where the data are plotted per participant and test schedule. The ascertainment of environmental effects in a consistent manner has clearly benefited from the use of round-robin testing, which gave the potential and, as it turned out, actual possibility of comparing many more data for each fatigue testing schedule and stress level.

3.3.4 Checking for sample size sufficiency and differences in data scatter

To check for sufficiency of sample size the method illustrated in Annex 2.7 was used. It involves selecting an acceptable error level, usually 5 % or 10 %, and finding the required sample size for a

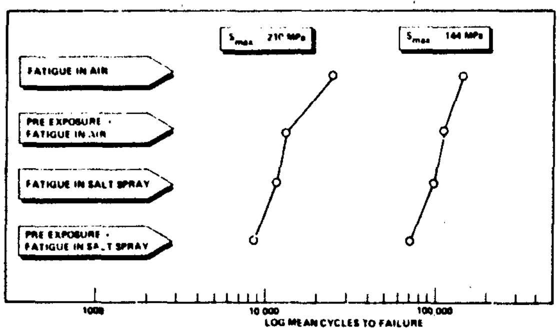


Fig. 3 Summary diagram of the CFCTP core programme fatigue life data

particular confidence level. For the CFCTP core programme data the sample size check was used for two purposes, namely

- to find the combination of error and confidence levels for which the actual sample size (4 specimens per test condition per participant) was sufficient
- to give an indication of differences in data scatter between laboratories and fatigue testing schedules.

The actual sample size was found to be sufficient for the combination of 10 % error and 90 % confidence levels. This result indicates a generally low data scatter and therefore high reproducibility of the specimens and testing conditions.

To indicate any differences in data scatter the required sample sizes were determined for the combination of 5 % error and 90 % confidence levels, figure 4. The shaded regions denote exceedance of the actual sample size, and since a larger required sample size reflects greater scatter the results indicate the following

- the RAE data exhibited more persistent scatter than data from the other participants
- the amount of scatter tended to increase with complexity of testing: this is particularly noticeable for pre-exposure + fatigue in salt spray
- for pre-exposure + fatigue in air there was much more scatter at the higher maximum stress level of 210 MPa.

These trends can also be seen in figure 1.

3.4 Locations of Primary Origins of Fatigue

All participants in the CFCTP core programme were requested to send fractured specimen halves to the NLR. These specimen halves were examined by the European coordinator using a stereo binocular at magnifications up to 100X. The primary origins of fatigue were determined, whenever possible, according to the schematic of locations indicated in the key to table 6, which gives the fatigue life and primary origin data for all but three specimens: two had been lost (NDRE) and the third failed at an edge remote from the fastener area (RAE).

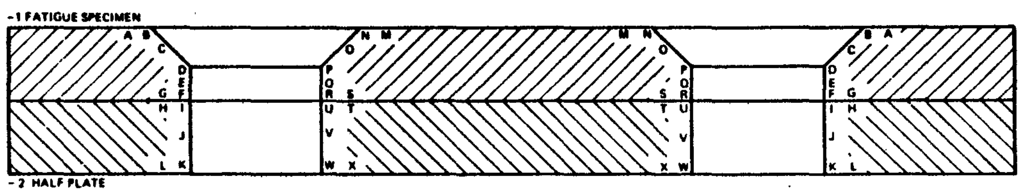
	S_{max} = 210 MPa				S_{max} = 144 MPa			
	FATIGUE IN AIR	PRE-EXPOSURE + FATIGUE IN AIR	FATIGUE IN SALT SPRAY	PRE-EXPOSURE + FATIGUE IN SALT SPRAY	FATIGUE IN AIR	PRE-EXPOSURE + FATIGUE IN AIR	FATIGUE IN SALT SPRAY	PRE-EXPOSURE + FATIGUE IN SALT SPRAY
NADC	3	6	3	6	4	4	3	4
UNIVERSITY OF SASKATCHEWAN	5	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

Fig. 4 Required sample sizes for 5% error and 90% confidence levels

TABLE 6: FATIGUE LIFE AND PRIMARY ORIGIN DATA FOR THE CFCTP CORE PROGRAMME

PARTICIPANTS	FATIGUE LIFE TO FAILURE (CYCLES)/LOCATIONS OF PRIMARY ORIGINS OF FATIGUE*								REMARKS CONCERNING FAILURE 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	
NADC	18,705 Q 25,606 F 25,894 Q 28,134 S	4997 E 6337 Q 10,970 F 16,458 E	11,737 E 11,360 Q 7935 E 7563 E	16,770 Q 8015 Q 4603 E 8354 E	76,186 F 133,611 R 147,107 F 199,893 G	96,085 G 106,206 S 109,712 S 234,427 F	14[illegible],4[illegible] G 150,6[illegible] Q 122,092 C 73,974 R	5[illegible],4[illegible] F 114,147 F [illegible] G 143,[illegible] E	corroded fracture surfaces for three specimens tested at 210 MPa
UNIVERSITY OF SASKATCHEWAN	9180 Q 13,800 Q,R 21,850 Q,R 26,950 R	18,310 F 7980 Q 10,093 E 13,023 E	12,626 E,F 18,577 F 17,893 Q 10,298 E	8841 F 5352 Q 5006 E 8129 Q	419,690 F 59,710 G 109,340 G 107,050 S	111,470 S 122,390 F 82,483 S 116,596 R	78,088 G 104,090 E 46,046 F 145,818 R	93,6[illegible] E 31,7[illegible] G 6[illegible],1[illegible]1 G 154,[illegible] G	corroded fracture surfaces for three specimens tested at 210 MPa
VOUGHT	12,165 R 25,841 Q 20,494 E 24,235 E	28,562 G 20,168 E 8353 R 20,332 E	7163 E 4933 Q 6373 E 6442 R	3760 E 7791 E 9395 Q 9538 E	176,242 R 170,330 F 183,450 S 174,962 S	119,047 G 85,912 R 95,243 G 105,261 F	122,468 Q 59,900 R 191,035 Q 35,[illegible]31 R	85,[illegible]6 Q 56,574 E 45,[illegible] E [illegible],6[illegible] F	corroded fracture surface for one specimen tested at 210 MPa and one at 144 MPa
AFWAL	[illegible],400 Q 22,600 E [illegible]4,000 G [illegible],400 C	12,300 R 15,700 Q 15,600 E 19,000 R	13,520 F,R 7460 R 9060 E 24,680 E	6120 E 4380 E 9890 R 7590 Q	152,700 G 244,600 G 104,200 G 293,800 F	122,800 C 112,900 G 153,600 G 129,100 F	68,170 G 22[illegible],600 F 75,530 Q 173,270 G	1[illegible],690 F 79,830 F 73,[illegible] C,D 67,[illegible]40 R	very slight corrosion near primary origin for one specimen tested at 210 MPa
NLR	23,713 Q 24,822 E 26,714 G 32,312 E	19,873 B 20,628 Q 24,778 Q 32,887 G	10,820 Q 11,524 Q 11,386 R 5957 Q	5215 E 10,030 E,F 11,393 E 16,186 E	114,916 G 123,105 G 162,947 G 197,197 G	83,246 R 110,280 G 186,964 B 196,915 N	55,317 F 127,344 F 82,008 F 46,824 R	38,512 R 60,019 E 31,116 R 144,344 Q	no corrosion on fracture surfaces
DFVLR	24,479 Q 25,373 F 25,841 F,Q 34,340 S	5393 F 16,254 Q 6268 E 8478 Q	11,370 E 18,970 E 22,546 F 19,523 F	5652 Q 15,777 E 5782 E 6898 E	103,842 G 111,862 G 181,364 G 109,060 G	86,862 E 134,522 Q 83,273 E 44,498 R	54,165 R 197,748 G 70,228 R 94,341 R	31,200 R 45,500 R 71,021 F 104,817 Q	corroded fracture surfaces for two specimens tested at 210 MPa; very slight corrosion near primary origin for another
NDRE	25,310 F 25,500 Q,R 19,210 E 21,940 Q	24,551 R,Q 18,670 R 12,200 F 13930 Q	13,626 E,R 9106 Q 11,026 E 10,137 F	10,100 Q 11,426 E 7093 Q 8794 E	175,510 R 81,170 R 111,500 G 146,240 G	71,820 B 71,920 B 72,111 R 76,120 E	92,929 F 82,561 G 45,240 G 121,584 -	106,209 F 22,608 E 76,442 R 121,927 -	corroded fracture surface for one specimen tested at 210 MPa; slight corrosion near primary origins for two specimens tested at 144 MPa
RAE	20,499 R 26,177 G 26,894 C 29,677 Q	14,492 Q 18,542 E 4565 F 8768 E	11,940 E 11,105 R 12,047 E 26,799 R	10,272 F 6330 F 19,523 E 11,345 Q	153,788 S 96,362 G 68,216 G 135,889 S	78,828 P 118,805 N 102,326 G 387,955 S	156,170 S 139,186 G 57,088 R 273,635 -	125,357 G 36,553 F 90,392 B 67,798 F	corroded fracture surfaces for three specimens tested at 210 MPa; corrosion near primary origin for one specimen tested at 144 MPa

*** Key to locations of fatigue origins**



3.4.1 Specimens pre-exposed and fatigue tested in air

In the last column of table 6 there are remarks concerning pre-exposed specimens fatigue tested in air. It was found, particularly for fatigue testing at a maximum stress level of 210 MPa, that some specimens exhibited corroded fracture surfaces near the primary fatigue origins. This is an indication that an aqueous solution was present inside the specimens while they were fatigue tested, even though a detailed cleaning procedure was specified in section 7.2 of Part 1 of this report. Further information is obtained from table 7, which presents results according to whether the fracture surfaces were corroded or not. It is seen that

- for both stress levels the log mean lives of corroded specimens were significantly shorter than those for uncorroded specimens
- for a maximum stress level of 210 MPa there was no essential difference in the locations of primary fatigue origins in corroded and uncorroded specimens
- for a maximum stress level of 144 MPa the presence of a corrodent might have resulted in some primary fatigue origins being in the bores (E/Q) or at the bore/faying surface corners (F/R) of fastener holes instead of at the faying surfaces (G/S).

It is concluded that an aggressive aqueous solution was present inside the specimens exhibiting corroded fracture surfaces. Most probably this was 5 % aqueous NaCl + SO_2 remaining from pre-exposure.

Information on the time delays between cleaning and fatigue testing in air was supplied by the participants. There was no strong correlation between time delays and subsequent fatigue lives and/or corroded fracture surfaces. However, from the NLR and AFWAL data it did appear that storing the specimens for several days in desiccators resulted in relatively long fatigue lives and uncorroded fracture surfaces. This is considered sufficient ground for amending the cleaning procedure, as will be discussed in section 4.4.

3.4.2 Classification of all primary origins of fatigue

Since table 7 shows that the locations of primary fatigue origins in specimens with corroded and uncorroded fracture surfaces did not differ very much, it was felt that all the data in table 6 could be classified together.

Classification of all the primary fatigue origin data is done in table 8. There are four subdivisions, which will be dealt with consecutively. First, listing the total numbers of each type of primary ori[illegible] shows that

- most failures began in the bores (E/Q) or at the bore/faying surface corners (F/R) of fastener holes: there was no 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 outsides of fastener holes (G), probably because the proximity of free edges facilitated relative displacements between the fatigue specimen -1 and half plate -2, 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).

Listing the primary fatigue origins for specimens tested by each participant reveals minor interlaboratory differences. For example, specimens tested by the AFWAL and RAE exhibited more faying surface (G/S) and fewer bore (E/Q) failures than specimens tested by other participants.

The third part of table 8 gives a complete breakdown of the locations of primary fatigue origins with respect to stress level and testing schedule, and the last part adds up the total numbers of primary fatigue origins per stress level and phase of the CFCTP core programme, i.e. fatigue in air (phase I) and fatigue in acidified salt spray (phase II). The data distribution in these two parts of the table reveals a predominant effect of stress level on the locations of primary fatigue origins. Accordingly, stress level has been treated as the primary variable in preparing figure 5, which supplements table 8. The table and figure show that

- stress level had a major effect:
  - for a maximum stress level of 210 MPa the primary fatigue origins were mainly in the bores of fastener holes
  - for a maximum stress level of 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 failure 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
  - less primary fatigue origins at the bore/faying surface corners of fastener holes for a maximum stress level of 210 MPa, but the same number for a maximum stress level of 144 MPa.

  Overall these effects caused a significant reduction in the number of failures initiating at 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. Also the number of failures initiating at bore/faying surface corners was promoted or maintained for a maximum stress level of 144 MPa.

TABLE 7: 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	C/O
corroded	3930	x				
	4565		x			
	4997	x				
	5393		x			
	6268	x				
	6337	x				
	7980	x				
	8353		x			
	8478	x				
	8768	x				
	10,093	x				
	10,970		x			
	13,023	x				
	14,492	x				
	15,600	x				
uncorroded	12,200		x			
	12,300		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	
	24,778	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	C/O
corroded	7933	11	4	0	0	0
uncorroded	19,322	9	5	2	2	0

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	44,498		x				
	72,111		x				
	76,120	x					
	78,828						x
	85,912		x				
	86,862	x					
uncorroded	71,820				x		
	71,920				x		
	82,483			x			
	83,246		x				
	83,273	x					
	95,243			x			
	96,085			x			
	102,326			x			
	105,261		x				
	106,206			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				
	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	72,371	2	3	0	0	0	1
uncorroded	119,567	2	6	12	5	1	0

TABLE 8: 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 $^D/_P$
55/53	36/44	43/16	9/2	3/0	1/1

● 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
UNIVERSITY OF 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

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

FATIGUE TESTING SCHEDULES	S_{max} = 210 MPa						S_{max} = 144 MPa					
	$^E/_Q$	$^F/_R$	$^G/_S$	$^B/_N$	$^C/_O$	$^D/_P$	$^E/_Q$	$^F/_R$	$^G/_S$	$^B/_N$	$^C/_O$	$^D/_P$
fatigue in air	20	9	7	0	0	0	0	9	23	0	0	0
pre-exposure + fatigue in air	20	9	2	2	0	0	4	9	12	5	1	1
fatigue in salt spray	22	13	0	0	0	0	6	13	10	0	1	0
pre-exposure + fatigue in salt spray	28	5	0	0	0	0	8	13	5	4	1	1

● TOTAL NUMBERS OF PRIMARY ORIGINS PER STRESS LEVEL AND PHASE OF THE CFCTP CORE PROGRAMME

PHASE	S_{max} = 210 MPa						S_{max} = 144 MPa					
	$^E/_Q$	$^F/_R$	$^G/_S$	$^B/_N$	$^C/_O$	$^D/_P$	$^E/_Q$	$^F/_R$	$^G/_S$	$^B/_N$	$^C/_O$	$^D/_P$
I (fatigue in air)	40	18	9	2	0	0	4	18	35	5	1	1
II (fatigue in salt spray)	50	18	0	0	0	0	14	26	15	4	2	1
I AND II	90	36	9	2	0	0	18	44	50	9	3	2

3.5 Correlation of Fatigue Lives and Primary Origins of Fatigue

Correlation of the fatigue lives and primary fatigue origins is given in table 9 and figures 6 and 7. Note that the two failures at the surface edges of countersinks (B) for pre-exposure + fatigue in air at a maximum stress level of 210 MPa have been omitted from figure 6, since there were no similar failures for other fatigue testing schedules at the same stress level.

The correlations show the following:

- most results do not indicate a significant influence of primary fatigue origin on the fatigue life for each testing schedule; however
  - for fatigue in air and pre-exposure + fatigue in air at a maximum stress level of 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 at a maximum stress level of 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

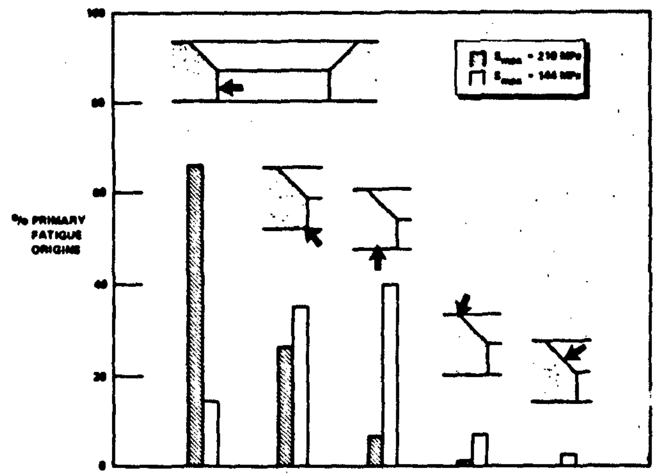


Fig. 5a Primary fatigue origins per stress level for the CFCTP core programme

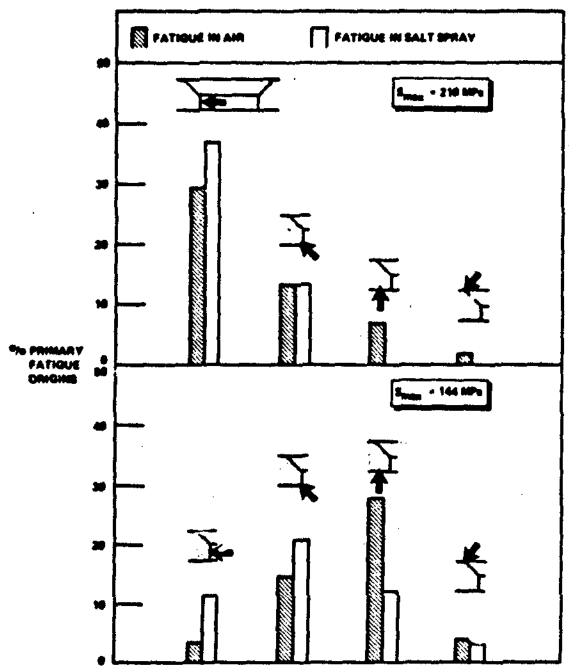


Fig. 5b Primary fatigue origins per fatigue environment for the CFCTP core programme

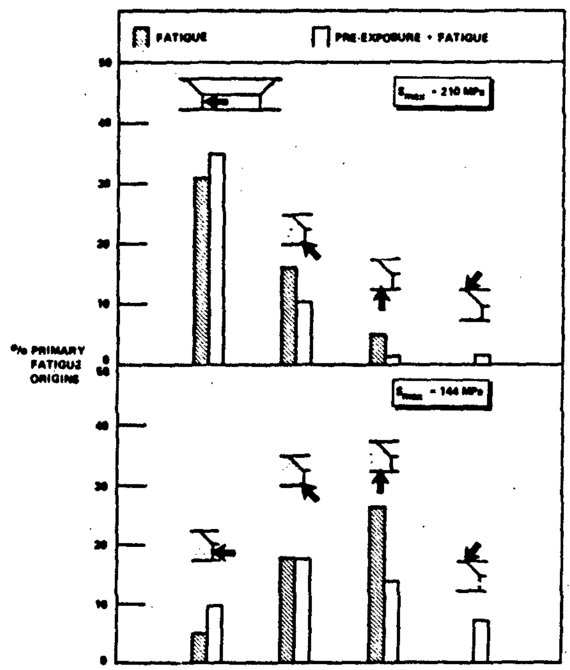


Fig. 5c Primary fa'igue origins for CFCTP core programme ιests with and without pre-exposure

- for a maximum stress level of 210 MPa the effect of pre-exposure and/or fatigue in salt spray in reducing fatigue life was similar for specimens in which failure initiated in the bores or at the bore/faying surface corners of fastener holes
- for a maximum stress level of 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.

4. DISCUSSION

4.1 The Primary Purpose of the CFCTP Core Programme

As mentioned in section 2.2 of this Part of the report, the primary purpose of the CFCTP core programme was to determine whether participants could be confident in one another's fatigue testing capabilities, including the use of a controlled atmospheric corrosion environment.

Analysis of the core programme data showed that there was only one significant inter-laboratory difference, and this was between only two participants. This excellent result is reinforced by the generally low data scatter, which indicates high reproducibility of both specimens and testing conditions.

In short: the primary purpose of the core programme has been achieved.

TABLE 9: LOG MEAN FATIGUE LIFE CORRELATED TO PRIMARY FATIGUE ORIGINS FOR THE CFCTP CORE PROGRAMME

TESTING SCHEDULES	LOCATIONS OF PRIMARY ORIGINS	S_{max} = 210 MPa		S_{max} = 144 MPa	
		NUMBERS OF PRIMARY ORIGINS	LOG MEAN FATIGUE LIFE (CYCLES)	NUMBERS OF PRIMARY ORIGINS	LOG MEAN FATIGUE LIFE (CYCLES)
fatigue in air	E/Q	20	22,606	0	-
	F/R	9	21,207	9	162,489
	G/S	7	29,699	23	129,873
pre-exposure + fatigue in air	E/Q	20	12,219	4	92,770
	F/R	9	10,914	9	100,472
	G/S	2	30,648	12	119,938
	B/N	2	22,089	5	117,704
	C/O	0	-	1	122,800
	D/P	0	-	1	78,828
fatigue in salt spray	E/Q	22	10,583	6	124,192
	F/R	13	13,342	13	65,701
	G/S	0	-	10	116,807
	C/O	0	-	1	122,092
pre-exposure + fatigue in salt spray	E/Q	28	8153	8	76,019
	F/R	5	8937	13	55,010
	G/S	0	-	5	80,906
	B/N	0	-	4	84,035
	C/O	0	-	1	73,840
	D/P	0	-	1	73,840

4.2 Environmental Effects

Analysis of all the data showed that there were consistent environmental effects for both stress levels. Both pre-exposure and fatigue in salt spray significantly reduced the fatigue lives, especially in combination, as may be seen in figure 3.

In view of the overall consistency there are three especially interesting aspects:

- the environmental effects were relatively greater for the higher maximum stress level of 210 MPa: many environmental fatigue data show that the reverse would be expected
- the effect of pre-exposure was similar to that of fatigue in salt spray, although environmental fatigue is generally much more damaging than prior environmental exposure
- for pre-exposure + fatigue in air there was much more scatter at the higher maximum stress level of 210 MPa, whereas scatter is usually less at higher stress levels.

Explanations of these apparently anomalous aspects will now be given based on examination of the fractured specimen halves.

4.2.1 Dependence of environmental effects on stress level

In section 3.4.2 of this Part of the report it was shown that stress level was the major parameter controlling the locations of primary fatigue origins, see figure 5 and table 8. At a maximum stress level of 210 MPa most failures began in the bores of fastener holes. On the other hand, at a maximum stress level of 144 MPa most failures began at bore/faying surface corners and the faying surfaces.

Pre-exposure and fatigue in salt spray especially promoted failure in the fastener holes. It is likely that environmental effects will be greater when they promote characteristic failure modes. This explains why the observed effects were relatively greater at the higher maximum stress level.

Some evidence for environmental effects being greater when they promote characteristic failure modes is provided by the correlation of fatigue lives and primary fatigue origins in figure 6, bearing in mind that pre-exposure and fatigue in salt spray promoted failures in the fastener holes at both stress levels and also that the number of bore/faying surface corner failures was promoted or maintained for a maximum stress level of 144 MPa.

There is a corollary to this explanation of why the environmental effects were relatively greater for a higher maximum stress level, in contrast to many other data. Correct assessment of environmental effects requires the specimens to be realistic: the CFCTP core programme specimens closely simulated a fatigue critical structural joint and their behaviour is more likely to be representative than that of coupons, which constitute the majority of specimens used in environmental fatigue testing.

4.2.2 Relative effects of pre-exposure and fatigue in salt spray

Corrosion on the fracture surfaces of some specimens pre-exposed and fatigued in air provides an explanation of the similar effects of pre-exposure and fatigue in salt spray.

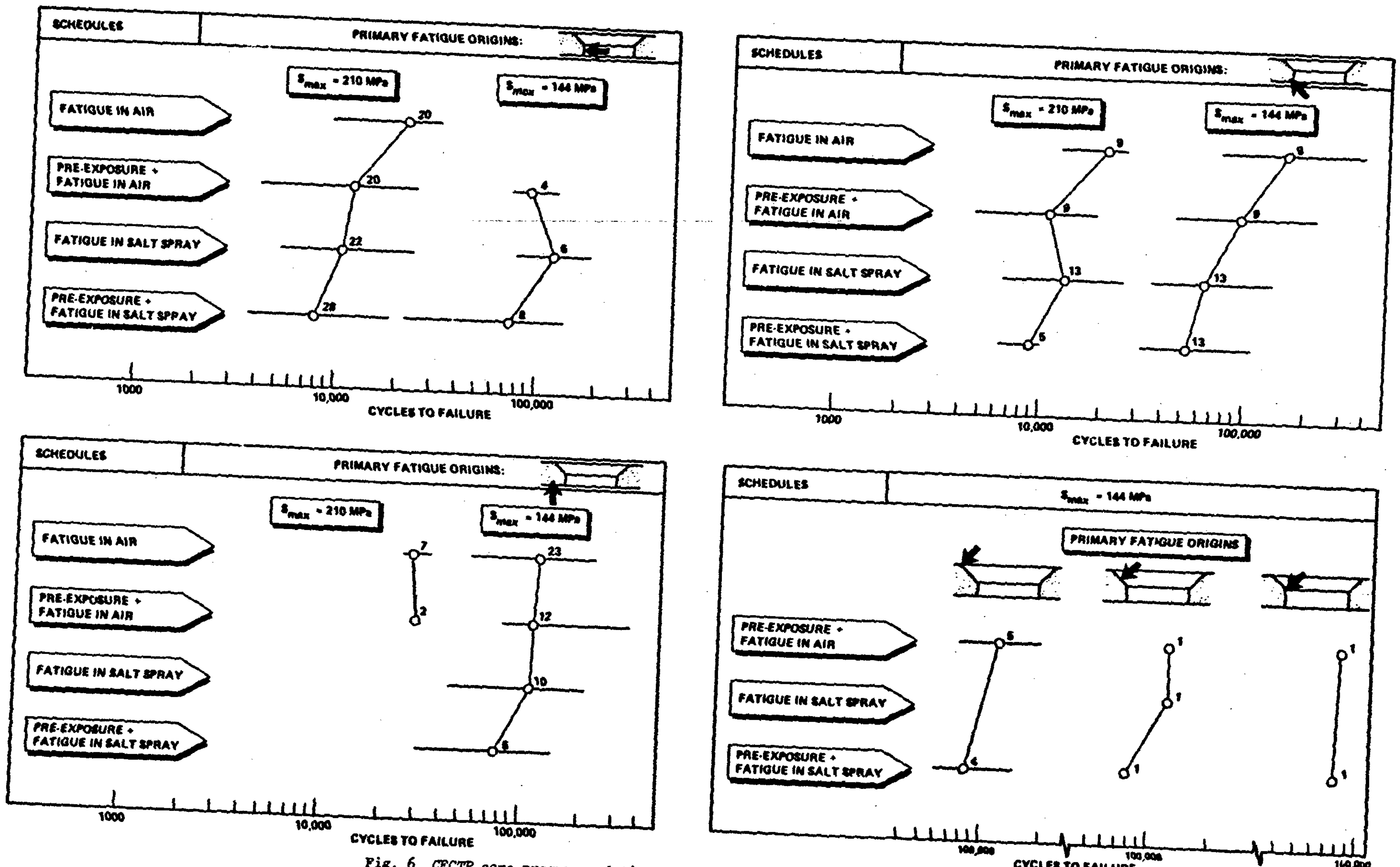


Fig. 6 *CFCTP core programme fatigue life data per primary fatigue origin and test schedule*

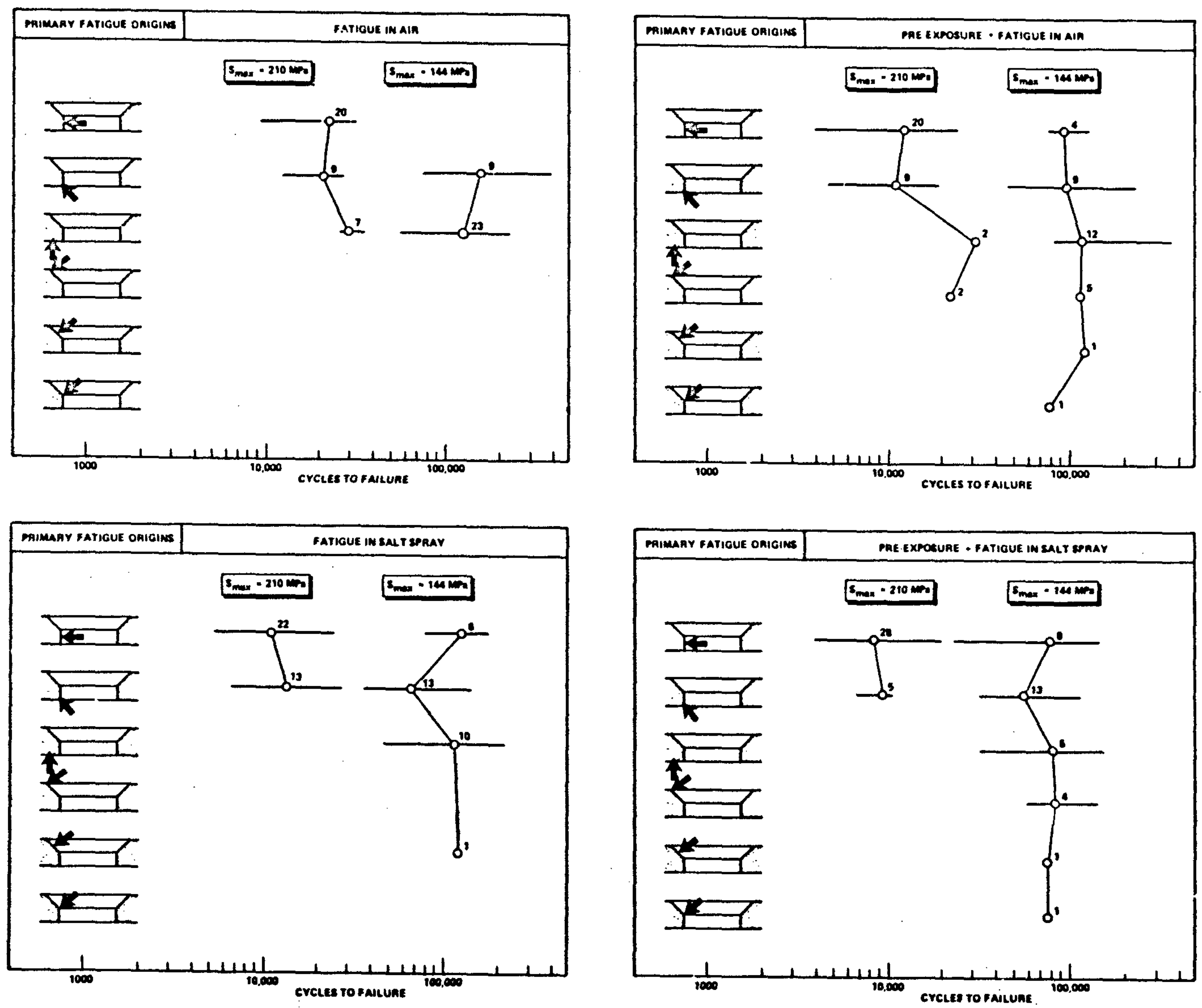


Fig. 7 CFCTP core programme fatigue life data per test schedule and primary fatigue origin

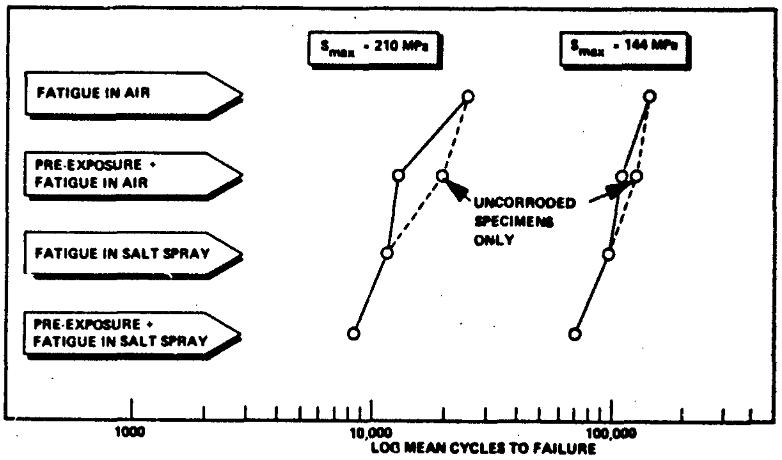


Fig. 8 Summary diagram (figure 3) and the mean fatigue lives of specimens with uncorroded fracture surfaces after pre-exposure + fatigue in air

For pre-exposure + fatigue in air the mean lives of specimens with corroded fracture surfaces were significantly shorter than those of uncorroded specimens, table 7. This corrosion must have been caused by an aggressive environment inside the specimens during fatigue testing, i.e. both pre-exposure and environmental fatigue took place. The occurrence of environmental fatigue in some tests resulted in overall mean lives similar to those obtained from fatigue in salt spray. This is shown in figure 8, which compares the summary diagram of figure 3 and the mean lives of specimens with uncorroded fracture surfaces after pre-exposure + fatigue in air.

4.2.3 Pre-exposure + fatigue in air data scatter

Greater scatter in the data for pre-exposure + fatigue in air at the higher maximum stress level of 210 MPa may be explained as a combination of the explanations in sections 4.2.1 and 4.2.2 plus an additional factor, the variation in efficacy of the cleaning procedure for specimens after pre-exposure.

At the higher maximum stress level of 210 MPa there were many more specimens with corroded fracture surfaces and they showed relatively large reductions in fatigue life, see table 7. This is most probably because the presence of an aggressive environment inside the specimens promoted the characteristic failure mode of fatigue initiation in the fastener holes. Since these specimens were distributed amongst most of the participants, as is remarked in table 6, it must be concluded that the efficacy of the cleaning procedure after pre-exposure was variable. This variability increased the overall scatter in the data.

The cleaning procedure after pre-exposure will be discussed further in section 4.4 with a view to amending it.

4.3 Primary Fatigue Origins

Primary fatigue origins were determined with the main purposes of classifying and correlating them with respect to environmental effects, stress levels and fatigue lives. This was necessary for explaining the results of the CFCTP core programme, as is made clear in sections 4.2.1 - 4.2.3.

In a wider context it is evident that examination with respect to fatigue origins and fracture surfaces is essential to the understanding of environmental fatigue behaviour for realistic specimens and testing conditions.

4.4 Amendment of the Cleaning Procedure After Pre-exposure

In section 7.2 of Part 1 of this report the cleaning procedure after pre-exposure of the CFCTP core programme specimens was specified to be

- 30 minutes rinse in copious amounts of tap water at 291-298K
- final rinse in distilled water at 291-298K for not less than 1 minute
- air dry at 323K for 30 minutes.

The specimens were then to be fatigue tested as soon as possible, preferably immediately. If delay was unavoidable the specimens were to be stored in a desiccator at room temperature until fatigue testing could begin.

Most of the participants fatigue tested pre-exposed core programme specimens within a few hours of cleaning. However, the NLR stored all, and the AFWAL some, of the specimens for several days in desiccators. Table 6 shows that only one of the specimens pre-exposed and fatigue tested in air by the

NLR and AFWAL had corrosion on the fracture surface. Also the fatigue lives tended to be relatively long and exhibited less scatter at a maximum stress level of 210 MPa as compared to those determined by most of the other participants.

As discussed in section 4.2.3 it must be concluded that the efficacy of the cleaning procedure was variable. Specimen storage in a desiccator for several days reduced the variability. This is considered sufficient ground for amending the cleaning procedure as follows:

- 30 minutes rinse in copious amounts of tap water at 291-298K
- final rinse in distilled water at 291-298K for not less than 1 minute
- air dry at 323K for 60 minutes
- desiccator storage at room temperature for not less than 1 week.

This change in specification refers to any further tests according to the core programme requirements and also to the cleaning procedure after pre-exposure of supplemental testing programme specimens, see sections 7.2, 7.4, 9.1, 9.2 and 10.2 of Part 1 of this report.

5. CONCLUSIONS

The core programme of round-robin testing for the AGARD-coordinated corrosion fatigue cooperative testing programme (CFCTP) has demonstrated that

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

(2) The specimens and testing conditions were highly reproducible.

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

(4) Choice of realistic specimens is necessary for correct assessment of environmental effects.

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

(6) The cleaning procedure after pre-exposure should be modified in further tests.

Finally, we conclude that 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

Here we take the opportunity formally to thank

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- the VOI-SHAN Corporation
- the CFCTP participants.

In particular, we are grateful to Prof. Dr. W. Bunk for initiating this activity, Dr. H.P. van Leeuwen for continuing to oversee it, and Ms. M.T. Russo for the statistical analysis.

ANNEX 1

NDRE SPECIMEN EXAMINATION AT THE RAUFOSS AMMUNITION FACTORY

1. INTRODUCTION

The fracture surfaces of CFCTP core programme specimens tested by the Norwegian Army Material Command (coordinator NDRE) were examined by Dr. K. Asbøll of the Raufoss Ammunition Factory. All these specimens were inspected using a stereo microscope. Several specimens were selected for detailed examination using scanning electron microscopy. In addition, metallographic sections of two specimens pre-exposed and fatigued in air were made through the countersink areas of fastener holes to determine the type of corrosion.

The data provided by Dr. Asbøll form the basis for the following discussion prepared by the European coordinator.

2. CLASSIFICATION OF PRIMARY AND SECONDARY ORIGINS OF FATIGUE

Classification of the primary and secondary fatigue origin data for the NDRE specimens is done in table 1. There are three sub-divisions, which will be considered consecutively. First, listing the fatigue lives and origins per stress level and fatigue testing schedule shows that fatigue origins determined by both observers generally agreed.

The most probable locations of primary fatigue origins were subtracted from the data to prepare the second and third parts of table 1. These have been simplified by allocating the five recorded D/P secondary fatigue origins to E/Q locations. The data show

- more than twice as many secondary fatigue origins for the higher maximum stress level of 210 MPa, namely 56:26
- no essential differences in the ratios of E/Q:F/R:G/S locations at each stress level
- no marked influence of pre-exposure and/or fatigue in salt spray on the locations of secondary fatigue origins.

Figure 1 compares percentages of the three main types of primary fatigue origin for the complete

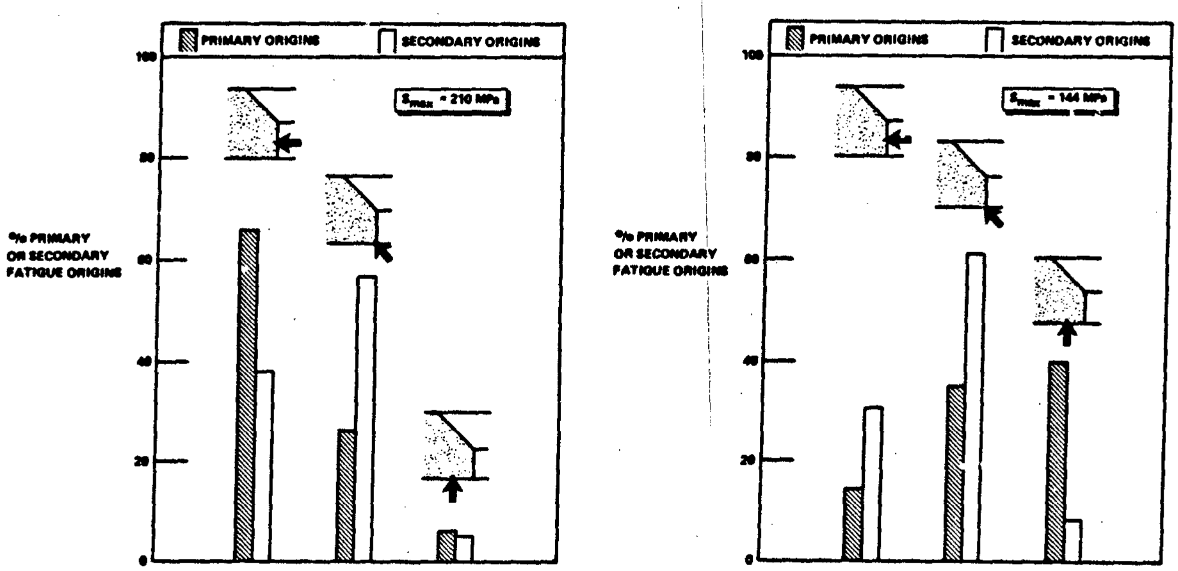


Fig. 1 Primary fatigue origins (complete CFCTP core programme) compared with secondary fatigue origins (NDRE) per stress level

core programme (see figure 5 in Part 2 of the report) with the percentages of types of secondary fatigue origins for the NDRE specimens. There is a strong tendency for secondary fatigue origins to occur at bore/faying surface corners (F/R) of fastener holes. This contrasts with the distribution of primary fatigue origins in two ways:

- for a maximum stress level of 210 MPa the primary fatigue origins were mainly in the bores (E/Q) of fastener holes
- for a maximum stress level of 144 MPa the primary fatigue origins were mainly at the bore/faying surface corners (F/R) and the faying surfaces (G/S).

The effect of stress level on the locations of primary fatigue origins provides a partial explanation of the distribution of secondary fatigue origins. Once a primary fatigue crack initiated the local decrease in stiffness would result in load shedding to other locations with the consequence of higher stresses there. These higher stresses might be expected to promote secondary fatigue crack initiation in the bores of fastener holes, notably at the expense of failures initiating at faying surfaces for a (nominal) maximum stress level of 144 MPa.

Figure 1 shows that there is some merit to this argument. However, the predominance of secondary fatigue origins at bore/faying surface corners of fastener holes indicates an additional, important factor besides load shedding. This additional factor is most likely to be local distortion owing to the presence of a pr mary fatigue crack. Such distortion could result in the bore/faying surface corners of the fatigue specimen -1 being preferentially damaged by rubbing against the half plate -2, thereby facilitating secondary fatigue crack initiation at these corners.

TABLE 1: FATIGUE LIFE AND ORIGIN DATA FOR THE NDRE CORE PROGRAMME SPECIMENS

● FATIGUE LIVES AND ORIGINS PER STRESS LEVEL AND FATIGUE TESTING SCHEDULE

FATIGUE TESTING SCHEDULES	S_{max} = 210 MPa			S_{max} = 144 MPa		
	FATIGUE LIFE TO FAILURE (CYCLES)	FATIGUE ORIGINS* (ASBØLL)	PRIMARY FATIGUE ORIGINS* (WANHILL)	FATIGUE LIFE TO FAILURE (CYCLES)	FATIGUE ORIGINS* (ASBØLL)	PRIMARY FATIGUE ORIGINS* (WANHILL)
fatigue in air	25,310	1FED,1Q,2F,2Q	E	175,510	1F,1R	R
	25,500	1E,1R,2R,2Q	Q,R	81,170	1E,1R,2F,2S	R
	19,210	1G,1RQ,2F,2RQ	E	111,500	1F,2F,2S	G
	21,940	1F,1R,2F,2Q	Q	146,240	1G,1R	G
pre-exposure + fatigue in air	24,551	1B,1Q,2B,2E; 2Q	B,Q	71,820	1F,1RP,2R	B
	18,670	1F,1R,2F,2R	R	71,920	2E,2N	B
	12,200	1FE,1R,2FE,2R	F	72,111	2F,2RP	R
	3930	2FE,2RQ	Q	76,120	2E,2Q	E
fatigue in salt spray	13,626	1R,2F,2R	E,R	92,929	1F,1Q	F
	9106	1E,1RQ,2F,2RQ	Q	82,561	1F,1R	G
	11,026	1E,1RQP	E	45,240	2G,2RQP	G
	10,137	1R,2FE,2R	F	121,584	-	-
pre-exposure + fatigue in salt spray	10,100	1FE,1Q,2F,2Q	Q	106,209	1R,2F,2R	R
	11,426	2F,2RQ	E	22,608	1F,1R	E
	7093	1FE,1R,2F,2Q	Q	76,442	1F,1S,2F,2R	R
	8794	1FE,1R,2E,2R, 2Q	E	121,927	-	-

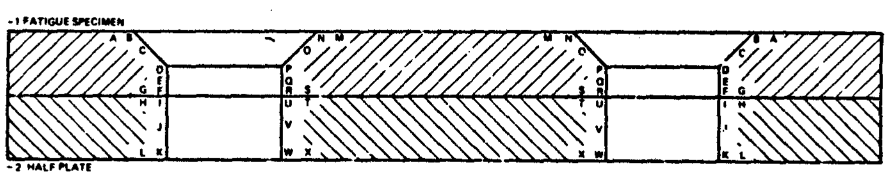
● NUMBERS OF SECONDARY ORIGINS PER STRESS LEVEL AND FATIGUE TESTING SCHEDULE

FATIGUE TESTING SCHEDULES	S_{max} = 210 MPa			S_{max} = 144 MPa		
	E/Q	F/R	G/S	E/Q	F/R	G/S
fatigue in air	6	8	1	1	5	1
pre-exposure + fatigue in air	5	8	2	4	4	0
fatigue in salt spray	4	7	0	3	2	0
pre-exposure + fatigue in salt spray	6	9	0	0	5	1

● TOTAL NUMBERS OF SECONDARY ORIGINS PER STRESS LEVEL AND PHASE OF THE CFCTP CORE PROGRAMME

PHASE	S_{max} = 210 MPa			S_{max} = 144 MPa		
	E/Q	F/R	G/S	E/Q	F/R	G/S
I (fatigue in air)	11	16	3	5	9	1
II (fatigue in salt spray)	10	16	0	3	7	1
I AND II	21	32	3	8	16	2

* KEY TO LOCATIONS OF FATIGUE ORIGINS



3. FRACTOGRAPHS OF FATIGUE ORIGINS

Examples of fatigue origins for the four fatigue testing schedules are arrowed in *figure 2*. Particular features to note are

- for the two fatigue origins at bore/faying surface corners of the fastener holes, (a) and (d), the fracture surface markings pointing back to the origin are less obvious for the specimen pre-exposed and fatigued in salt spray
- fatigue initiation at a corrosion pit for a specimen pre-exposed and fatigued in air
- multiple fatigue origins in the bore of a fastener hole for a specimen fatigued in salt spray.

4. METALLOGRAPHY OF CORROSION DUE TO PRE-EXPOSURE

Metallographic sections through corrosion pits in the countersink areas of fastener holes were made from two specimens pre-exposed and fatigue tested in air. Examples are given in figure 3. The corrosion appears to be mainly intergranular, although it could be a combination of intergranular corrosion and pitting corrosion preferentially in the longitudinal (rolling) direction of the 7075-T76 aluminium alloy sheet.

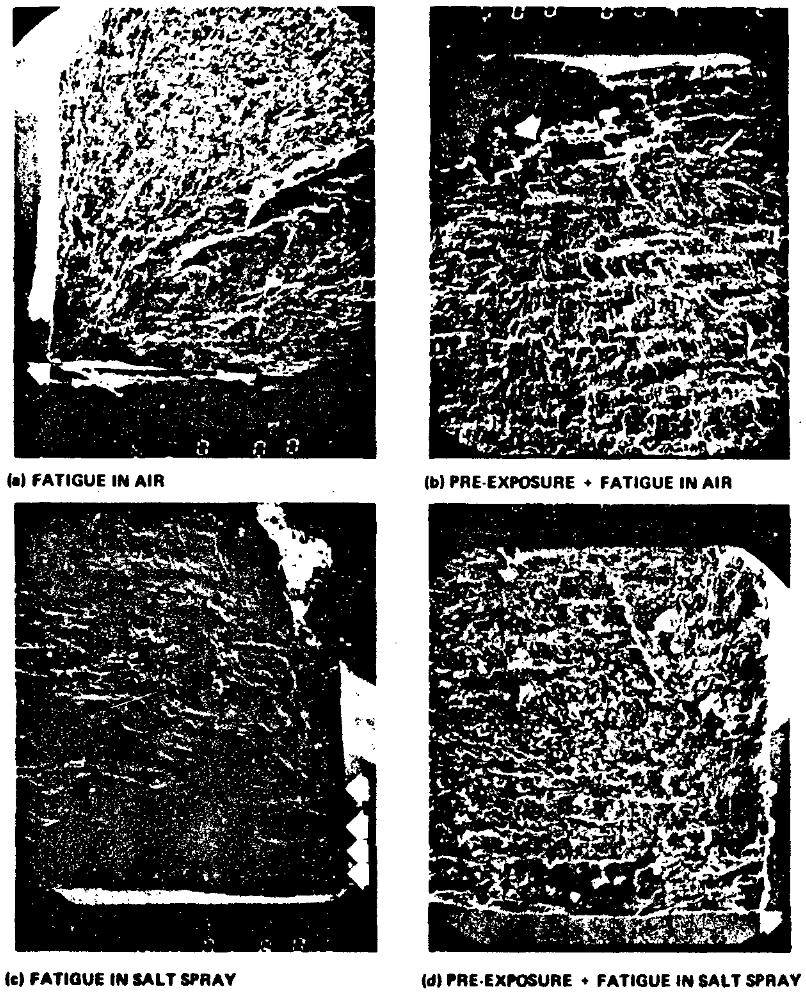


Fig. 2 Examples of fatigue origins in NDRE specimens fatigue tested at a maximum stress level of 144 MPa

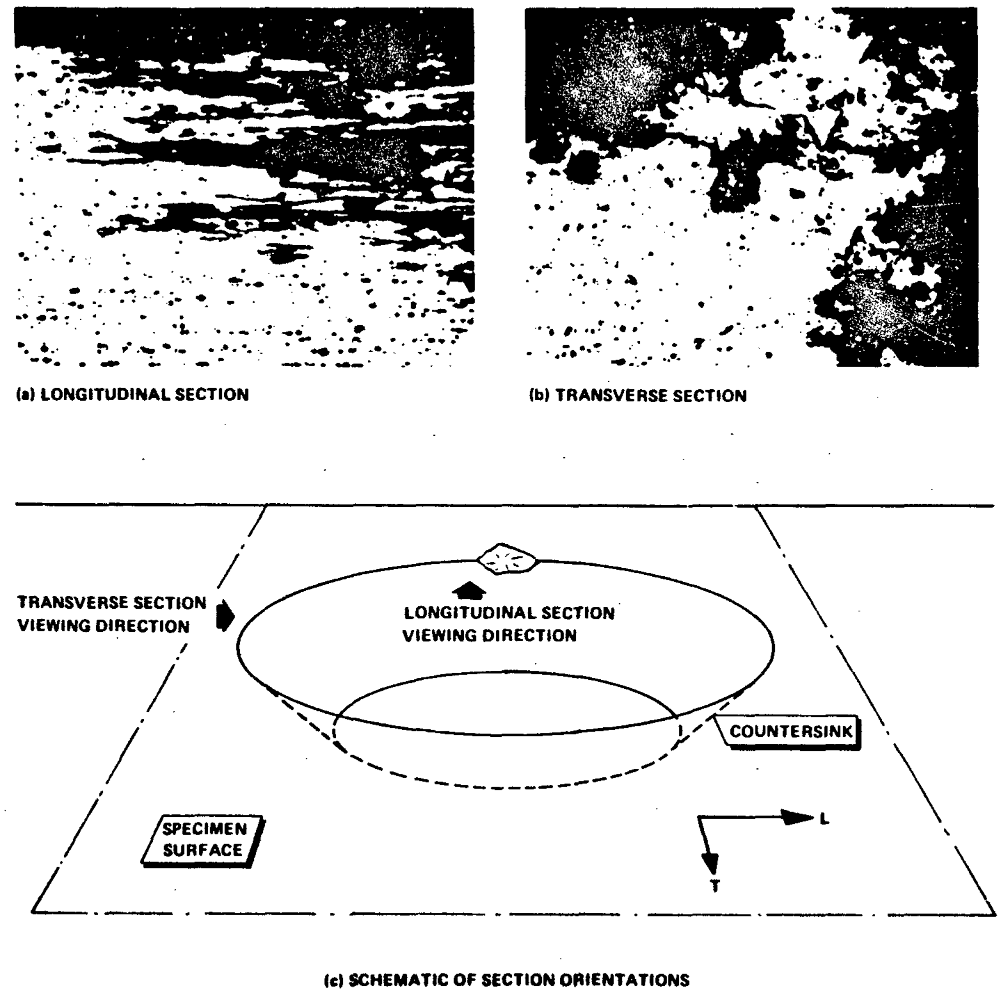


Fig. 3 Metallographic sections through corrosion pits for two specimens pre-exposed and fatigue tested in air at a maximum stress level of 144 MPa

ANNEX 2

ILLUSTRATION OF STATISTICAL METHODS

1. INTRODUCTION

The statistical methods used to analyse the CFCTP core programme fatigue life data were listed according to purpose in table 4 of Part 2 of the report. This table is repeated here as table 1. The methods will be illustrated in sections 2.1-2.7 of this Annex.

TABLE 1: STATISTICAL METHODS USED TO ANALYSE THE CFCTP CORE PROGRAMME DATA

PURPOSE OF ANALYSIS	TEST FOR NORMALITY	BOX TEST FOR HOMOGENEITY OF VARIANCES	BARTLETT TEST FOR HOMOGENEITY OF VARIANCES	SINGLE FACTOR ANALYSIS OF VARIANCE	SCHEFFE TEST FOR INDIVIDUAL COMPARISONS	t-STATISTIC EVALUATION	LIPSON AND SHETH METHOD
CHECK FOR DIFFERENCES BETWEEN LABORATORIES	•	•		•	•		
CHECK FOR ENVIRONMENTAL EFFECTS	•		•			•	
CHECK SUFFICIENCY OF SAMPLE SIZE							•

2. ILLUSTRATION OF METHODS

2.1 Checking for Normal Distribution

The 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 sample size was 32. Each population was arranged in ascending order of fatigue life and a cumulative probability of failure was assigned to each datum. Then the data were plotted on arithmetic normal and logarithmic normal probability paper.

It was found that straight lines fitted the data closely when plotted on logarithmic normal probability paper, figure 1. Thus the data for each population approximate to a log-normal distribution. This means that the data 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 The Box Test for Homogeneity of Variances

To check for differences between laboratories the data were considered to belong to sixty-four populations with a sample size of 4, corresponding to the number of specimens tested by each laboratory for each fatigue testing schedule and stress level. The small sample size required the Box test to be used to determine whether the variances of the populations were equal (homogeneous).

TABLE 2: THE BOX TEST PROCEDURE

FATIGUE IN AIR AT A MAXIMUM STRESS LEVEL OF 210 MPa							
SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES SS	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	0.018	3	0.333	0.006	-2.216	-6.648
2 SASKATCHEWAN	4	0.131	3	0.333	0.044	-1.359	-4.078
3 VOUGHT	4	0.066	3	0.333	0.022	-1.657	-4.972
4 AFWAL	4	0.027	3	0.333	0.009	-2.040	-6.119
5 NLR	4	0.010	3	0.333	0.004	-2.455	-7.365
6 DFVLR	4	0.014	3	0.333	0.005	-2.339	-7.017
7 NDRE	4	0.010	3	0.333	0.003	-2.467	-7.401
8 RAE	4	0.014	3	0.333	0.005	-2.332	-6.994
$(k = 8)$							
SUM	-	-	-	2.664	-	-	-50.594
POOLED	-	0.290	24	0.042	0.012	-1.918	-46.028
DIFFERENCE	-	-	-	$D_1 = 2.622$	-	-	$D_2 = 4.566$
FURTHER COMPUTATION	$K = 2.3026\ D_2 = 10.514$ $L = \frac{D_1}{3(k-1)} = 0.125$ $\nu_1 = k - 1 = 7$ $\nu_2 = \frac{k+1}{L^2} = 576$ $D = \frac{\nu_2}{1 - L + (2/\nu_2)} - K = 645.170$ $F = \frac{K/\nu_1}{D/\nu_2} = 1.341$ $F_{0.05;\nu_1;\nu_2} = F_{0.05;7;576} = 2.03$ $1.341 < 2.03$, ∴ the eight population variances are equal						

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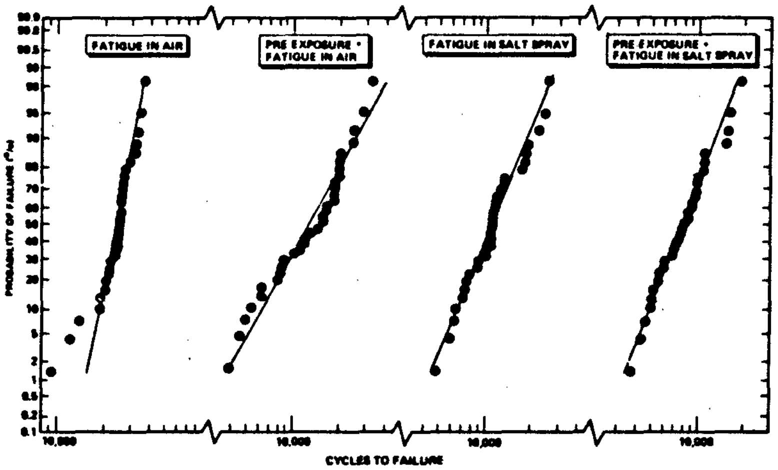


Fig. 1a Cumulative probability of failure versus log fatigue life for CFCTP core programme specimens with S_{max} = 210 MPa

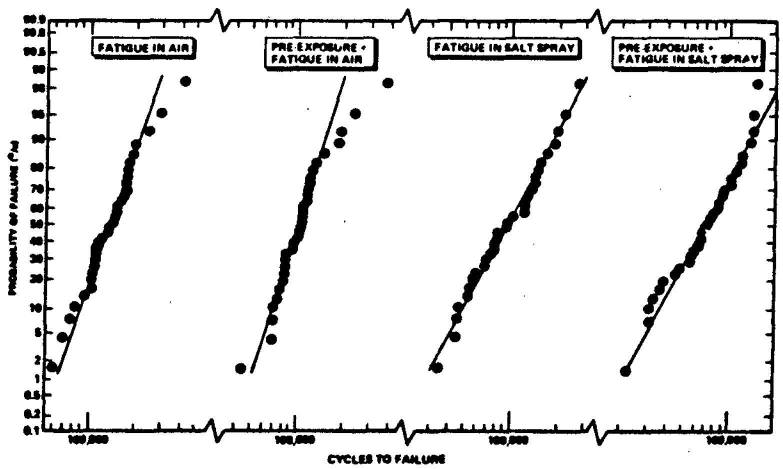


Fig. 1b Cumulative probability of failure versus log fatigue life for CFCTP core programme specimens with S_{max} = 144 MPa

The Box test procedure is illustrated in table 2. More details are available in: J.C.R.Li, Statistical Inference I, Edwards Brothers Inc., Ann Arbor, Michigan (1964).

2.3 The Bartlett Test for Homogeneity of Variances

To check for environmental effects the data for each fatigue testing schedule and stress level were treated as coming from the same population. Thus no distinction was made between the data from different laboratories, and the sample size was 32. This fairly large sample size enabled the Bartlett test to be used to determine whether the variances of the populations were equal.

The Bartlett test procedure is illustrated in table 3. More details are available in: J.C.R.Li, Statistical Inference I, Edwards Brothers Inc., Ann Arbor, Michigan (1964).

2.4 Single Factor Analysis of Variance

Single factor analysis of variance was applied to check for significant differences in the data from different laboratories for each fatigue testing schedule at each stress level. Thus the data were considered to belong to sixty-four populations with a sample size of 4. Before proceeding to analysis of variance it was necessary to check whether the population variances were equal. As already mentioned in section 2.2 of this Annex, the small sample size required the Box test to be used for this check. It was found that the population variances were equal except for a moderate violation in the case of comparison of the eight populations for pre-exposure + fatigue in air at a maximum stress level of 144 MPa.

This result enabled application of single factor analysis of variance, which is illustrated in three consecutive stages in table 4. More details are available in: C. Lipson and N.J. Sheth, Statistical Design and Analysis of Engineering Experiments, McGraw-Hill Book Company, New York (1973).

TABLE 3: THE BARTLETT TEST PROCEDURE

COMPARISON OF POPULATION VARIANCES FOR FATIGUE IN AIR AND PRE-EXPOSURE + FATIGUE IN AIR AT A MAXIMUM STRESS LEVEL OF 210 MPa							
SAMPLE NUMBER	SAMPLE SIZE n	SUM OF SQUARES SS	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	32	0.496	31	0.032	0.016	-1.796	-55.685
2 pre-exposure + fatigue in air	32	1.870	31	0.032	0.060	-1.220	-37.808
k = 2							
SUM	-	-	-	0.064	-	-	-93.493
POOLED	-	2.336	62	0.016	0.038	-1.418	-87.939
DIFFERENCE	-	-	-	$D_1 = 0.048$	-	-	$D_2 = 5.554$
FURTHER COMPUTATION	$K = 2.3026\ D_2 = 12.789$ $\quad L = \frac{D_1}{3(k-1)} = 0.016$ $\chi^2 = \frac{K}{1+L} = 12.588$ with k - 1 degrees of freedom $\chi^2_{0.05;k-1} = \chi^2_{0.05;1} = 3.841$ 12.588 > 3.841, ∴ the two population variances are <u>not</u> equal						

A significant inter-laboratory difference was indicated with 95 % confidence for fatigue in salt spray at a maximum stress level of 210 MPa. To locate the source, or sources, of this significant difference the Scheffé test was applied to the relevant data.

2.5 The Scheffé Test

This is a test of significance for a difference between any two means. The Scheffé test was used to locate the source, or sources, of a significant inter-laboratory difference in the data for fatigue in salt spray at a maximum stress level of 210 MPa. The test procedure is illustrated in table 5. More details are available in: G.M. Smith, A Simplified Guide to Statistics, Fourth Edition, Holt, Rinehart and Winston Inc., New York (1970).

2.6 The t-Statistic Evaluation

The t-static evaluation procedure was used to check the significance of environmental effects. This procedure was used instead of two factor analysis of variance because the Bartlett test, Annex 2.3, showed that several population variances were not equal when the data were compared for different fatigue testing schedules at each stress level.

The t-statistic evaluation procedure was standard for comparisons of data with equal variance and modified for comparisons of data with unequal variance. Both kinds of procedure are illustrated in table 6. More details are available in: J.C.R.Li, Statistical Inference I, Edwards Brothers Inc., Ann Arbor, Michigan (1964).

2.7 The Lipson and Sheth Method

This method was used to check for sufficiency of replicate test sample size, namely 4 specimens per test condition per participant. The method involves selecting an acceptable error level, usually 5 % or 10 %, and finding the required sample size for a particular confidence level. It is illustrated in table 7. More details are available in: C. Lipson and N.J. Sheth, Statistical Design and Analysis of Engineering Experiments, McGraw-Hill Book Company, New York (1973).

TABLE 4: SINGLE FACTOR ANALYSIS OF VARIANCE

• DATA AND INITIAL COMPUTATION

FATIGUE IN AIR AT A MAXIMUM STRESS LEVEL OF 210 MPa								
SAMPLE COLUMNS	NADC	SASK.	VOUGHT	AFWAL	NLR	DFVLR	NDRE	RAE
LOG FATIGUE LIFE	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
TOTAL, T_c	17.543	16.873	17.193	17.954	17.706	17.741	17.435	17.632

c = number of columns (participants) = 8 N = total number of data = 32

n = replicate test sample size = 4 Σx = total value of data = 140.077

Σx^2 = total value of squares of data = 613.666

• SUMS OF SQUARES FOR THE SOURCES OF VARIATION

AMONG COLUMNS	$SS_c = \frac{\Sigma T_c^2}{n} - \frac{T^2}{N} = 0.204$
TOTAL VARIANCE	$SS_{TOTAL} = \Sigma x^2 - \frac{(\Sigma x)^2}{N} = 0.496$
RESIDUAL	$SS_r = SS_{TOTAL} - SS_c = 0.291$

• ANALYSIS OF VARIANCE TABLE FOR A SINGLE FACTOR EXPERIMENT

SOURCE OF VARIATION	SUM OF SQUARES (SS)	DEGREES OF FREEDOM (DF)	MEAN SQUARE MS $\left(\frac{SS}{DF}\right)$	MEAN SQUARE RATIO MSR $\left(\frac{MS}{MS_{RESIDUAL}}\right)$	MINIMUM MSR REQUIRED FOR FACTORS TO BE SIGNIFICANT AT 95 % CONFIDENCE $(F_{0.05;7;24})$
COLUMNS (PARTICIPANTS)	0.204	c - 1 = 7	0.029	2.404	2.42
RESIDUAL	0.291	(N-1) - (c-1)=24	0.012		

As shown in the table the mean square ratio MSR is less (2.404) than the F ratio for 95 % confidence (2.42). Hence it can be concluded with 95 % confidence that there is no significant difference in the data from the eight participants.

TABLE 5: THE SCHEFFE TEST

● DATA AND INITIAL COMPUTATION

FATIGUE IN SALT SPRAY AT A MAXIMUM STRESS LEVEL OF 210 MPa								
PARTICIPANTS	NADC	SASK.	VOUGHT	AFWAL	NLR	DFVLR	NDRE	RAE
LOG MEAN FATIGUE LIFE	3.976	4.159	3.790	4.088	3.982	4.244	4.036	4.158

c = number of participants = 8

N = total number of data = 32

n = replicate test sample size = 4

$\bar{x}$ = mean value of data for each participant

s = standard error of difference for all comparisons of two means in the C groups

$= \sqrt{\frac{2MS_{RESIDUAL}}{n}} = \sqrt{\frac{2(0.020)}{4}} = 0.100$, where $MS_{RESIDUAL}$ is obtained from the appropriate analysis of variance table for a single factor experiment

t'_{CL} = criterion of significance $= \sqrt{(C-1)F_{CL;c-1;(N-1)-(c-1)}}$

$t'_{0.05} = \sqrt{7F_{0.05;7;24}} = \sqrt{7(2.42)} = 4.116$

● TESTING FOR SIGNIFICANT DIFFERENCE BETWEEN ANY TWO MEANS

NUMBER OF POSSIBLE COMPARISONS OF TWO MEANS FOR c = 8 PARTICIPANTS

NADC : SASK.	SASK. : VOUGHT	VOUGHT : AFWAL	AFWAL : NLR	NLR : DFVLR	DFVLR : NDRE	NDRE : RAE
NADC : VOUGHT	SASK. : AFWAL	VOUGHT : NLR	AFWAL : DFVLR	NLR : NDRE	DFVLR : RAE	
NADC : AFWAL	SASK. : NLR	VOUGHT : DFVLR	AFWAL : NDRE	NLR : RAE		
NADC : NLR	SASK. : DFVLR	VOUGHT : NDRE	AFWAL : RAE			
NADC : DFVLR	SASK. : NDRE	VOUGHT : RAE				
NADC : NDRE	SASK. : RAE					
NADC : RAE						

$t = \frac{\bar{x}_1 - \bar{x}_2}{s}$, where $\bar{x}_1$ and $\bar{x}_2$ are the mean values of data for participants 1 and 2

If the absolute value of an obtained t is equal to or greater than t' the difference between the means is considered significant. For the comparison between the DFVLR and VOUGHT $t = \frac{4.244 - 3.790}{0.100} = 4.540$, which is greater than 4.116. Hence it can be concluded with 95 % confidence that there is a significant difference in the data from these two participants. No other values of t were greater than t'.

TABLE 6: THE t-STATISTIC EVALUATION

COMPARISON OF DATA FOR FATIGUE IN AIR AND PRE-EXPOSURE + FATIGUE IN AIR AT A MAXIMUM STRESS LEVEL OF 144 MPa

SAMPLE NUMBER	LOG MEAN FATIGUE LIFE $\bar{x}$	SAMPLE SIZE* n	SUM OF SQUARES SS	DEGREES OF FREEDOM = n − 1
1 fatigue in air	5.125	31	0.753	30
2 pre-exposure + fatigue in air	5.019	31	0.629	30

* Note that the sample size is 31 and not 32. This is because two suspect outliers are excluded. These are the University of Saskatchewan datum of 419,690 cycles for fatigue in air and the RAE datum of 387,955 cycles for pre-exposure + fatigue in air.

• STANDARD PROCEDURE FOR DATA WITH EQUAL VARIANCE

$$s^2 = \text{variance} = \frac{SS_1 + SS_2}{\nu_1 + \nu_2} = \frac{0.753 + 0.629}{30 + 30} = 0.023$$

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} = \frac{5.125 - 5.019}{\sqrt{0.023\left(\frac{1}{31} + \frac{1}{31}\right)}} = 2.752, \text{ with } \nu_1 + \nu_2 = 60 \text{ degrees of freedom}$$

The 95 % confidence interval for the t-statistic with 60 degrees of freedom is (-2.000,2.000). The calculated t-statistic (2.752) falls outside this confidence interval. Hence it can be concluded with 95 % confidence that there is a significant difference between the data for fatigue in air and pre-exposure + fatigue in air at a maximum stress level of 144 MPa, i.e. the effect of pre-exposure was significant at this stress level.

COMPARISON OF DATA FOR FATIGUE IN AIR AND PRE-EXPOSURE + FATIGUE IN AIR AT A MAXIMUM STRESS LEVEL OF 210 MPa

SAMPLE NUMBER	LOG MEAN FATIGUE LIFE $\bar{x}$	SAMPLE SIZE n	SUM OF SQUARES SS	DEGREES OF FREEDOM $\nu = n-1$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$
1 fatigue in air	4.337	32	0.496	31	0.016
2 pre-exposure + fatigue in air	4.105	32	1.870	31	0.060

• MODIFIED PROCEDURE FOR DATA WITH UNEQUAL VARIANCE

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} = \frac{4.337 - 4.105}{\sqrt{\frac{0.016}{32} + \frac{0.060}{32}}} = 5.581, \text{ with } \frac{\nu_1\nu_2\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\nu_2\left(\frac{s_1^2}{n_1}\right)^2 + \nu_1\left(\frac{s_2^2}{n_2}\right)^2} = 46 \text{ degrees of freedom}$$

The 95 % confidence interval for the t-statistic with 46 degrees of freedom is (-2.009,2.009). The calculated t-statistic (5.581) falls outside this confidence interval. Hence it can be concluded with 95 % confidence that there is a significant difference between the data for fatigue in air and pre-exposure + fatigue in air at a maximum stress level of 210 MPa, i.e. the effect of pre-exposure was significant at this stress level.

TABLE 7: THE LIPSON AND SHETH METHOD

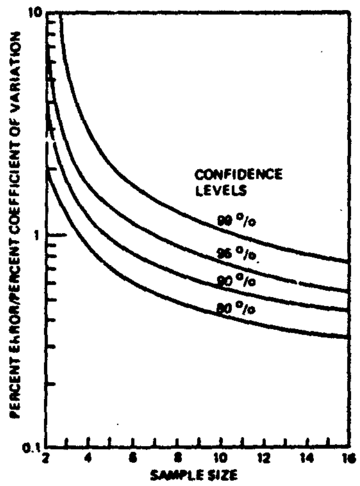
● DATA AND INITIAL COMPUTATION

NADC DATA FOR FATIGUE IN AIR							
MAXIMUM STRESS MPa	LOG MEAN FATIGUE LIFE $\bar{x}$	SAMPLE SIZE n	SUM OF SQUARES SS	DEGREES OF FREEDOM $\nu = n - 1$	SAMPLE VARIANCE $s^2 = \frac{SS}{\nu}$	STANDARD DEVIATION s	% COEFFICIENT OF VARIATION $\frac{s}{\bar{x}}$
210	4.386	4	0.018	3	0.006	0.078	1.778
144	5.119	4	0.0918	3	0.0306	0.175	3.415

● SELECTION OF ERROR LEVELS

PERCENT ERROR	PERCENT ERROR / PERCENT COEFFICIENT OF VARIATION	
	S_{max} = 210 MPa	S_{max} = 144 MPa
5 %	2.812	1.464
10 %	5.624	2.928

● GRAPHICAL DETERMINATION OF REQUIRED SAMPLE SIZES FOR A GIVEN COMBINATION OF ERROR AND CONFIDENCE LEVELS (ENTER ORDINATE, MOVE TO REQUIRED CONFIDENCE CURVE AND READ OFF NEAREST INTEGER SAMPLE SIZE ON THE ABSCISSA)



● EXAMPLE OF REQUIRED SAMPLE SIZES

PERCENT ERROR	REQUIRED SAMPLE SIZE FOR THE 90 % CONFIDENCE LEVEL	
	S_{max} = 210 MPa	S_{max} = 144 MPa
5 %	3	4
10 %	2	2

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14. Abstract

The objectives of the programme are:

- to assess the effectiveness of state-of-the-art protection schemes for aluminium alloys with respect to corrosion fatigue and corrosion + fatigue
- to stimulate the development of new protection products, procedures and techniques
- to bring researchers on both sides of the Atlantic together 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
- to enable participating laboratories to add to their fatigue testing capabilities by using a controlled atmospheric corrosion environment.

Within this context, a core programme was conceived as a two-phase programme of round-robin testing to establish whether participants could obtain confidence in one another's fatigue testing capabilities. At the same time the programme was designed to be sufficiently straightforward to encourage participation, particularly by those with relatively little experience of corrosion fatigue testing.

This report is comprised of the programme manual and a description of the scope and purpose of the core programme, followed by presentation of the results, statistical analysis, discussion and conclusions.

This Programme was sponsored by the Structures and Materials Panel of AGARD.

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