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US/AUSTRALIA COLLABORATIVE RESEARCH PROJECT ON CORROSION FATIGUE IN D6AC STEEL JOINTS

Systems Support Division
U.S. Air Force Materials Laboratory
and
Aeronautical Research Laboratories
Australian Department of Defence

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AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
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This technical report has been reviewed and is approved for publication.

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A U.S./Australian Program has been conducted to determine the effect of manufacturing-induced and environmental corrosion on D6AC steel Taper-Lok bolted joints as used in the F-111 aircraft. Under constant amplitude, traces of distilled water or concentrated hydrochloric acid in the bolt holes did not reduce fatigue life. Under spectrum loading, traces of water did not affect fatigue life but traces of hydrochloric acid reduced the mean fatigue life of the joint by a factor of 110. The results of

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further constant amplitude tests and a limited series of spectrum tests confirmed previous findings that the life of those original joints in the F-111 which were manufactured using a six-flute hand reamer could be appreciably extended by rework with an 18-flute tapered reamer as used in later F-111 production. Other rework procedures involving cold working of the hole by a mandrel or specially designed fasteners showed little improvement when used in this relatively high-strength steel joint material. The effects of improved sealants and the capability of ultrasonic and magnetic NDI techniques for inspection of cracks at fastener holes were also investigated. It is concluded that the life of uncontaminated, properly fabricated and sealed D6AC steel joints as used in the F-111 wing carry through should not be a source of fatigue failure during a normal aircraft lifetime.

AFML-TR-78-150

FOREWORD

This report was prepared jointly by the Materials Integrity Branch (MXA), Systems Support Division, U.S. Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, with Mr. C. L. Harmsworth as the Project Manager and by the Structures and Materials Divisions, Australian Aeronautical Research Laboratories, Department of Defense, Melbourne, Victoria, with Dr. D. S. Kemsley originally, and subsequently Dr. J. M. Finney as Project Officer.

The work was conducted under a Project Arrangement between the respective governments. The U.S. portion of the work was conducted under Project 2418, "Metallic Structural Materials," Task 241807 "Systems Support for Metallic Materials Applications." The Australian portion was covered under Task DEF 73/03. The report covers research conducted from January 1974 to August 1978.

The authors would like to extend recognition of Messrs. Harris, Revill, and Williams of ARL and Mr. Ruschau of the University of Dayton for technical and analytical support to this effort.

This report was submitted by the authors in August 1978.

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SECTION I

INTRODUCTION

The structure of the F-111 aircraft, which is used by both U.S. and Australia, includes components of ultra-high strength D6AC steel which are bolted together with tapered interference-fit fasteners (Taper-Lok" fasteners). Both the fasteners and the adjacent joints are coated with sealant to prevent fuel leakage. An investigation (1, 2, 3) made at the Australian Aeronautical Research Laboratories (ARL) had suggested that small amounts of liquids may have been retained in the bolt holes following the machining and assembly process. Such liquids might have a serious deleterious effect on the fatigue life of the aircraft. Further, there was concern that the exposure of sealed bolted joints to high humidity and temperature might result in a deterioration of the sealant and reduce the resistance of the structure to subsequent corrosion and fatigue.

In response to these concerns a "Project Arrangement Between the United States Department of the Air Force and the Commonwealth of Australia for a Joint Research Project on Corrosion Fatigue in D6AC Steel Joints" was drawn up, and was signed in June 1973. Briefly, it was agreed that the U.S. Air Force Materials Laboratory (AFML) would investigate the effects of humidity and temperature ("external" environment), while ARL would investigate the effects of contaminants in the bolt holes ("internal" environment). AFML was to procure the necessary materials, oversee the manufacture of specimens, and forward to ARL those specimens for the Australian part of the Project.

Initially both the AFML and the ARL were to conduct constant amplitude axial load control tests on "clean" lap joint specimens from a single fabrication lot. These control tests were to provide a base for determining the various corrosion effects on fatigue life, and to determine any differences in laboratory testing conditions. Subsequently, the respective environmental tests were to be undertaken under constant amplitude and spectrum loading conditions. Information was to be exchanged during and at the completion of all phases of the test program and a final composite report produced when all fatigue tests and analyses of data had been concluded.

SECTION II

SPECIMEN MANUFACTURE

The form of the bolted single shear lap joint specimens used by both ARL and AFML in this co-operative program is shown in Figure 1. This high load transfer configuration represents the primary type of construction used in the F-111 wing carry through. Each joint consisted of two pieces of shot-peened, cadmium-plated and epoxy-painted D6AC steel plate (UTS - 233,000 psi; 1610 MPa) connected together with four Taper-Lok interference fit fasteners. In addition a limited number of steel-aluminum 2024-T351 and steel-steel double dogbone specimens were also fabricated for the AFML portion of the investigation. The steel-aluminum specimens were included to represent areas of dissimilar metal contact in the carry through where corrosion could be of greater concern. The double dogbone specimens were included to represent areas of low load transfer across an F-111 joint.

The D6AC steel was manufactured to Specification AMS 6438A by the Republic Steel Corporation, U.S.A. and supplied as 7/16-inch (11.1-mm) thick plate. Three different heats were employed to produce ten plates each 48 inches (1.2 m) square. Chemical analyses provided by Republic Steel, together with the Specification composition ranges, are given in Appendix I. Details of the heat treatment schedule for the D6AC joint components are also given in Appendix I. Table I indicates the tensile properties and fracture toughness values provided by the manufacturer of the specimens for the heat-treated steel. Table II shows comparative tensile properties obtained by AFML from specimens machined from broken ends of several of the fatigue specimens.

Each steel-steel Taper-Lok assembly consisted of a 3/8-inch (9.5-mm) Taper-Lok fastener, an aluminum washer, and a washer-nut (Figure 1). The manufacturers designation was TLHC-2-6-9 (P528-10). The fasteners for the thicker steel-aluminum lap-joint specimens were designated

TLHC-2-6-13 (TLN-100-6). All fasteners were manufactured from H-11 (5CrMoV, Modified AISI No. 610) steel, heat-treated to an ultimate tensile strength of 260 to 290 KSI (1800 to 2000 MPa). One pair of diagonally opposite holes in each specimen was taper-reamed from one face of the joint while the other pair was reamed from the opposite face.

The sealant used on the faying surfaces of all the specimens was EC 5106* as used in all but the last few F-111's produced. That sealant was also applied to the Taper-Lok fasteners and over their heads and nuts except for the two fasteners on each specimen assembled at ARL. These fasteners were covered with Proseal 899** which was more readily available in Australia at that time and is currently approved for use on the F-111. The sealant applied during the reworking process to the reworked joints tested at the AFML was PR 1436G***. This is a chromate inhibited polysulfide sealant which at the time of the program initiation was being considered as a replacement sealant in the F-111.

The manufacturing sequence for the fatigue specimens is detailed in Appendix II. They were manufactured by Metcut Research Associates Inc., 3980 Rosslyn Drive, Cincinnati, Ohio 45209, to the requirements of the General Dynamics Specifications referred to in the Appendix. All of the AFML Specimens and seventeen of the 61 ARL specimens were supplied in the fully assembled condition, i.e. with the four Taper-Lok fasteners inserted in the holes, fully torqued, and sealed. These seventeen ARL Specimens and seven of the ARL specimens formed the "clean" control group of specimens. The remaining 44 ARL specimens were delivered to ARL in a "partially assembled" condition, i.e. with only two Taper-Lok fasteners completely fitted in the pair of holes at one end of the joint. The pair of holes at the other end were finish taper reamed but were temporarily fitted with clearance-fit fully-torqued parallel fasteners and without sealant. These partially assembled specimens were allocated

* Made by Three M Company
** Made by Essex Chemical Corporation
*** Made by Products Research Company

for contamination of the bolt holes by either distilled water or concentrated hydrochloric acid. The procedures adopted are described in detail in Section V.

One of the objectives of the AFML portion of the program was to show the capability of various proposed rework processes in improving the fatigue life of the D6AC joints. Those specimens with reinstalled Taper-Lok fasteners were reworked at Metcut using variations of the original manufacturing process as shown in Table III. The specimens which were reworked with the mandrelizing or coldwork process were reworked by the Boeing Airplane Company as described in Appendix III. The specimens with K-Lobe fasteners installed in reworked straight shank holes were reworked as described in Appendix IV by the Kaynar Manufacturing Company who produce the K-Lobe fasteners.

The configuration of the steel-aluminum lap joint specimen is the same as for the steel-steel specimen except for the 0.500" thick plate of 2024-T351 aluminum replacing one of the 0.200" steel plates. The configuration of the double dogbone specimen is shown in Figure 2. Assembly of these specimens was essentially the same as described above for the steel-steel lap joints.

SECTION III

INTERLABORATORY TEST PROCEDURES

A. Fatigue Equipment

All fatigue testing at AFML was conducted in MTS closed-loop electro-hydraulic machines of 165 and 200 KIP (734 kN and 890 kN) capacities. Constant amplitude loads were applied at frequencies of approximately 2.5 to 3.0 Hz and at a stress ratio of R=0.1. The AFML spectrum tests were conducted at frequencies from 0.05 to 3.0 Hz, depending on the number of cycles at a given stress level within the loading block. The AFML test setup for both constant amplitude and spectrum loading is shown in Figures 3 and 4.

At ARL two machines were used. The constant amplitude tests were made in a 220 KIP (979kN) Amsler hydraulic pulsator, also at the 0.1 stress ratio. The spectrum tests were conducted in a 165 KIP (734kN) MTS closed-loop electro-hydraulic machine. All constant amplitude and spectrum loads at ARL were applied at a frequency of 2.5 Hz. The ARL fatigue test set-up is shown in Figure 5.

Both laboratories used sine wave loading and both employed a programmable function generator (EMR profiler) using punched tape to control the spectrum load sequence. During the spectrum tests both laboratories continuously monitored the load magnitudes and sequences. All machines employed hydraulic grips; at ARL it was necessary to use hardened-toothed inserts between the jaws and the specimen ends to prevent slippage.

B. Flexural Restraint

Any single lap shear specimen has an inherent tendency to warp or bend during loading, thus introducing high axial loads in the fasteners. Initially, an attempt was made to adapt fixtures recommended in "MIL-STD-1312, Fastener Test Methods." This standard contains recommendations for both a "flexural pivot restraining device" and a "sandwich" fixture. Both of these devices were tried and proven unsatisfactory for use with the material and joint design necessary to simulate the F-111 wingbox conditions. Even with such restraining devices the joint rotated to the point where the fasteners failed in an axial fatigue mode at the head or nut.

The final fixture design combined the pivot restraint and the sandwich configuration as shown in Figure 6. During development the effect of bending was monitored with strain gages located on both sides of the specimen just above the lower hydraulic grip. In addition each of the four arms of the flexural restraining device had a strain gage attached to it. The strain gages were used to insure that the device did not induce any warpage into the test specimen at a zero loading condition, and to measure the side loads necessary to prevent bending during the loading cycle. Very little bending was noted, and the axial strain was the value predicted under load.

C. Laboratory Environment

At both AFML and ARL the temperature and relative humidity were continuously monitored during testing. At ARL they were found to vary between 68°F (20°C) and 77°F (25°C) and 35% to 45% RH respectively. At AFML the temperature varied between 68°F (20°C) and 80°F (27°C), and the humidity between 40% and 70%.

D. Control Tests and Results

Control tests were made by both laboratories on clean steel-steel lap joint specimens, using constant amplitude loading and the laboratory air environment. These tests were made to provide a base for determining the various corrosion effects on fatigue life and to determine any differences in laboratory testing conditions.

The majority of the control tests were to be at two stress levels selected to give failure in approximately 5000 or 500,000 cycles. These lives were chosen in order to cover both low and high-cycle fatigue regimes yet without facing the likelihood of runouts or other experimental problems.

The results of exploratory S/N tests made at AFML are shown in Table IV. A primary maximum stress level of 80 ksi (552 MPa) (on the net section of one plate), designated stress level "A", was chosen for inter-laboratory comparison, giving a life range from 0.07 X 10^6 to 0.22 X 10^6 cycles, only slightly below the goal of 0.5 X 10^6 average. The S/N data indicated that a stress level between 115 ksi (793 MPa) and 162 ksi (1117 MPa) would be required to produce failure near the desired goal of 0.5 X 10^4 cycles. Since such a stress level would be well above the peak level encountered in the F-111 spectra, a stress level of 100 ksi (689 MPa) was selected as a secondary stress level for comparison, designated stress level "B". This level represented the maximum condition encountered in the F-111 spectra and was still representative of a distinctly lower cyclic life condition than that encountered at 80 ksi (552 MPa).

Table IV also gives the lives of all steel-steel lap joint control tests made in the two laboratories at 80 ksi (552 MPa) and 100 ksi (689 MPa). The various types of failure, based on fatigue crack paths, are noted in this table and illustrated in Figure 7.

Standard F and t tests (indicating equivalance or otherwise in scatter and mean life respectively) were made on these fatigue lives to compare the USA and the Australian test results. These tests were based upon log life and a 0.05 level of significance.

Arguments could be developed as to whether comparisons should be made for Type A failures only, or whether all fatigue lives in the various groups should be considered. Both comparisons were made and the results are shown in Table V. Additionally, comparisons using the AFML 80 ksi (552 MPa) clean control series were made after deleting the life of 74,890 cycles - the specimen giving this life had been subjected to an inadvertent overload during test.

It is clear from Table V that there is no significant difference between the variances or the means of log lives obtained from the AFML and ARL tests at either 80 ksi (552 MPa) or 100 ksi (689 MPa). This conclusion applies irrespective of whether all results are used, whether Type A failures only are considered, or whether the overload AFML result at 80 ksi (552 MPa) is deleted.

In addition to the tests on joints, a limited number of constant amplitude fatigue tests were also run at AFML on specimens machined from the broken ends of several of the lap joint specimens. Both open hole (K_t=3.0) and smooth specimen data were obtained and the results are shown in Table VI and plotted in Figure 8. These indicate that the fatigue properties of the high load transfer lap-shear joints using fatigue improvement fasteners were approximately the same as non-joint open hole data on the same material.

SECTION IV

EFFECTS OF EXTERNAL ENVIRONMENT

A. Experimental Procedure

The primary objective of the AFML portion of the project was to evaluate the effects of a simulated service environment on the fatigue properties of D6AC steel Taper-Lok joints. To achieve this goal a test matrix was developed as shown in Table III. Initially, an S/N diagram was established for the lap shear specimens. Data from these S/N tests were then used to establish two stress levels for the interlaboratory control tests as have been described in Section III.D. The Group I series of tests were conducted at three increasing severities of exposure. These tests were to define a consistent fatigue life for a joint of original F-111 manufacture after a simulated exposure to the elements. The Group II and Group III tests were then conducted to determine the ability of various rework procedures to increase the life of these joints under this simulated environment. These groupings now are discussed in more detail.

1. Group 1 Tests

The Group I series of tests were conducted to determine the effect of environmental exposure on the fatigue life of the wing carry through joints simulating early F-111 manufacturing practice. The newly fabricated specimens were first exposed to a room temperature distilled water spray for seven days to allow moisture to work its way into any typical unsealed cracks or crevices which might be present. The specimens were then precycled for approximately 25% of their expected life based on the unexposed control data. For the steel-steel lap joint constant amplitude and spectrum specimens this was taken as 50,000 cycles at 80 ksi (552 MPa) maximum load (R=0.1). For the steel-aluminum specimens this was 50,000 cycles at 25 ksi (172 MPa) and for the steel-steel double dogbone specimens the precycling was 20,000 cycles at 115 ksi (792 MPa). The purpose of this precycling was to open up any poorly installed and/or sealed areas to subsequent exposure. Group I specimens were then subdivided into three subgroups with different severities of a final exposure cycle. These cycles ran from 7 days exposure at room temperature in a water spray to 140 days in the water spray of which 93 days were at room temperature and the remaining 47 days at 160°F (71°C). This temperature was selected as being realistic of the worst possible condition for an aircraft in a tropic environment. The 140 day exposure period was based on data from a previous evaluation of D6AC steel by the F-111 contractor. These data indicated that 120 days were necessary to initiate stress corrosion cracking of the unprotected metal under stress.[4] Following these various secondary exposure periods the Group I specimens were then cycled to failure.

2. Group II Tests

The Group II tests were selected to represent a field repair condition where the fastener might be removed and then reinstalled after stripping and cleaning. Sealing was done with the same sealant (EC-5106) as used in the original installation of most F-111 aircraft. The tests in Groups II and III were further sub-divided into those in which specimens were: (a) reworked prior to the secondary exposure and (b) the reverse of (a), e.g., initial exposure, partial fatigue test, secondary exposure, rework, and test to failure. These sub-divisions are referred to as "Re-Ex" and "Ex-Re" throughout the test and illustrations.

3. Group III Tests

The Group III tests were selected to represent more advanced field or depot rework. Group IIIa was similar to Group II except that a new improved sealant, PR 1436G, was used during reinstallation of the old fastener. Group IIIb was to represent currently recommended rework procedures involving a new Taper-Lok fastener, the improved sealant and the use of an 18-flute hand reamer to refinish the fastener hole which had been previously finished with the 6-flute reamer as used in early

F-111 production. Groups IIIc and IIId were to look at other possible rework procedures using different types of fatigue improvement concepts other than the original Taper-Lok fastener.

Group IIIc specimen holes were resized to a straight shank condition and then coldworked or mandrelized by inserting a thin sleeve in the hole, drawing an oversize mandrel through the hole, and then removing the sleeve and finish reaming the hole. A standard straight shank aircraft fastener was then installed in the hole. Additional details of this process are given in Appendix III.

Group IIId specimens were also resized to a straight shank hole condition and then reassembled using a straight shank interference fit longitudinally fluted K-lobe fastener. This concept was developed as a more economical and easily applied approach to the fabrication of fatigue improved joints, however, it had not previously been used with high-strength-steel joints. Details of this process are given in Appendix IV.

4. Spectrum Tests

The limited spectrum testing in the AFML portion of the program was included to determine whether or not the effects of the exposure and Group IIIb rework would be similar under spectrum loading as under constant amplitude loading. The spectrum chosen was similar to the basic 58 layer 5G MAC spectrum established for the F-111 development program However, it was necessary to increase the cyclic frequency and to uniformly increase the loads in this spectrum in order to obtain failure in the joints within a reasonable period of time. Actual loads are discussed in Section IV.B.7 and Appendix V.

B. Results and Discussion

1. Group I Tests

The Group Ia, Ib, and Ic exposure tests resulted in a slight decrease in mean fatigue life with exposure time; however, this decrease is not statistically significant. The fatigue results are shown in Table VII and Figure 9. (The fatigue lives in Table VII and Figure 9 are those obtained after the secondary exposure cycle.) Statistical comparisons of the various groups are shown in Table VIII and are based upon log life and a 0.05 level of significance. The relatively little difference between the Group Ib and Ic average results was particularly interesting in view of the fact that the EC-5106 sealant had severely reverted during the 160°F (71°C) exposure portion of the Group Ic exposure cycle. Although the sealant had reverted to the consistency of corn syrup, it still apparently formed a tight enough film along with the paint, cadmium plating and shot peening to protect the specimen from corrosion under the test conditions. The epoxy paint on these Group Ic specimens was blistered, but no corrosion or rust was observed except at the gripped ends where the testing machine grip serrations had apparently cut through the protective Cd plate. As the RT/160°F (71°C) exposure cycle represented the most severe condition to which the aircraft could be expected to be exposed, this cycle was selected as the secondary exposure cycle for the remaining constant amplitude and spectrum tests.

2. Group II Tests

Tables VII and VIII show that little is to be gained by cleaning and reinstalling the old fastener using the same EC-5106 sealant. In fact there is the possibility that such rework may further degrade the joints resistance to further exposure, doing more damage than good.

3. Group III Tests

Group III data shown in Table VII quantitatively confirmed the F-111 recovery constant amplitude data which showed that a substantial improvement in fatigue life can be obtained using the current "improved" GD rework procedures. These procedures involve both the use of the improved PR-1436G sealant and the 18-flute reamer. The results shown in Table IX indicate that the use of the improved sealant, as such, had no influence on fatigue life. Comparisons within Groups IIIb and IIIc indicate that the original and improved sealants equally resist environmental penetration which would otherwise degrade fatigue life. The comparison between Group II (Ex-Re) and Group IIIa (Ex-Re) indicates that the change in sealant after exposure and just before final fatigue testing also has no influence on subsequent life. It is thus concluded that the substantial increase in mean life of Group IIIb specimens arises from the rework procedures.

4. Failure Modes in Steel-Steel Lap Joint Specimens

The specimens were examined to determine the failure initiation site(s) and the mode of failure. Most of the cracks appeared to initiate at the corner of the hole and the faying surface or in the shank area of the hole as identified by areas #2 and #3 in Figure 10. A typical failure surface for each group of specimens is shown in Figures 11 through 20. As can be seen, most of the specimens exhibited multisite initiation and propagation from both of the holes on the fracture surface. In general the cracks propagated across the joint toward a similar crack from an adjacent hole resulting in the failure configuration shown in Figure 21 labeled Type A (see Figure 7). Only one AFML specimen failed in a different mode and in this case (specimen 129/133) the failure occurred across one hole only as shown in Figure 22 (labeled Type B). (The failure modes in the ARL constant amplitude program were predominantly Type A but other modes occurred which, in some cases, may have been influenced by the presence of corrodents.) Magnetic rubber and ultrasonic examination of the pair of unfailed holes in the AFML specimens indicated that cracks were also propagating from these holes at the time of failure.

5. Additional Rework Procedures with Steel-Steel Lap Joint Specimens

The mandrelizing process and the K-lobe fastener both rely on a working of the surface of the hole to achieve fatigue improvement. Both systems have shown considerable promise for joining aluminum and other softer materials. The results with the relatively hard heat-treated steel were, however, disappointing. At least for the mandrelized specimens it appears as though the heat-treated steel is already in an optimum fatigue condition and any additonal work of the metal by mandrelizing is detrimental. Results from the more limited K-lobe testing exhibited considerable scatter. It appears as though additional development would have to be done to consistently realize the full potential of this system for high-strength steel.

6. Low Load Transfer Joints

The results of the steel-steel low load transfer or double dog-bone tests are shown in Table X and analysed in Table XI. Due to the smaller number of specimens per group the confidence in the comparisons is smaller, but the results tend to confirm the previous observation that mandrelizing does not improve the fatigue performance of these high-strength-steel joints.

7. Steel-Aluminum Lap Shear Joints

The steel-aluminum specimen was designed for failure in the aluminum member. The results as shown in Tables XII and XIII generally followed the steel-steel results in that cleaning and reinstalling the old fastener (Group II) gives no improvement in fatigue life, whereas using the 18-flute-reamer rework (Group IIIb) significantly increases fatigue life. An exception was that mandrelizing the holes in the aluminum plates significantly increased fatigue life. This confirms similar literature data on aluminum installations which shows that equal fatigue improvement can be obtained by mandrelizing as by using property installed Taper-Lok fasteners.

8. NDI

A number of steel-steel lap joint specimens were examined with magnetic rubber and other NDI inspection techniques prior to re-working. These specimens had been precycled for 50,000 cycles at 80 ksi (552 MPa) or approximately 25% of expected life. Ultrasonic techniques were used to detect cracks with the fastener in place. No cracks were found in any of the fastener holes. Magnetic rubber techniques were used after fastener removal. No cracks were found in any of these holes either. The accuracy of both NDI techniques had previously been verified by examination of the unfailed pair of fastener/holes from the failed control specimens. In these specimens the cracks were easily identified. A magnetic rubber replica from one of these specimens is shown in Figure 23. Note the crack initiating at the corner of the faying surface, branching off and propagating along the hole shank, and extending along the specimen surface under the fastener head.

These results indicated that no crack propagation was initiated during the first 25% of the specimen life. A number of specimens were then ultrasonically examined with the fastener in place every 50,000 cycles up to 500,000 cycles and then every 10,000 cycles to failure. The fatigue machine was shut off at the time of readings but the specimen remained in the machine under no load, simulating a NDI field inspection of the F-111 wing box.

Three specimens yielded useful results as shown below:

Group	Spec. Nr.	First Crack Found At:	Total life:	Discovered at % of Life:
IIIa(Ex-Re)	179/55	714830	721370	99%
IIIb(Ex-Re)	184/300	594700	601650	99%
II (Ex-Re)	42/48	337000*	358000	> 94%

* Specimen was observed at this life and no crack was found.

In obtaining the above data the NDI operator estimated a crack depth of .075" (1.90 mm) to .100 (2.54 mm) at the time of detection in both of the two specimens with cracks. The obvious conclusion was that currently available ultrasonic techniques could not identify critical cracks under the fastener head within a useful percentage of life for this particular material/joint/stress level combination.

9. Spectrum Tests

The AFML Spectrum Tests were conducted to determine if the relative effects of exposure on the fatigue life of the joints would be the same under spectrum loading as under constant amplitude loading. The basic 5G MAC (Mission Analysis Composite) spectrum shown in Table XIV and used during the F-111 recovery program was selected. However, this spectrum was developed for precracked specimens without the benefit of fatigue retarding fasteners. Consequently, it was necessary to uniformly increase the spectrum loads to obtain failures within a reasonable time period. Initially, the loads were increased to 120% of the 5G MAC spectrum and the loading frequency was also increased. An initial test ran 85 spectrum blocks without failure. As this simulated approximately

17,000 hours of aircraft flight which exceeded the 16,000 four life-time cutoff for the aircraft, the loads were increased to 130% and specimen failure occurred after 45 additional blocks. Stresses were then raised to 135% and then to 145% of the basic 5G MAC spectrum. The end result was that even at 145% of the spectrum all the specimens exceeded the 4 aircraft lifetime value. In fact, the Group IIIb rework specimen was left under test for a total of 257 blocks or over 128 aircraft lifetimes. While this was very encouraging from the standpoint of the F-111 reliability, it did require considerable testing time even at an average cyclic frequency of 2.0 Hz. The results of these tests are shown in Table XV and plotted (without the retest values) in Figure 24. These results are consistent with the constant amplitude results which also showed the longest life for the Group IIIb specimens.

Two spectrum tests were also conducted using the steel-aluminum lap-shear specimen which was designed for failure in the aluminum member. The initial spectrum level investigated was 90 percent of the 5G MAC spectrum based on the steel member. This spectrum did not prove to be severe enough to cause failure. Consequently, both tests were terminated after each specimen had undergone 172 blocks. The spectrum stresses were then raised on the same specimens to 105 percent of the 5G MAC spectrum, which produced failure in less than 11 blocks for the specimen with the original fastener system and in 96 blocks for the specimen that underwent a fastener system rework. This is a substantial increase in life obtained by reworking the original fastener holes and installing new Taper-Lok fasteners and parallels the results of the constant amplitude tests.

SECTION V

EFFECTS OF CONTAMINANTS IN THE BOLT HOLES

A. Contamination of Partially-Assembled Specimens

In a previous ARL investigation on Taper-Lok bolted configurations containing D6AC steel components (1, 2, 3), water and hydrochloric acid were considered the most significant (as regards D6AC steel corrosion) of substances either positively identified or deduced from substances positively identified in the bolt holes. Water was positively identified and its origin traced to the initial reaming fluid (oil plus water). Hydrochloric acid, on the other hand, was deduced to have been present after phosphine gas (PH_3) was found in the Taper-Lok bolt holes. It was thought that water from the initial reaming fluid reacted with remnants of the trichloroethane, used in the final-stage reaming fluid, to produce hydrogen chloride gas. This gas then dissolved in water to form hydrochloric acid which, in turn, reacted with the phosphides present in the D6AC steel plates and the steel fasteners to form phosphine. It was for these reasons that water (deionized and triply distilled) and concentrated (10 N) hydrochloric acid were chosen as contaminants in the present investigation.

One pair of holes only in each partially-assembled specimen was to be contaminated, i.e., the holes temporarily fitted with clearance parallel shank fasteners. A preliminary examination showed the necessity of removing from these holes excess sealant which remained from the original assembly of the joint. This was done by scraping with a wooden scraper. A small circumferential groove about 0.004-inch (0.10-mm) deep was then formed in the sealant layer (which was approximately 0.004-inch (0.010-mm) thick) between the faying surfaces to retain the contaminant in the bolt holes. For this process, a fine stainless steel scalpel cut from a hypodermic needle was used. This did not scratch or otherwise damage the D6AC steel.

Two microlitres of either water or hydrochloric acid were inserted in each of the two grooves in every "contaminated" specimen. With the specimen on its long edge, a one-microlitre drop of contaminant was placed in each groove and smeared around it, using the pipette tip; the specimen was then placed on its other long edge and the process repeated. Microlitre pipettes were used for adding the measured drops, one for each contaminant. A fresh pipette tip was used for each specimen.

A new Taper-Lok fastener was then inserted in each hole, Proseal 899B sealant applied around the thread, the nut screwed on and partially tightened, further sealant applied between the fastener head and the washer under the head, and the nut then fully torqued up to the standard value of 570 in.-lb (64 .4 Nm) (5). Finally, further sealant was applied over the head and the nut to completely cover both ends of the fastener. Specimens so contaminated were not fatigue tested until the 140-day waiting period had elapsed.

Prior to contamination of the specimens, the adequacy of procedures was established by using a water-soluble fluorescent dye instead of the contaminants. Using the procedure described above, the joint was formed, then disassembled and exposed to ultraviolet light. The spread of the dye was clearly visible; it was found to be, at least, along part of the bore adjoining the faying surfaces, and some distance around the circumference from a centreline joining the pair of contaminated holes. It was assumed that the contaminants would spread likewise.

B. CONSTANT AMPLITUDE TESTS

1. Test Conditions and Results

a. Testing sequence and fatigue lives

Constant amplitude tests at ARL were carried out at maximum stress levels of 80 and 100 ksi (552 and 689 MPa). Seven "clean" specimens, five specimens containing distilled water as a contaminant in a pair of bolt holes, and five specimens containing hydrochloric acid as the contaminant, were tested to fracture at both stress levels.

Five clean control specimens were first tested at both stress levels, the testing sequence being quasi-randomized between the two levels. Three 80 ksi (552 MPa) and two 100 ksi (689 MPa) water-contaminated specimens were tested next, then a sixth clean specimen at each of the two stress levels. Finally, all remaining contaminated specimens were fatigued, followed by a seventh clean specimen at each stress level. The sixth and seventh clean specimen at each stress level were included in the general sequence of tests to ensure that the behaviour of the testing machine had not changed significantly since the initial series of control tests.

The fatigue lives to fracture obtained at ARL on the contaminated specimens are given in Table XVI. For comparison with the fatigue lives of clean specimens (obtained at both ARL and AFML), the appropriate clean-specimen life data from Table IV are repeated in Table XVI. The results presented in Table XVI follow the order of testing. In addition, to allow visual comparison, Figure 25 shows the fatigue lives of all clean and contaminated specimens tested at ARL under constant amplitude loading.

b. Fatigue crack paths and types of failure

The various types of failure, based on fatigue crack paths and noted in Table XVI are indicated in Figure 7. Figure 26 shows the predominant failure paths through the bolt holes in the plates and also illustrates macroscopic features of the fractures.

Of the total of 34 specimens tested under constant amplitude at ARL, 27 failed in one of the D6AC steel plate components by transverse cracking through one pair of bolt holes. This is referred to as Type A failure.

Five specimens failed in one of the steel plate components, but through only one bolt hole. The crack took a diagonal path after a relatively short transverse growth from one bolt hole. The fastener in the other hole usually failed. This is referred to as Type B failure.

In one specimen, cracking was not observed in either of the steel plate components, but all four H-11 Taper-Lok fasteners failed. This is designated Type C failure.

The remaining specimen (clean, 100 ksi (689 MPa)) exhibited two cracks in the D6AC steel plate, each originating at one of the two bolt holes of a pair. Since both holes of a pair were cracked, and the fatigue life came within the scatter band of Type A failures of the test group in which it occurred, this failure may also be considered to be Type A. Hence, 28 (82%) specimens showed Type A failure.

c. Type A failures in contaminated specimens

Each contaminated specimen possessed one transverse pair of contaminated holes and one transverse pair of clean (uncontaminated) holes. Type A failures in hydrochloric acid-contaminated specimens tested at both stress levels occurred through the clean pair of holes. Similarly, all Type A failures in water-contaminated specimens tested at 80 ksi (552 MPa) occurred through the clean pair of holes. With water-contaminated specimens tested at 100 ksi (689 MPa) however, four of the five Type A failures occurred through the contaminated pair of holes, and the other Type A failure (which occurred at a much lower life than the other four - 40,900 cycles) took place through the clean pair of holes.

d. Test for phosphine

After fatigue testing, all of the specimens were disassembled, and, during the removal of the fasteners holding the unfractured parts of the D6AC steel plates, the presence of phosphine was tested for by manually sniffing, immediately after a fastener was freed. Phosphine was detected in one hole only, in one of the two "clean" bolt holes (USA assembled) in a hydrochloric acid-contaminated specimen tested at 80 ksi (552 MPa) giving a life of 36,500 cycles.

2. Analysis of Results

a. Effects of contamination on fatigue life

The fatigue lives of contaminated specimens were compared with the lives of clean specimens tested at ARL and also with the combined ARL/AFML clean specimen lives. Table XVII indicates the conditions under which the contaminants have affected mean fatigue life, the assessments being based upon log life and a 0.05 level of significance. When the F test indicated a significant difference between variances, a modified t test (6) was used for comparing means.

Although it was expected that both contaminants would produce a marked decrease in the fatigue life of D6AC steel in a bolted joint configuration, this was not found experimentally. On the contrary, considering Tables XVI and XVII, it is clear that specimens contaminated with distilled water exhibit fatigue lives at both 80 and 100 ksi (552 and 689 MPa) which are significantly greater than those for the clean specimens.

The apparent increase in life with hydrochloric acid contamination (Table XVI) is, however, not significant according to the statistical tests adopted (Table XVII). A generalisation of the fatigue results obtained from clean and hydrochloric acid-contaminated specimens, is, therefore, that contamination by 10 N hydrochloric acid does not result in inferior fatigue resistance of the bolted joint configuration or of the D6AC steel components.

The fatigue lives of clean control specimens tested during and at the conclusion of tests on contaminated specimens were not significantly different from those of similar specimens tested prior to the contaminated specimens. (This statement is supported by statistical examination of the results, testing for any difference between the sixth and seventh result, in turn, and the first set of results. Various combinations were examined in the testing, such as the inclusion of Type A failures only, or of all failures, and by pooling or excluding the individual result with the first set of results. The generalisation above holds in all cases except at 100 ksi (689 MPa) where, comparing Type A failures and by not pooling results, the sixth and seventh fatigue lives are significantly different from the first set of four

Type A lives). It thus appears that there was no change in the testing facility to which the effects of contamination could be attributed.

b. Failures in contaminated specimens

At first sight, the fatigue lives and failure locations in most of the contaminated specimens present a puzzle. Consider Type A failures only, that is, fatigue failure in a D6AC steel component through one pair of bolt holes. Since contaminated specimens contained one pair of clean and one pair of contaminated holes, fatigue lives greater than those obtained with clean specimens were not expected. And yet, (by way of example) all Type A failure in water-contaminated specimens tested at 80 ksi (552 MPa) occurred through the clean pair of holes and at a life very much greater (Table XVII) than for clean specimens tested at the same stress.

The resolution of this problem is not entirely clear, but at this point, it may be stated that more than one variable has been introduced in the testing of clean and contaminated specimens. Clean specimens were fully assembled in the USA by Metcut; whereas contaminated specimens were partially assembled by that company, and the final assembly done at ARL. Some of the possible differences arising specifically from the assembly operations are examined in the general discussion (Section VD).

C. SPECTRUM LOAD TESTS

1. Test Conditions

a. Test spectrum

The 58- layer block-loading sequence employed in the ARL spectrum loading tests is detailed in Table XVIII. It is based on the 5G MAC spectrum used at AFML, which is given in Table XIV, with the following modifications:

(i) stresses: the minimum stresses are 45% and the maximum stresses 165%, of the corresponding values in the 5G MAC spectrum; and

(ii) frequency: the frequency of cycling in every layer of the ARL spectrum is 2.5 Hz.

The reasons for these modifications are given in Appendix V.

b. Specimens and sequence of testing

In an attempt to compare the performance of the Amsler pulsator used for the constant amplitude tests and the MTS machine planned to be used for the spectrum load tests, two USA-fully assembled clean specimens were tested under constant amplitude in the MTS machine. The frequency, waveform and stress levels corresponded to the equivalent conditions in the Amsler tests.

At this stage of the project no further USA-assembled clean specimens were available. Seven partially-assembled specimens were then fitted with new Taper-Lok fasteners, torqued as specified and sealed with Proseal 899B, to constitute a group of Australian-assembled clean specimens. A further fourteen partially assembled specimens were contaminated (seven with water and seven with 10 N hydrochloric acid) and reassembled as described previously. (These specimens were contaminated about 15 months after those tested initially under constant amplitude.) The minimum waiting period of 140 days was again observed before testing.

Before proceeding with the program of spectrum loading, one Australian-assembled clean specimen was tested under constant amplitude in the MTS machine, using the same frequency, waveform and R-ratio as for all previous constant amplitude tests. The maximum stress was 100 ksi (689 MPa).

Spectrum load tests were then made on five Australian-assembled clean specimens, five water-contaminated and six hydrochloric acid-contaminated specimens. The testing order followed roughly the pattern: clean, hydrochloric acid, water.

Finally, the remaining specimens, one clean, one hydrochloric acid-contaminated, and two water-contaminated were tested under constant amplitude in the Amsler machine. These tests were made in order to compare the second batch of prepared specimens with the batch prepared originally.

2. Results

a. Fatigue lives

Table XIX gives the lives obtained in the spectrum load tests, both in terms of spectrum blocks and cycles. The means and standard deviations of log life are also included for the three groups. Within each group the results are presented in the order of testing.

The cycles to failure of the additional constant amplitude tests are given in Table XXI, together with the range of cycles to failure obtained in the previous set of ARL constant amplitude tests (Table XVI). Table XXI also notes the failure locations in these additional tests.

b. Fatigue crack paths and types of failure

The locations of all spectrum load failures are listed in Table XX and examples of the various fatigue fractures are shown in Figure 27. All Australian-assembled clean and water-contaminated specimens gave Type A failures in the plates. In all cases but one, failure occurred through the USA-assembled bolt holes; in the remaining case (specimen 271/272 - water contaminated) failure occurred through the Australian-assembled (contaminated) bolt holes. In addition to the plate failures, about one-third of all the fasteners in the clean and water-contaminated specimens fractured predominantly by fatigue. Both Australian and USA-assembled fasteners failed in this fashion - Figure 27 (b) shows an example.

All plate fractures exhibited spectrum fatigue markings as illustrated in Figure 27 (e). In most cases fretting damage was evident in the initial area of fracture. Spectrum markings were frequently visible in this area which was followed by an undamaged area of clearly-visible spectrum markings. On some fractures it is evident that a crack has existed for a substantial part of the spectrum life. On the fracture shown in Figure 27 (f), about 25 spectrum blocks can, unambiguously, be identified by low-power microscopy; the total number of spectrum blocks to failure for this specimen is 43.

All hydrochloric acid-contaminated specimens gave Type C (fastener) failures. In every case fatigue cracking occurred in fasteners located in the contaminated holes; the other pair of fasteners (USA-assembled) sheared as the joint finally separated. Figure 27 (d) shows a typical contaminated-fastener fracture, the staining around the periphery of the fracture is corrosion due to the contaminant.

c. Failing stresses

All clean and water-contaminated specimens except one failed during the stress cycle with the highest or second-highest magnitude (both S_{max} and S_a) - six failed on the first cycle of layer 15 and three on the first cycle of layer 11.

The one exception (specimen 271/272) failed during the second cycle of layer 12. These were all Type A plate failures, in some cases with fastener failures.

The hydrochloric acid-contaminated specimens (fastener failures only) failed in one of three layers, three specimens failed at the first cycle in layer 15 or layer 11 (the highest and second-highest magnitude stress cycles respectively), and three specimens failed during layer 8.

3. Analysis

a. Influence of contaminants on fatigue life

As shown in Table XIX, the log mean lives of clean and water-contaminated specimens were 32.18 and 31.17 blocks, and the standard deviations of log life were 0.206 and 0.205 respectively. It is clear that contamination with water has not affected either the mean life or the scatter. This result is in contrast with the initial expectation that the contaminants (including water) would reduce fatigue life, and with the apparent beneficial effect of water under constant amplitude loading.

Contamination with hydrochloric acid has resulted in a drastic reduction in fatigue life of the joint; all specimens failed at less than one-third of a spectrum block (Table XIX). Again the contaminant (hydrochloric acid) appears to have a different effect on fatigue life under spectrum loading than under constant amplitude loading.

b. Types of failure

The puzzle presented by the failure locations and lives under constant amplitude loading (see Section VB) does not occur under spectrum loading. Under spectrum loading both the clean and water-contaminated specimens failed in the same location (through a pair of USA-assembled bolt holes, except in one case) and at the same mean fatigue life (Tables XIX and XX).

The fatigue failures in the hydrochloric acid-contaminated specimens occurred only in the fasteners in the contaminated holes. As the fasteners are made from H-11 alloy steel, the effect of hydrochloric acid contamination on D6AC steel (the plate material) under spectrum loading remains unknown.

c. Implications of additional constant amplitude results

The additional constant amplitude test results (Table XXI), obtained just before and just after the spectrum load tests, may be compared with the appropriate ranges of cycles to failure obtained in the original series (Table XVI). In some cases the additional result falls within the previous range, in others it is outside the previous range.

To establish any differences, t-tests were made on these results and the findings are shown in Table XXII. The conclusions from this Table are: there is no significant difference between -

(i) the performance of the Amsler and MTS machines,
(ii) specimens finally-assembled in the USA and Australia,
(iii) the first and second batches of contaminated specimens.

Within the limitations of the small samples available for testing, it is clear that any apparent differences in the effects the contaminants have on fatigue life between constant amplitude and spectrum loading cannot be attributed to the different test machines or the different batches contaminated.

A further implication of the additional test results is that the single result of fastener failures with very low life in the original constant amplitude series (a hydrochloric acid-contaminated specimen - Table XVI), is not to be rejected as an **outlyer.** The only hydrochloric acid-contaminated specimen tested under constant amplitude subsequent to the original group also failed through the fasteners in the contaminated holes and at a very low life.

D. DISCUSSION

1. General Influence of Contaminants

The general influence of the contaminants on the fatigue life of the joints was different for constant amplitude and spectrum loading. One possible 'explanation' is the intersecting S/N effect as shown schematically in Figure 28, where the influence of the contaminants on fatigue life is stress level dependent. The largest S_{max} in the original 5G MAC spectrum was 106.6 ksi (735 MPa), not greatly different from the upper stress level under constant amplitude. But in order to achieve reasonable testing times, the largest S_{max} in the spectrum applied was 175.9 ksi (1213 MPa), and 15 of the 58 layers had S_{max} values exceeding 100 ksi (689 MPa) - in the spectrum of 17,241 cycles there were 618 cycles whose S_{max} exceeded 100 ksi (689 MPa). When examining one variable in fatigue the intersecting S/N effect is not an unusual phenomenon. It is also not unusual to find that the influence of a particular variable on fatigue life depends on the loading sequence, and effects shown up in constant amplitude loading are not always evident to the same degree under program or random loading.

A further possibility, examined but rejected, is that the relative influence of the contaminants depended upon the contamination period. Table XXIII lists the contamination periods for all specimens. The average contamination period for the original series constant amplitude specimens was 152 days and, for the spectrum load specimens, 180 days. However, it is quite evident that within each grouping shown in Table XXIII there is no obvious correlation between fatigue life and the contamination period.

Although it was indicated in Section VC that the different effects which the contaminants have on fatigue life cannot be attributed to the different test machines employed for the two types of loading, in the two cases where machines may be compared (see Tables XXI and XXII), the single MTS result was higher than the scatter band obtained in the Amsler machine. Even if further tests established a significant machine difference, this also is not believed a sufficient explanation of the different effects of the contaminants under the two types of loading. The reasoning here is that any machine differences will affect the absolute values of the fatigue lives in any one group, but not the relative differences between the groups.

2. Problem of Constant Amplitude Lives and Failure Locations in Contaminated Specimens

In addition to the result that the general influence of the contaminants depends on the loading sequence, there is the unanticipated result that, under constant amplitude, contaminated specimens give a longer fatigue life than clean specimens (significant for water contamination, but not demonstrable for hydrochloric acid contamination) and yet, in most cases, they fail through the clean pair of holes. It is as though the contaminants have 'strengthened' the material around both the contaminated and clean pairs of holes. Although future research may demonstrate 'contamination strengthening' as a reality, the idea can be supported in the present program only if the USA-fully-assembled specimens tested at ARL constitute a valid control group. The discussion above relating to the general effects of the contaminants was also developed on this assumption, a point which is now examined.

Apart from the contaminants, the differences between the USA-assembled clean control specimens and the ARL-finally-assembled contaminated specimens tested under constant amplitude are as follows.

(i) The clean specimens were fully assembled with four Taper-Lok fasteners in the USA and remained so until fatigue testing was completed. The contaminated specimens were originally assembled in the USA with only two Taper-Lok fasteners finally assembled, and parallel shank fasteners temporarily fitted in the remaining pair of holes. The latter were replaced by new Taper-Lok fasteners after contamination at ARL.

(ii) Torquing of the Taper-Lok fasteners in the contaminated holes was carried out in Australia but for all the fasteners in clean holes it was carried out in the USA.

(iii) The sealant used for the Australian-assembled Taper-Lok fasteners in the contaminated holes differed from that employed in the USA for the fasteners in the clean holes.

In essence, the question is whether, of itself, partial disassembly of the joint followed by re-torquing of the two new fasteners and then coating them with a different sealant to that originally used, could affect fatigue performance. Since the Taper-Lok fasteners for re-fitting were supplied by the USA and were identical to those used by the USA in the clean holes, two differences apparently remain, namely, re-torquing and re-sealing with a different sealant.

The application of a different sealant to the fasteners in contaminated holes does not invalidate the USA-fully-assembled clean specimens as a control group, however, simply because contaminated specimens failed through the USA-assembled bolt holes and not through the contaminated holes. Thus, re-torquing needs examination.

There are, however, other possible differences not immediately apparent, such as bell-mouthing of some contaminated holes, fastener lubricants, and the clamping/fastener insertion procedure used in the USA but not in Australia. These are now discussed before examining re-torquing.

Although the parallel-shank fasteners (temporarily installed in the USA in those holes to be contaminated in Australia) were to be a clearance fit, in some holes the fit was such as to cause bell-mouthing of the tapered holes at the smaller end. Of those specimens which were bell-mouthed the typical geometry was a change in angle of about 5° over a distance of about 0.050 inch (1.3 mm) which is 25% of the length of the hole. This geometry was not altered in the contamination/reassembly procedure.

Bell-mouthing of contaminated holes, of itself, does not invalidate the USA-fully-assembled specimens as a control group for the same reason that the different sealants do not, namely, because the failures did not occur through the contaminated holes. But the force involved in the bell-mouthing could help to "spring" the joint and therefore alter the fastener tension in the USA-assembled Taper-Loks. This possibility is simply speculation and would require further experimentation to determine its validity.

The question of fastener lubrication should be mentioned since lubricity markedly affects fastener tension for a given torque. The Taper-Lok fasteners, made by Omark Industries, were to be dry-film lubricated with 'Lubeco no. 2123', a baked coating consisting of 3% graphite in an organic type lubricant. The shanks of unused Taper-Lok fasteners supplied to ARL for use with the contaminated specimens were observed to be covered with a black substance which was positively identified, by X-ray analysis, as molybdenum disulphide. Two Taper-Lok fasteners were then removed from an untested USA-assembled specimen and the lubricant examined similarly. Again, molybdenum disulphide was identified although this time it had a different crystal structure. It would appear that fastener lubricity is not a factor in determining differences in fatigue behaviour.

The specimen fabrication procedure, carried out in the USA and listed in Appendix II, calls for the clamping of the two D6AC steel plates in a fixture in order to drill, ream and clean the holes, and to install and torque the Taper-Lok fasteners. Only after final assembly was the specimen removed from the fixture. This procedure could have the effect of adding the fixture clamping force (unknown) to the fastener tension due to torquing, upon removal of the specimen from the fixture. The tensions in those fasteners fitted in Australia were due entirely to the torque applied, as no clamping fixture was used during the re-assembly.

Another difference arising from the above, although considered to be of minor significance, is the detailed seating of the Taper-Lok fasteners in the holes. As the sealant layer between the faying surfaces is pliable, different fastener tensions will produce different amounts of mismatch of the taper in the adjoining plates. There is no doubt that mismatch occurred (Figure 29 shows some evidence), but any differences in amounts between the assemblies of the two countries should easily lie within the hole expansion tolerance designed for the Taper-Lok bolting system.

There remains then the question of whether re-torquing two of the four fasteners could affect the fatigue life of the joint. It is believed that this could be so for two reasons. First, the torque of 570 in-lb. (64.4 Nm) applied was, in Australia at least, only the nominal value applied. It was the value set on a normal workshop torque wrench. From other experiences at ARL it is known that a properly-calibrated torque wrench may give torque values differing by 20% or more from a normal workshop torque wrench. Torque differences are expected to change fatigue life because of the different amounts of interference in the tapered fastener and hole assembly. The second reason is that the D6AC steel plates forming the specimen were found to be curved to varying degrees upon delivery of the specimens to ARL. The worst case in the specimens tested in constant amplitude was a misalignment of 0.044 inch (1.1 mm) from one end of the specimen to the other. With curved plates the sequence in which the fasteners were inserted and tightened may be important in determining the degree of fastener interference (and hence fatigue life). The USA sequence of torquing is unknown; the Australian procedure was to remove one fastener and carry out the contamination/re-torquing procedure before removing the other fastener of the pair. Table XXIV gives the amounts of misalignment due to plate curvature for most of the specimens tested in the original constant amplitude series. No attempt was made to straighten any of the plates before testing; the specimens were simply clamped at one end in the bottom grip and the other end was forced into the aligned top grip.

There is no obvious correlation in Table XXIV between fatigue life and misalignment within any one group, and this would appear to partly negate the reasoning above. Also, whereas the possible differences in fastener torques between the two countries could, of itself, lead to a greater 'strengthening' of material around the contaminated holes, it should not alter the 'strengthening' of material around the holes with USA-assembled fasteners. Thus, material around Australian-assembled bolt holes could perform better in fatigue than material around USA-assembled ones (and thus negate any corrosive effect), but this reasoning could not lead to failure through USA-assembled bolt holes in contaminated specimens at a longer life than in clean specimens, as observed.

However, the combination of bent plates and torque variations could possibly lead to the experimental result. The amount of interference of any fastener (and hence the fatigue strength of the surrounding region) could, in principle, be influenced by the value of the torque as well as the sequence of tightening, when the plates being joined are curved.

This idea was examined experimentally. Two D6AC steel plates with a ground finish, of the same dimensions as those used in the test programs and heat-treated similarly, were drilled and taper reamed to suit the Taper-Lok fasteners. These plates were also slightly curved. Sealant (Proseal 899B) was applied to the faying surfaces before the reaming (its thickness was subsequently measured as approximately 0.0005 inch (0.01 mm)). Four clearance-fit parallel-shank fasteners (3/8-inch (9.5-mm) diameter) torqued to 150 in-lb. (16.9 Nm) were used to keep the joint firm during the reaming and Taper-Lok installation. These fasteners were replaced, one at a time, by Taper-Lok fasteners torqued to 110 in-lb. (12.4 Nm). The extensions of the Taper-Lok fasteners were measured each time a new fastener was added and torqued to the specified value of 570 in-lb. (64.4 Nm). The sequence of fastener insertion was such as to complete a transverse pair before starting on the second pair. The results are as follows.

Taper-Lok extension on torquing from 110 in-lb. (12.4 Nm) to 570 in-lb. (64.4 Nm).

Fastener No.	1	2	3	4
Extensions	0.0027			
(inches	0.0027	0.0025		
only)	0.0027	0.0021	0.0026	
	0.0025	0.0021	0.0025	0.0026

From these figures, by tightening one pair of fasteners (fasteners 3 and 4), the other pair (fasteners 1 and 2) have relaxed an average of 0.0003 inch, which is approximately 12%. The accuracy of measurement is considered to be about 0.0001 inch or 4% of the extension.

Similar findings were obtained on two other specimens, both without a sealant layer, one free of lubricant and the other lubricated with a light oil. Although the effect is small, there does appear to be a significant change in tension in a Taper-Lok fastener when the other pair of fasteners are torqued to the required value.

From the discussion above it is concluded that the USA-fully-assembled group of specimens may not be an adequate control group for the ARL contaminated specimens tested under constant amplitude loading. Moreover this conclusion is strongly supported by the spectrum load test results. The control group for this loading was finally-assembled in Australia, and the presence of the contaminant was the only difference between the clean and contaminated specimens. The experimental result under these circumstances was that where fracture modes were identical (as with clean and water-contaminated specimens in which failure occurred through the USA-assembled bolt holes) the fatigue lives were also identical.

There remains, in this Section, a need to comment on the note made in Section VC that, statistically, there appears to be no significant difference between the fatigue lives of clean specimens finally-assembled in the USA and Australia. This comparison was made between the fatigue lives of five USA-fully-assembled specimens, ranging from 19,900 to 51,000 cycles, and that for a single Australian-finally assembled specimen - 67,400 cycles (see Tables XXI and XXII). On these figures alone no difference can be declared between the two groups, but the confidence in this result is so low as to render the conclusion in the above paragraph still valid.

3. Particular Effects of Contaminants

a. Effects of water

Distilled water as a bolt hole contaminant did not adversely affect the fatigue strength of the bolted joint under either the constant amplitude or spectrum loading conditions adopted. In the one case (spectrum loading) where water contamination was the only variable, clean and contaminated specimen lives were identical.

As all specimen failures in both clean and water-contaminated specimens under both forms of loading were in the D6AC steel plates, it may also be asserted that distilled water in Taper-Lok bolt holes in this material did not adversely affect its fatigue resistance. Moreover, under the constraints of a simple specimen configuration and the loading conditions adopted, the H-11 alloy steel fasteners had adequate fatigue resistance under water contamination.

b. Effects of hydrochloric acid

Under constant amplitude, hydrochloric acid contamination does not adversely influence the fatigue life of the joint, as determined by statistical comparisons with lives obtained on clean or water-contaminated specimens (although Section VD2 precludes a valid comparison with the clean specimen lives). There is no doubt, however, that under spectrum loading, contamination of specimens with hydrochloric acid results in a drastically shortened fatigue life of the bolted joint.

These results suggest the possibility that, for spectrum loading with maximum stress levels below 100 ksi (689 MPa), hydrochloric acid contamination may be less deleterious as regards fatigue life than as indicated by the present spectrum load test results. In view of this, and as the modified 5G MAC spectrum used appears unrealistic in that the uniaxial stresses are higher than those developed in a structural configuration, it may be argued that there is little concern for F-111 Taper-Lok joint integrity. On the other hand it is more conservative to regard the spectrum load results as indicating the effect of hydrochloric acid contamination on the fatigue life of F-111 Taper-Lok bolted joints.

The question of the effect of hydrochloric acid contamination on failure in D6AC steel plate under spectrum loading is not resolved, since under these conditions no plate failures occurred. Hydrochloric acid contamination reduced the average life of the joint by a factor of 110 under the spectrum loading applied. As the contaminated specimens failed in the fasteners, and the clean specimens in the plates, the factor of 110 is the maximum reduction in life that could occur for plate failures enhanced by hydrochloric acid contamination, under the spectrum loading applied.

The effect of hydrochloric acid contamination of the fatigue of H-11 alloy steel Taper-Lok fasteners is now discussed. The peripheral corrosion on the fracture surfaces of fasteners fatigued under spectrum loading (Figure 27 (d) is an example) indicates, either, that stress corrosion cracks have formed during the waiting period or that hydrochloric acid has remained as a liquid in the joint until fatigue cracks have formed in the fasteners. As hydrochloric acid contamination did not appear deleterious in the constant amplitude tests, the argument for stress corrosion cracking appears weak. The more likely situation, then, is that hydrochloric acid remains in the joint and results in a true corrosion-fatigue effect, with the H-11 steel fasteners being more susceptible than the D6AC steel plates. The susceptibility of the fasteners to fatigue in the presence of hydrochloric acid is quite dependent on stress level. No fastener failures occurred under constant amplitude at 80 ksi (552 MPa), two out of six specimens failed in the fasteners at 100 ksi (689 MPa), and all specimens failed in the bolts under spectrum loading - the failing stresses in this case are noted in Section V.C.

Finally, it should be noted that, as regards the fatigue performance of the F-111 Taper-Lok bolted joint configuration, two other factors must be considered; namely, the corrosive severity of any entrapped fluids with respect to 10 N hydrochloric acid, and the variability of any contamination effect with different load spectra. There is no information in the current project relevant to these considerations.

SECTION VI

CONCLUSIONS

A. The results confirmed the benefits of the revised General Dynamics Taper-Lok installation procedure using the 18 flute reamer.

B. The data failed to demonstrate the advantage of mandrelizing as a rework process for high strength steel joints, although an improvement was shown for the aluminum joints. The results using the K-Lobe fastener in the steel-steel joints were inconclusive.

C. Surprisingly, increasing the exposure cycle from seven days in water spray at room temperature to 140 days at temperatures to up to 160°F did not appreciably decrease the subsequent fatigue life of the joint. Even though the original sealant (EC-5106) severely reverted to a rather sticky consistency during the most severe exposure cycles, it did appear to retain its sealing integrity. Whether this same integrity would be retained in an actual aircraft subjected to additional cycles of extreme dry air, cold, and occasional abrasion is problematical. The current sealant (PR1436G) used in the more recently manufactured aircraft and also used in current reworking practice showed no reversion tendencies under the 140 day cycle.

D. The lap joint spectrum test results were encouraging from the standpoint of demonstrating the reliability of this general type of joint in simulated F-111 applications. It was necessary to increase the overall load level of the 5G MAC spectrum, well above the basic specification to achieve failures within four aircraft lifetimes.

E. The efforts to identify cracks growing under the fastener heads were disappointing. The cracks did not grow to an ultrasonically identifiable size until after 95% or more of their total fatigue life.

F. For uncontaminated (clean hole) lap-joint specimens, fully-assembled in the USA and composed of D6AC steel plates joined with H-11 steel Taper-Lok fasteners, there was no significant difference between the constant amplitude axial load fatigue lives of those tested at ARL and those tested at AFML.

G. Contrary to expectation, the mean fatigue lives of specimens contaminated with either distilled water of 10 N hydrochloric acid were greater than those of clean specimens tested under the same constant amplitude conditions. This difference was significant for water-contaminated specimens, but not demonstrably so for hydrochloric acid-contaminated specimens. Additionally, most failures occurred through clean holes in the D6AC steel plates; each contaminated specimen containing one pair of clean holes and one pair of contaminated holes. The puzzle arising from these facts is thought to result from differences in assembly conditions, clean specimens were finally-assembled in the USA, contaminated ones in Australia.

H. Deliberate contamination of specimens with distilled water in the bolt holes did not affect the fatigue life of the lap-joint specimen (or the D6AC steel components) under spectrum loading. The Taper-Lok fasteners had adequate fatigue resistance under these conditions.

I. Hydrochloric acid contamination reduced the mean life of the joint specimens, under the spectrum loading applied, by a factor of 110. Under constant amplitude loading, although the mean lives of hydrochloric acid-contaminated specimens were less than those of water-contaminated specimens, the differences were not statistically significant.

J. In hydrochloric acid-contaminated specimens tested under spectrum loading, all fatigue failures occurred in the fasteners. The effect of hydrochloric acid contamination on fatigue failure in D6AC steel plates under spectrum loading was therefore not resolved.

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TABLE I

TENSILE AND FRACTURE PROPERTIES OF D6AC STEEL JOINT COMPONENTS

Heat No.	Test No.	0.2% P.S.		U.T.S.		RA %	ELONG. %	K_{IC}	
		ksi	MPa	ksi	MPa			ksi$\sqrt{in.}$	MPa$\sqrt{m}$
8061365	1	215	1482	234	1613	44	14		
	2	218	1503	234	1613	46	15		
	3							75.3	83
8061936	1	219	1510	233	1607	41	12		
	2	219	1510	234	1613	37	12		
	3							73.6	81
8064194	1	216	1489	233	1607	47	14		
	2	217	1496	233	1607	50	15		
	3							81.5	90

TABLE II

TENSILE PROPERTIES OF SPECIMENS FROM BROKEN D6AC STEEL SPECIMEN HALVES

Specimen	Yield Strength		U.T.S.		Elongation %	Reduction in Area %
	ksi	MPa	ksi	MPa		
76 A	217	1500	234	1611	10.3	39.2
76 B	209	1445	232	1602	10.4	40.2
278	210	1449	225	1549	11.1	41.8

TABLE III
D6AC JOINT EVALUATION PROGRAM AT AFML

						Steel - Steel Lap Joint		Steel-Aluminum	Steel-Steel-
						Load Level	Nr. Spec.	Lap Joint	Dog Bone
CONTROL	- - - - - - - - - - - →					S/N, A, B	13	6	6
GROUP Ia	INITIAL 7 DAY ROOM TEMPERATURE WATER SPRAY EXPOSURE	PARTIAL FATIGUE TEST	- - - - - - - →	7 Day, R. T. Water Spray Exp.	FATIGUE TEST TO FAILURE	A	3	2	3
GROUP Ib			- - - - - - - →	140 Day, R. T. Water Spray Exp.		A	3	—	—
GROUP Ic			- - - - - - - →	140 Day R.T./160° Water Spray Exp.		A, (B)	6, (3)	3	3
GROUP II			Strip, clean reinstall old fastener, reseal with EC-5106 sealant.	140 Day R.T./160° Water Spray Exp.		A	3	3	3
			140 Day R.T./160° Water Spray Exp.	Strip, clean reinstall old fastener, reseal with EC-5106 sealant.		A	3	—	—
GROUP IIIa			Strip, clean reinstall old fastener, new type sealant (PR 1436G)	140 Day R.T./160° Water Spray Exp.		A	1	—	—
			140 Day R.T./160° Water Spray Exp.	Strip, clean reinstall old fastener, new type sealant (PR 1436G)		A	3	—	—
GROUP IIIb			Strip, clean, rework per current General Dynamics procedures, install new Taper-lok, new type sealant (PR 1436G)	140 Day R.T./160° Water Spray Exp.		A	3	2	2
			140 Day R.T./160° Water Spray Exp.	Strip, clean, rework per current General Dynamics procedures, install new Taper-lok, new type sealant (PR 1436G)		A	3	—	—
GROUP IIIc			Strip, clean, install mandrelized hole fastener, new type sealant (PR 1436G)	140 Day R.T./160° Water Spray. Exp.		A	3	3	3
			140 Day R.T./160° Water Spray Exp.	Strip, clean, install mandrelized hole fastener, new type sealant (PR 1436G)		A	3	—	—
GROUP IIId			140 Day R.T./160° Water Spray Exp.	Rework and replace Taper-lok with K-lob fastener new PR 1436G		A	3	—	—
SPECTRUM A		- - - - - - - - →				S	1	—	—
SPECTRUM B		PARTIAL FATIGUE TEST	- - - - - - - →	140 Day R.T./160° Water Spray Exp.		S	1	1	1
SPECTRUM C			140 Day R.T./160° Water Spray Exp.	Rework per condition for Group "IIIb" above		S	2	1	1
					TOTAL		57	21	22

1. Load Level: "A"=80 KSI, Load Level "B" = 100 KSI (Steel-Steel Lap Joint only)
2. 140 Day RT/160° consisted of 93 days in water spray at RT followed by 47 days in the water spray at 160 °F (71 C).

TABLE IV

CONSTANT AMPLITUDE CONTROL TESTS.
FATIGUE LIVES TO FAILURE (CYCLES)
R = 0.1

Max. Stress		Laboratory	
ksi	MPa	AFML	ARL
170	1172	741 (1)	
162.3	1119	580 (1)	
162.3	1119	724 (1)	
115	793	13,720 (1)	
90	621	116,770 (1)	
70	483	1,000,000 (4)	
80	552	74,890 (1) (5)	192,500 (1)
		223,600 (1)	1,041,600 (3a)
		216,800 (1)	136,000 (1)
		113,510 (1)	129,300 (1)
			134,600 (1)
			92,200 (1)
			199,300 (1)
Log. Mean (cycles) (6)		142,480	142,500
Std. Dev. of Log. Life (6)		0.23	0.12
100	689	13,110 (1)	23,000 (1)
		41,230 (1)	19,900 (1)
		51,730 (1)	24,400 (1)
			23,000 (2)
			52,100 (3b)
			37,700 (1)
			51,000 (1)
Log. Mean (cycles) (6)		30,350	28,100
Std. Dev. of Log. Life (6)		0.32	0.16

(1) Each of these specimens failed through one pair of bolt holes (Type A failure).
(2) Separate fatigue crack from each bolt hole of a pair; grouped as Type A.
(3) Failure occurred through one bolt hole only (Type B failure); fastener in the other hole of the pair (a) did not fail; (b) failed in shear.
(4) Runout.
(5) Specimen inadvertently overloaded during test.
(6) Calculated for Type A failures only.

TABLE V
F AND t TESTS ON AFML AND ARL CONSTANT AMPLITUDE CONTROL FATIGUE LIVES

Comparisons	Results used	Statistical test	80ksi (552 MPa)	100ksi (689 MPa)
AFML clean/ ARL clean	All results	F	NS	NS
		t	NS	NS
	All AFML, ARL Type A	F	NS	NS
		t	NS	NS
	AFML deleting 74,890 result, all ARL	F	NS	
		t	NS	
	AFML deleting 74,890 result, ARL Type A	F	NS	
		t	NS	

NS Difference not significant at 5% level

TABLE VI

FATIGUE DATA FROM NON-JOINT SPECIMENS MACHINED FROM BROKEN ENDS OF STEEL-STEEL LAP JOINT SPECIMENS, R = 0.1

Type	Specimen	Max. Stress		Cycles to Failure	Remarks
		KSI	MPa		
Smooth	190A	210	1448	23,300	
		200	1379	25,400	
	190B	180	1241	45,000	
	34	160	1103	297,700	
	279	160	1103	41,400	
	277	140	965	153,400	
	33	115	793	1,141,900	
Notched (K_t=3.0)	97B	125	862	9,800	
	97A	120	827	12,200	
	107B	100	689	48,800	
	34	100	689	34,000	
	277	80	552	261,800	
	107A	80	552	$+10^7$	Runout
	40	50	345	$+10^7$	Runout

TABLE VII

FATIGUE LIVES OF GROUPS I, II AND III
SINGLE LAP JOINT SPECIMENS (STEEL-STEEL).
R = 0.1.

Group	Specimen	Max. Stress		Cycles to failure	Log. Mean (Cycles)	Std. Dev. of Log. Life
		ksi	MPa			
Ia	170/124	80	552	291,530		
	295/251			104,160	245,370	0.34
	67/69			486,500		
Ib	149/151	80	552	215,660		
	193/257			117,890	200,780	0.22
	60/90			318,360		
Ic	263/264	80	552	58,340 (1)		
	285/287			201,720		
	51/57			256,650	179,571	0.27
	35/m			351,580		
	189/291			224,510		
	247/253			140,640		
	15/19	100	689	52,140		
	146/173			99,850	78,512	0.15
	118/240			92,960		
II(Re-Ex)	112/g	80	552	178,040		
	23/245			87,540	123,070	0.15
	148/243			119,600		
II(Ex-Re)	81/101	80	552	137,120		
	183/186			139,450	189,875	0.24
	42/48			358,000		
IIIa (Re-Ex)	194/b	80	552	270,480	-	-
IIIa (Ex-Re)	55/179	80	552	721,370		
	239/281			94,480	179,339	0.52
	41/297			84,630		
IIIb (Re-Ex)	130/110	80	552	885,500		
	23/32			1,752,000	1,023,080	0.21
	31/154			690,250		
IIIb (Ex-Re)	184/300	80	552	601,650		
	129/133			715,500	952,748	0.28
	84/86			2,009,000 (2)		

.../contd.

TABLE VII (Continued)

Group	Specimen	Max. Stress		Cycles to failure	Log. Mean (Cycles)	Std. Dev. of Log. Life
		ksi	MPa			
IIIc (Re-Ex)	127/172	80	552	172,440		
	144/f			73,230	99,138	0.21
	288/k			77,160		
IIIc (Ex-Re)	103/104	80	552	197,000		
	80/140			219,000	164,660	0.18
	12/156			103,480		
IIId (Ex-Re)	155/174	80	552	155,500		
	303/H			152,520	298,171	0.50
	244/117			1,117,740 (2)		
	84/86			1,176,550 (2)(3)		

(1) Large crack in specimen prior to long term exposure.
(2) Runout.
(3) Reworked from a Group IIIb runout.
Result not included in calculating mean and standard deviation.

TABLE VIII

F and t TESTS ON CONSTANT AMPLITUDE FATIGUE LIVES OF STEEL-STEEL LAP JOINT SPECIMENS TESTED AT 80 KSI (552 MPa) TO DETERMINE THE EFFECTS OF VARIOUS EXTERNAL ENVIRONMENTS.

Comparison of (i) and (ii)		Statistical test	Result
(i) Group	(ii) Group		
Ia	AFML Control	F	NS
		t	NS
	AFML & ARL Control	F	NS
		t	NS
Ib	AFML Control	F	NS
		t	NS
	AFML & ARL Control	F	NS
		t	NS
Ic	AFML Control	F	NS
		t	NS
	AFML & ARL Control	F	NS
		t	NS
Ic	II (Re-Ex)	F	NS
		t	NS
	II (Ex-Re)	F	NS
		t	NS
	IIIa (Ex-Re)	F	NS
		t	NS
	IIIb (Re-Ex)	F	NS
		t	**
	IIIb (Ex-Re)	F	NS
		t	**
	IIIc (Re-Ex)	F	NS
		t	NS
	IIIc (Ex-Re)	F	NS
		t	NS
	IIId (Ex-Re)	F	NS
		t	NS

NS Difference not significant at 5% level.

** Difference significant at 1% level.

TABLE IX

F and t TESTS ON CONSTANT AMPLITUDE FATIGUE LIVES OF STEEL-STEEL LAP JOINT SPECIMENS TESTED AT 80 KSI (552 MPa) TO DETERMINE THE RELATIVE INFLUENCE OF SEALANTS

Comparison of (i) and (ii)		Statistical test	Result
(i) Group	(ii) Group		
II (Ex-Re)	IIIa (Ex-Re)	F	NS
		t	NS
IIIb (Re-Ex)	IIIb (Ex-Re)	F	NS
		t	NS
IIIc (Re-Ex)	IIIc (Ex-Re)	F	NS
		t	NS

NS Difference not significant at 5% level.

TABLE X

FATIGUE LIVES OF DOUBLE DOGBONE SPECIMENS
R = 0.1.

Group	Specimen	Max. Stress		Cycles to failure	Log. Mean (Cycles)	Std. Dev. of Log. Life
		ksi	MPa			
Control	207/226	130.6	900	85,000	-	-
	235/204	115	793	68,150	80,341	0.34
	221/224			151,420		
	197/206			80,900		
	218/209			171,251 (1)		
	217/c			23,413 (1)		
Ia	222/234	115	793	47,050	107,680	0.34
	211/214			221,840		
	201/232			119,620		
Ic	205/212	115	793	278,400	613,058	0.48
	196/236			1,350,000 (2)		
II (Re-Ex)	198/216	115	793	217,600	169,985	0.17
	a/219			108,000		
	200/228			209,000		
IIIb (Re-Ex)	213/231	115	793	298,800	482,365	0.29
	223/b			778,700		
IIIc (Re-Ex)	203/208	115	793	58,600	57,995	0.01
	220/229			56,900		
	199/223			58,500		

(1) Alternate test machine.
(2) Low load on some cycles.

TABLE XI

F and t TESTS ON DOUBLE DOGBONE SPECIMEN FATIGUE LIVES OBTAINED AT 115 KSI (793 MPa)

Comparison of (i) and (ii)		Statistical test	Result
(i) Group	(ii) Group		
Control	Ia	F	NS
		t	NS
	Ic	F	NS
		t	*
Ic	II (Re-Ex)	F	NS
		t	NS
	IIIb (Re-Ex)	F	NS
		t	NS
	IIIc (Re-Ex)	F	***
		t	NS(t')

NS Difference not significant at 5% level.
* Difference significant at 5% level.
*** Difference significant at 0.1% level.
(t') Modified t test (Ref. 6)

TABLE XII

FATIGUE LIVES OF SINGLE LAP JOINT SPECIMENS (STEEL-ALUMINIUM) R = 0.1.

Group	Specimen	Max. Stress		Cycles to failure	Log. Mean (Cycles)	Std. Dev. of log. life
		ksi	MPa			
Control	259/9T	40	276	6,801(1)		
	273/10	35	241	16,230(2)		
	275/20	30	207	29,020		
	245/12	25	172	155,940	-	-
	284/7	23	159	283,460		
	259/9T	20	138	10^6 + (3)		
	273/10	15	103	10^6 + (3)		
	305/21	10	69	10^6 + (3)		
Ia	265/2	25	172	124,440	237,114	0.40
	298/17			451,810		
Ic	294/14	25	172	188,020		
	261/4			95,640	141,974	0.15
	260/3			159,140		
II (Re-Ex)	283/8	25	172	203,308		
	307/16			155,980	190,604	0.08
	249/18			218,360		
IIIb (Re-Ex)	259/19	25	172	839,720	1,372,251	0.30
	262/1			2,242,500		
IIIc (Re-Ex)	274/11	25	172	637,180		
	256/6			1,646,210	1,019,283	0.21
	295/15			1,009,570		

(1) Retested from 20 ksi (138 MPa).
(2) Retested from 15 ksi (103 MPa).
(3) Runout.

TABLE XIII

F AND t TESTS ON STEEL-ALUMINIUM SINGLE LAP JOINT SPECIMEN FATIGUE LIVES OBTAINED AT 25 KSI (172 MPa).

Comparison of (i) and (ii)		Statistical test	Result
(i) Group	(ii) Group		
Ic	II (Re-Ex)	F	NS
		t	NS
	IIIb (Re-Ex)	F	NS
		t	*
	IIIc (Re-Ex)	F	NS
		t	**

NS Difference not significant at 5% level.
* Difference significant at 5% level.
** Difference significant at 1% level.

TABLE XIV

5G MAC SPECTRUM

Layer No.	S_{min}, ksi	S_{max}, ksi	N	Frequency, cpm	Layer No.	S_{min}, ksi	S_{max}, ksi	N	Frequency, cpm
1	27.0	46.1	66	6	30	23.0	75.2	5	6
2	1.5	49.7	34	60	31	23.6	37.3	230	6
3	19.5	24.8	1621	6	32	23.0	31.0	1338	6
4	23.0	33.9	1589	6	33	0.2	57.2	19	60
5	1.3	30.7	1374	60	34	11.1	29.9	1546	60
6	0	25.4	67	60	35	0	18.4	238	60
7	20.4	82.0	1	6	36	1.4	46.4	114	60
8	21.3	65.7	250	6	37	20.4	43.1	370	6
9	0.2	63.8	8	60	38	11.1	59.9	7	60
10	4.7	40.1	2	60	39	5.8	40.0	478	150
11	22.9	100.7	2	6	40	0.2	48.0	63	60
12	10.5	46.3	37	60	41	20.3	77.9	76	6
13	21.8	48.3	367	6	42	1.3	39.5	371	60
14	20.6	73.9	109	6	43	17.0	76.0	37	6
15	22.8	106.6	1	6	44	2.3	50.5	111	60
16	4.7	18.3	265	60	45	30.6	73.2	2	6
17	2.3	59.9	34	60	46	2.2	40.8	363	60
18	22.5	58.1	318	6	47	11.6	82.6	5	6
19	10.6	34.2	6	60	48	10.5	30.7	1280	60
20	0	32.7	21	60	49	19.5	65.9	62	6
21	20.7	51.7	374	6	50	10.5	47.9	1	60
22	5.8	40.0	478	150	51	17.5	50.5	89	6
23	4.6	25.4	46	60	52	24.9	63.0	41	6
24	0.2	34.2	300	60	53	27.9	55.2	57	6
25	4.6	32.6	10	60	54	10.9	40.4	491	60
26	22.8	91.4	4	6	55	0	40.2	6	60
27	0	47.2	4	150	56	11.0	50.4	74	60
28	21.8	41.9	306	6	57	22.7	38.7	682	6
29	23.8	71.8	15	6	58	2.1	29.9	1376	60

TABLE XV

RESULTS OF AFML SPECTRUM TESTS

Specimen Type	Specimen	Exposure/Rework Condition	Loading Severity % 5G MAC	Fatigue Life Blocks	Fatigue Life Layers	Fatigue Life Cycles
Steel - Steel Lap - Joint	150/87	140 Day RT-160°F (71°C)	120	85.0	4,930 NF	1,465,000
	150/87	Retest of above spec.	130	45.2	2,624 (15)	779,000
	286/206	7 Day RT	135	177.5	10,294 (11)	3,603,000
	2/75	140 Day RT - 160°F (71°C)	145	87.9	5,102 (15)	1,515,000
	L/132	140 Day RT - 160°F/Rework IIIb	145	257.5	14,933 NF	4,440,000
	L/132	Retest of above spec	155	<1.0	15 (15)	5,528
	47/45	140 Day RT - 160°F/Rework IIIb	145	134.2	7,783 (11)	2,314,000
Steel - Aluminum Lap Joint	282/5	140 Day RT - 160°F (71°C)	90	172.4	9,999 NF	2,973,000
		Retest of above spec.	105	10.8	628 (?)	186,000
	252/13	140 Day RT - 160°F/Rework IIIb	90	172.4	9,999 NF	2,973,000
	252/13	Retest of above specimen	105	95.8	5,556 (15)	1,652,000

a. N.F. = No Failure

b. Layer at which failure occurred shown in parenthesis.

c. Equipment records layers to failure. "Blocks" and "cycles" are calculated from "layers".

TABLE XVI

CONSTANT AMPLITUDE FATIGUE LIVES (CYCLES) OF SPECIMENS WITH BOLT HOLE CONTAMINANTS

Max Stress		Type of Specimen			
		Clean Control		ARL - contaminated	
(ksi)	(MPa)	AFML	ARL	Water	Conc.HCl
80	552	74,890 (1) 223,600 (1) 216,800 (1) 113,510 (1)	192,500 (1) 1,041,600 (3a) 136,000 (1) 129,300 (1) 134,600 (1) 92,200 (1) 199,300 (1)	689,900 (1) 661,500 (1) 333,900 (3c) 638,800 (1) 442,100 (1)	817,400 (1) 1,821,400 (1) 36,500 (3c) 201,900 (1) 243,400 (1)
Log. mean (Cycles) (5)		142,480	142,500	599,200	520,100
Std. Dev. (5) of log. life		0.23	0.12	0.09	0.45
100	689	13,110 (1) 41,230 (1) 51,730 (1)	23,000 (1) 19,900 (1) 24,400 (1) 23,000 (2) 52,100 (3b) 37,700 (1) 51,000 (1)	138,700 (1) 186,700 (1) 278,700 (1) 143,900 (1) 40,900 (1)	26,200 (1) 1,600 (4) 246,200 (3c) 67,400 (1) 62,600 (1)
Log. mean (Cycles) (5)		30,350	28,100	133,500	48,000
Std. Dev. (5) of log. life		0.32	0.16	0.31	0.23

(1) Each of these specimens failed through one pair of bolt holes (Type A failure).
(2) Separate fatigue crack from each bolt hole of a pair; grouped as Type A.
(3) Failure occurred through one bolt hole only (Type B failure); fastener in the other hole of the pair (a) did not fail; (b) failed in shear; (c) failed by fatigue.
(4) No failure in either steel plate; all four fasteners failed, two by fatigue, two by shear (Type C failure).
(5) Calculated for Type A failure ONLY.

TABLE XVII

F AND t TESTS ON CONSTANT AMPLITUDE FATIGUE LIVES TO DETERMINE THE EFFECTS OF BOLT-HOLE CONTAMINANTS

Comparisons	Clean-specimen results from:	type of failure considered	Statistical test	80 ksi (552 MPa)	100 ksi (689 MPa)
Clean/water	ARL	all types	F	NS	NS
			t	*	**
		type A only	F	NS	NS
			t	***	**
	ARL & AFML	all types	F	NS	NS
			t	**	***
		type A only	F	NS	NS
			t	***	***
Clean/hydro-chloric acid	ARL	all types	F	NS	**
			t	NS	NS(t')
		type A only	F	*	NS
			t	NS(t')	NS
	ARL & AFML	all types	F	*	**
			t	NS(t')	NS(t')
		type A only	F	**	NS
			t	NS(t')	NS

NS Difference not significant at 5% level.
* Difference significant at 5% level.
** Difference significant at 1% level.
*** Difference significant at 0.1% level.
(t') Modified t test (Ref. 6)

TABLE XVIII

58-LAYER ARL BLOCK LOADING SEQUENCE

(Frequency 2.5 Hz)
1 ksi = 6.89 MPa

Layer No.	S_{min}, ksi	S_{max}, ksi	No. of Cycles N	Layer No.	S_{min}, ksi	S_{max}, ksi	No. of Cycles N
1	12.2	76.1	66	30	10.4	124.1	5
2	0.7	82.0	34	31	10.6	61.5	230
3	8.8	40.9	1621	32	10.4	51.2	1338
4	10.4	55.9	1589	33	0.1	94.4	19
5	0.6	50.7	1374	34	5.0	49.3	1546
6	0	41.9	67	35	0	30.4	238
7	9.2	135.3	1	36	0.6	76.6	114
8	9.6	108.4	250	37	9.2	71.1	370
9	0.1	105.3	8	38	5.0	98.8	7
10	2.1	66.2	2	39	2.6	66.0	478
11	10.3	166.2	2	40	0.1	79.2	63
12	4.7	76.4	37	41	9.1	128.5	76
13	9.8	79.7	367	42	0.6	65.2	371
14	9.3	121.9	109	43	7.7	125.4	37
15	10.3	175.9	1	44	1.0	83.3	111
16	2.1	30.2	265	45	13.8	120.8	2
17	1.0	98.8	34	46	1.0	67.3	363
18	10.1	95.9	318	47	5.2	136.3	5
19	4.8	56.4	6	48	4.7	50.7	1280
20	0	54.0	21	49	8.8	108.7	62
21	9.3	85.3	374	50	4.7	79.0	1
22	2.6	66.0	478	51	7.9	83.3	89
23	2.1	41.9	46	52	11.2	104.0	41
24	0.1	56.4	300	53	12.6	91.1	57
25	2.1	53.8	10	54	4.9	66.7	491
26	10.3	150.8	4	55	0	66.3	6
27	0	77.9	4	56	5.0	83.2	74
28	9.8	69.1	306	57	10.2	63.9	682
29	10.7	118.5	15	58	0.9	49.3	1376

TABLE XIX

SPECTRUM LOAD TEST LIVES OF CLEAN AND CONTAMINATED SPECIMENS

CLEAN (AUST.-ASSEMBLED)			CONTAMINATED					
			WATER			HYDROCHLORIC ACID		
Spec. No.	Blocks plus cycles	Total Cycles	Spec. No.	Blocks plus cycles	Total Cycles	Spec. No.	Blocks plus cycles	Total cycles
289/276	55 + 5012	953,267	162/175	27 + 5527	471,034	258/267	0 + 4875	4875
192/268	46 + 5012	798,098	58/59	58 + 5527	1005,505	188/246	0 + 5012	5012
160/163	34 + 5527	591,721	306/N	23 + 5012	401,555	6/8	0 + 5527	5527
53/63	19 + 5527	333,106	82/100	43 + 5527	746,890	143/137	0 + 5012	5012
106/145	20 + 5527	350,347	271/272	18 + 5016	315,354	152/147	0 + 4876	4876
						68/70	0 + 4882	4882
log. mean	32.18	554,745		31.17	537,338		0.29	5026
std. dev. of log. life		0.206			0.205			0.021

TABLE XX

SPECTRUM LOAD TEST FAILURES

Notation for fastener failures: F = failure, S = Shear failure

Condition	Spec. No.	Cycles to failure	Failure Locations				
			Fasteners assembled in: AUST. fastener (a)	AUST. fastener (b)	USA fastener (a)	USA fastener (b)	Plates
Clean	289/276	953,267	-	-	-	-	Failure through USA - assembled bolt holes. Fatigue cracking from both holes. (Type A failures)
	192/268	798,098	-	-	-	-	
	160/163	591,721	-	-	-	-	
	55/63	333,106	F+	-	F+*	-	
	106/145	350,347	F+	-	F+	-	
Water Contaminated	162/175	471,034	F+	F+	-	-	Failure through USA - assembled bolt holes. / Failure through AUST- assembled bolt holes. Fatigue cracking from both holes. (Type A failures)
	58/59	1,005,505	F+	-	F*	-	
	306/N	401,555	F	-	F+	-	
	82/100	746,890	-	-	-	-	
	271/272	315,354	F*	F*	F	F*	
H Cl contaminated	258/267	4875	F	F	S	S	No plate failures
	188/246	5012	F	S	S	S	
	6/8	5527	F	S	S	S	
	143/137	5012	F	S	S	S	
	152/147	4876	F	F	S	S	
	68/70	4882	F	F	S	S	

NOTES: 1. Fatigue failures in the fasteners initiated in the thread region except those marked with * which initiated in the shank between the thread and the head.

2. Fastener failures marked + were detected only on disassembly after the test.

TABLE XXI

ADDITIONAL CONSTANT AMPLITUDE TEST RESULTS

Condition	Final Assembly	Test Machine	Max. Stress	Cycles to failure	Previous Range of Cycles to failure (Table XVI)	Failure Location
Clean	USA	MTS	80 ksi (552 MPa)	217,000	92,200-199,300 Type A 92,200-1,041,600 all failures	Plate failure through one pair of bolt holes. (Type A failure)
		MTS	100 ksi (689 MPa)	76,237	19,900-51,000 Type A 19,900-52,100 all failures	Plate failure through one pair of bolt holes. (Type A failure)
	AUST	MTS	100 ksi (689 MPa)	127,160		Plate failure through USA-assembled bolt holes (Type A failure)
		Amsler	100 ksi (689 MPa)	67,400		Plate failure through USA assembled bolt holes. (Type A failure)
Water contaminated	AUST	Amsler	80 ksi (552 MPa)	316,200	442,100-689,900 Type A 333,900-689,900 all failures	Plate failure through USA - assembled bolt holes. (Type A failure)
		Amsler	100 ksi (689 MPa)	69,800	40,900-278,700 all failures were Type A	Plate failure through USA-assembled bolt holes. (Type A failure)
H Cl contaminated	AUST	Amsler	100 ksi (689 MPa)	300 (+ ~1000 run-up cycles)	1600-246,200	Fatigue failure of contaminated fasteners. USA-assembled fasteners sheared. (Type C failure)

TABLE XXII

T-TEST COMPARISONS BETWEEN ADDITIONAL CONSTANT AMPLITUDE RESULTS (TABLE XXI) AND THE ORIGINAL GROUP OF CONSTANT AMPLITUDE RESULTS (TABLE XVI)

Comparison	Result of t-test
Amsler/MTS	
(i) 80 ksi, (552 MPa) clean, Type A failures. 217,000 cycles in MTS (Table XXI)/original group (Table XVI)	NS
(ii) 100 ksi, (689 MPa) clean, Type A failures. 76,237 cycles in MTS (Table XXI)/original group (Table XVI)	NS
USA/AUST, final assembly, clean control group	
100 ksi, (689 MPa) Type A failures. 67,400 cycles (Table XXI)/original group (Table XVI)	NS
1st batch/2nd batch, contaminated specimens	
(i) 80 ksi, (552 MPa) water-contaminated, Type A failures. 316,200 cycles (Table XXI)/original group (Table XVI)	NS
(ii) 100 ksi, (689 MPa) water-contaminated, Type A failures. 69,800 cycles (Table XXI)/original group (Table XVI)	NS
(iii) 100 ksi, (689 MPa) hydrochloric acid-contaminated, all results. 300 cycles (Table XXI)/original group (Table XVI)	NS

NS Difference not significant at 5% level.

TABLE XXIII

NUMBER OF DAYS BETWEEN CONTAMINATION AND FATIGUE TESTING.

(a) Constant Amplitude

Test Conditions		Specimen No.	Cycles	Contamination period (days)
Water-Contaminated	80 ksi (552 MPa)	49/52	689,900	140
		73/77	661,500	145
		30/39	333,900	149
		65/66	638,800	168
		191/304	442,100	167
	100 ksi (689 MPa)	142/195	138,700	139
		14/18	186,700	144
		131/128	278,700	145
		126/122	143,900	157
		22/25	40,900	158
	80 ksi (552 MPa) AUST.-assembled. MTS.	78/79	316,200	239
	100 ksi (689 MPa) AUST.-assembled. Amsler	37/11	69,800	236
Hydrochloric Acid-contaminated	80 ksi (552 MPa)	102/105	817,400	140
		178/182	1,821,400	147
		54/62	36,500	154
		43/46	201,900	161
		29/56	243,400	165
	100 ksi (689 MPa)	61/91	26,200	144
		72/98	1,600	150
		242/241	246,200	152
		92/93	67,400	152
		185/187	62,600	153
	100 ksi (689 MPa) AUST.-assembled. Amsler	71/94	300	236

.../contd.

TABLE XXIII. (CONTINUED)

(b) Spectrum Loading

Test Conditions	Specimen No.	Cycles	Contamination period (days)
Water-Contaminated	162/175	471,034	132
	58/59	1,005,505	174
	306/N	401,555	185
	82/100	746,890	198
	271/272	315,354	204
Hydrochloric Acid-Contaminated	258/267	4875	159
	188/246	5012	171
	6/8	5527	186
	143/137	5012	188
	152/147	4876	190
	68/70	4882	190

TABLE XXIV

MISALIGNMENTS OF SPECIMENS TESTED AT
ARL UNDER CONSTANT AMPLITUDE LOADING

Condition	Max. Stress	Specimen No.	Cycles to failure	Misalignment * (inch.)	Configuration *
Clean	80 ksi (552 MPa)	269/270	136,000	0.014	1
		108/180	129,300	0.044	1
		120/299	134,600	0.010	2
		13/38	92,200	0.039	1
	100 ksi (689 MPa)	168/169	23,000	0.012	2
		16/26	52,100	0.027	1
		135/136	37,700	0.003	2
Water-Contaminated	80 ksi (552 MPa)	49/52	689,900	0.006	2
		73/77	661,500	0.012	2
		30/39	333,900	0.016	1
		65/66	638,800	0.007	2
		191/304	442,100	0.017	1
	100 ksi (689 MPa)	142/195	138,700	0.036	1
		14/18	186,700	0.025	1
		131/128	278,700	0.013	2
		126/122	143,900	0.012	2
		22/25	40,900	0.034	1
Hydrochloric Acid-Contaminated	80 ksi (552 MPa)	102/105	817,400	0.026	2
		178/182	1,821,400	0.032	1
		54/62	36,500	0.012	2
		43/46	201,900	0.026	1
		29/56	243,400	0.003	1
	100 ksi (689 MPa)	61/91	26,200	0.008	2
		72/98	1600	0.018	2
		242/241	246,200	0.026	2
		92/93	67,400	0.008	1
		185/187	62,600	0.017	2

.../contd.

TABLE XXIV (CONTINUED)

*Definition of misalignment and configuration.

Misalignment

CONFIGURATION 1

Misalignment

CONFIGURATION 2

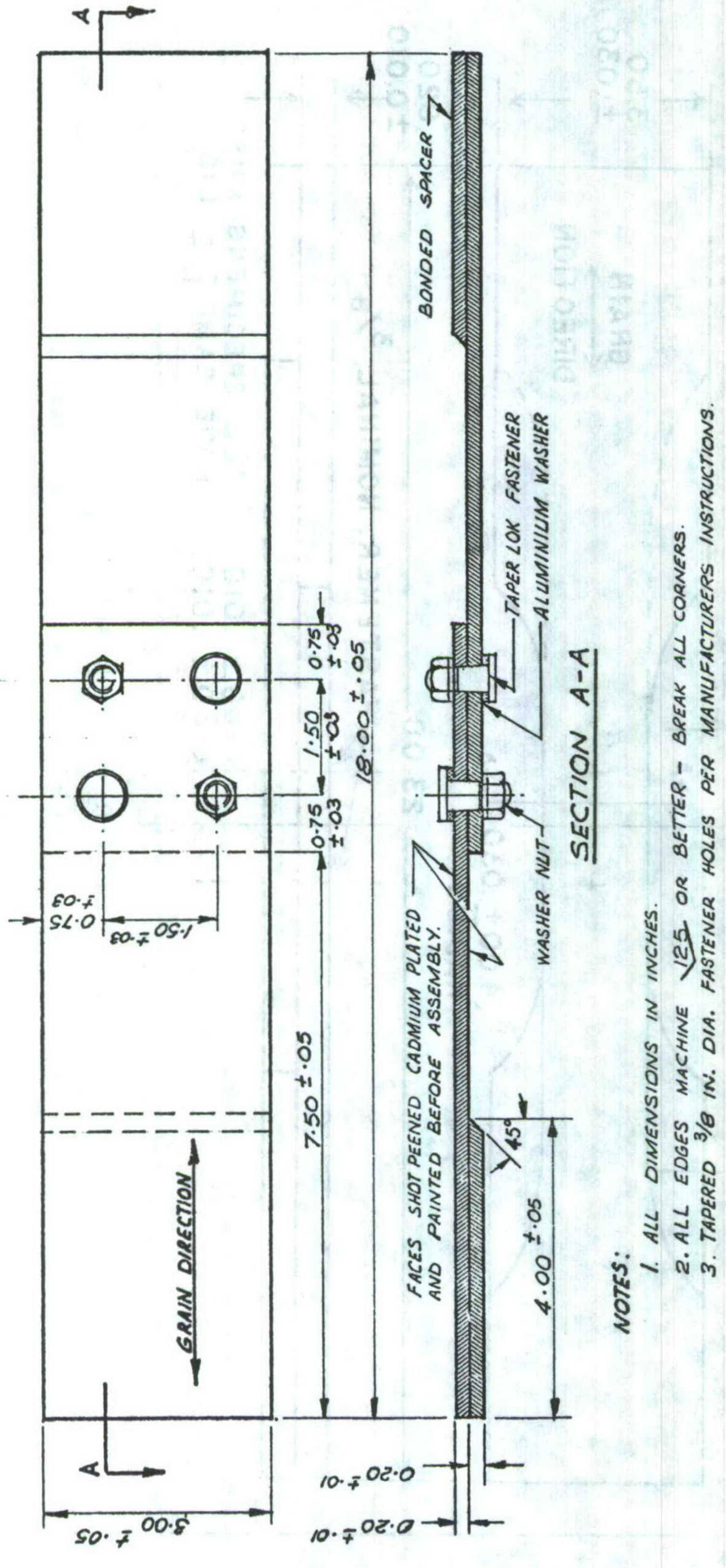
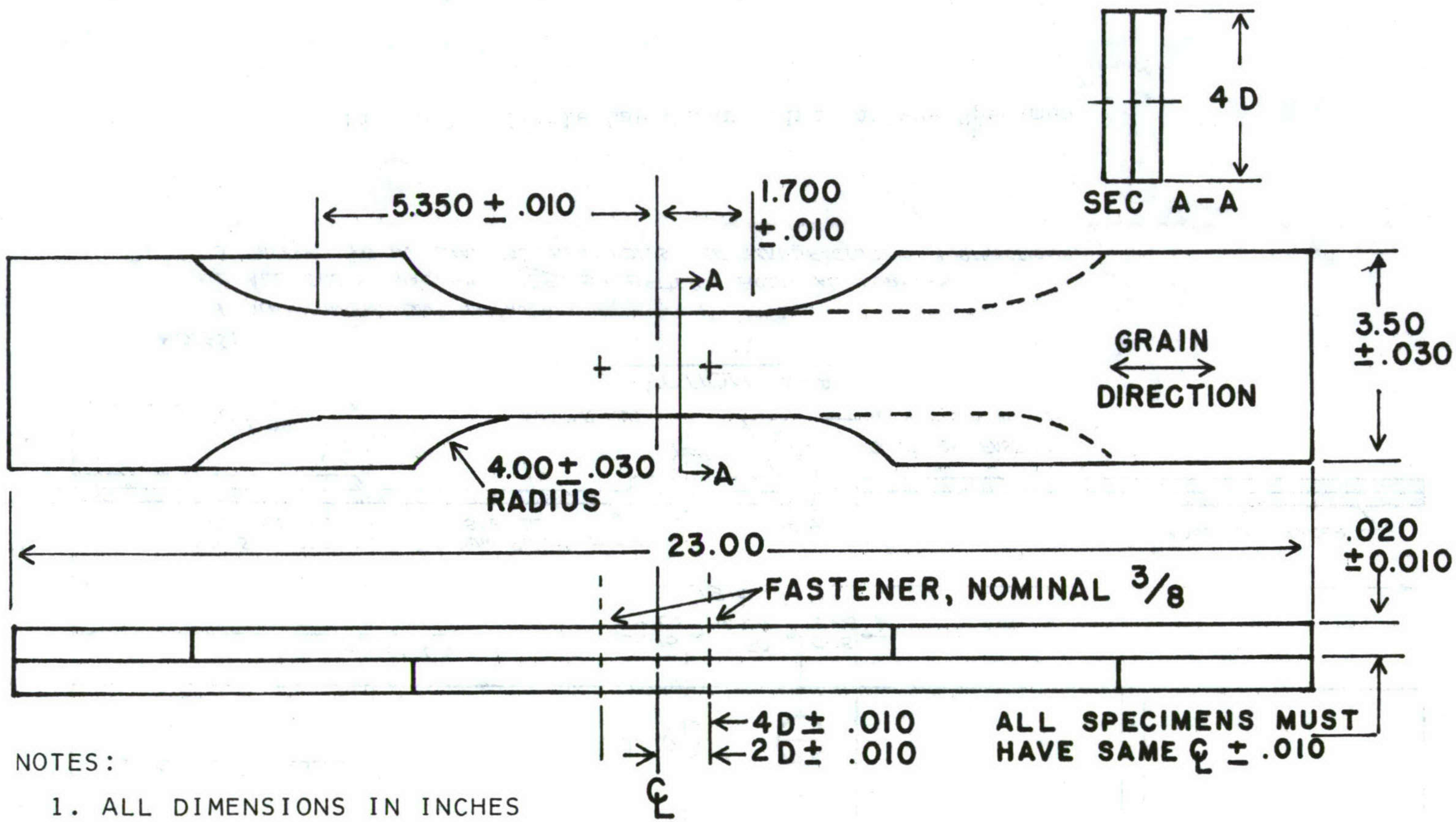


Figure 1. Single Lap Shear Joint Fatigue Specimen



NOTES:

1. ALL DIMENSIONS IN INCHES
2. ALL EDGES MACHINE 125 OR BETTER - BREAK ALL CORNERS
3. TAPERED 3/8 IN. DIA. FASTENER HOLES PER MANFACTURERS INSTRUCTIONS

Figure 2. Reverse Dogbone Low Load Transfer Joint

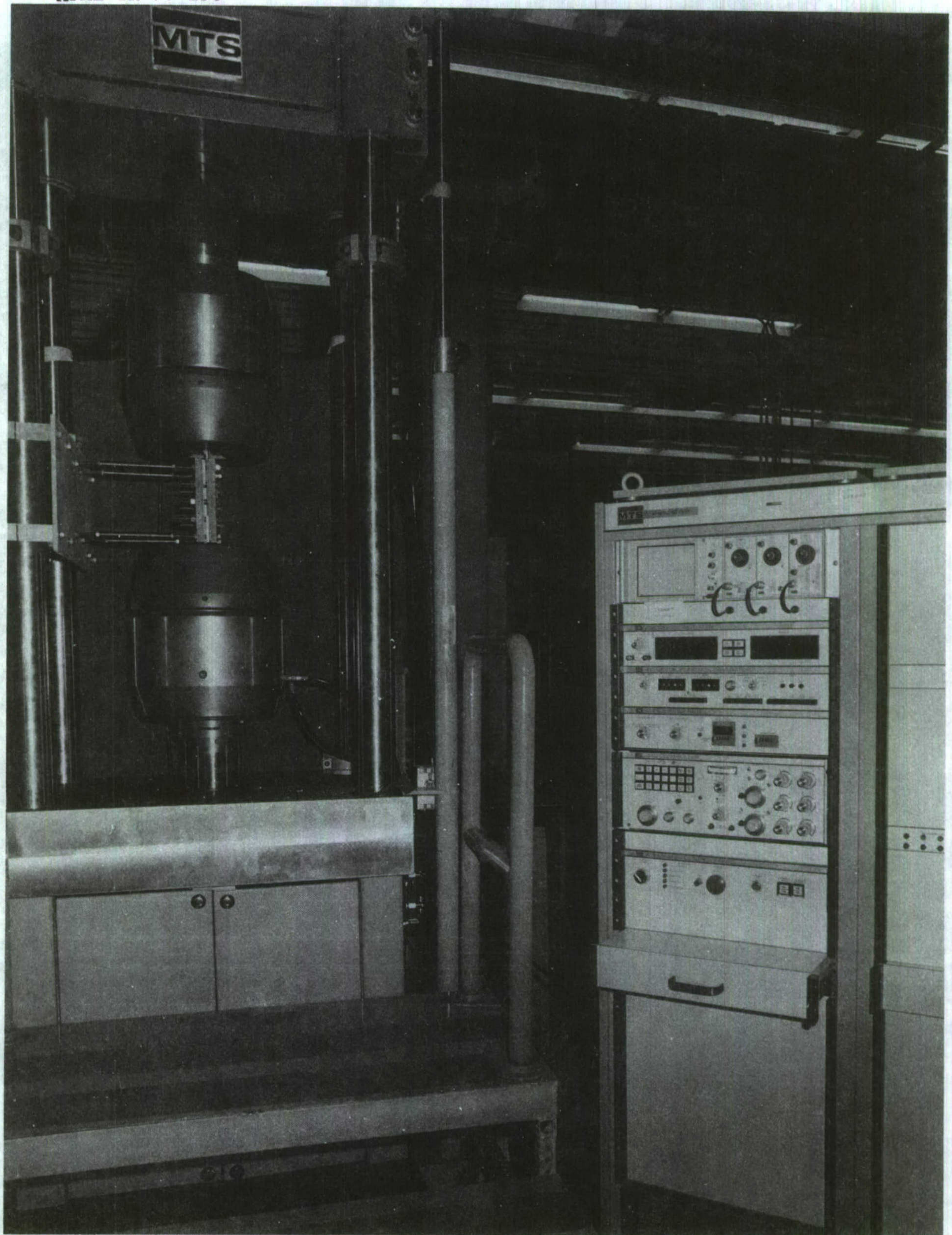


Figure 3. AFML 150 Kip Fatigue Machine

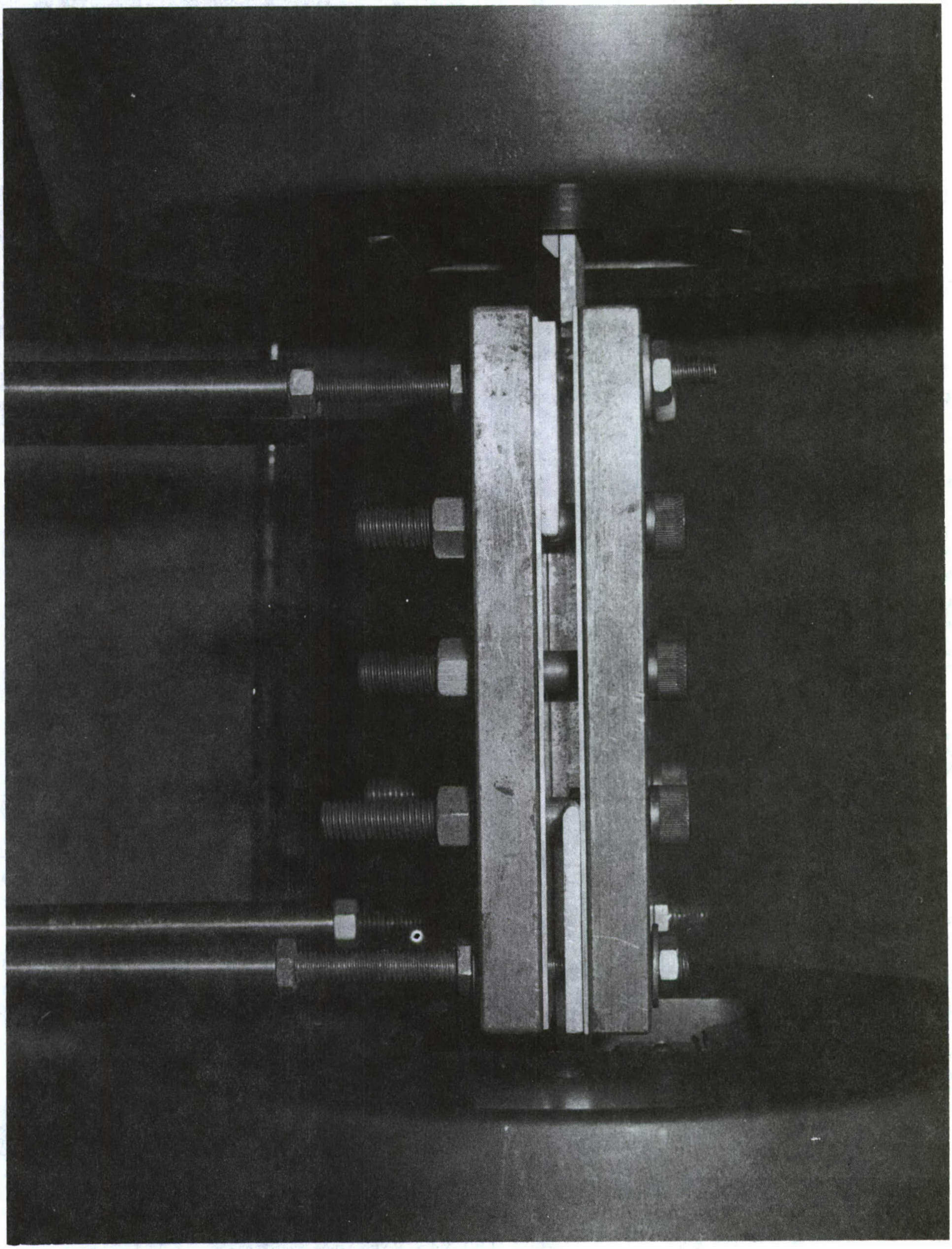


Figure 4. Close-up of AFML Specimen And Loading Fixture

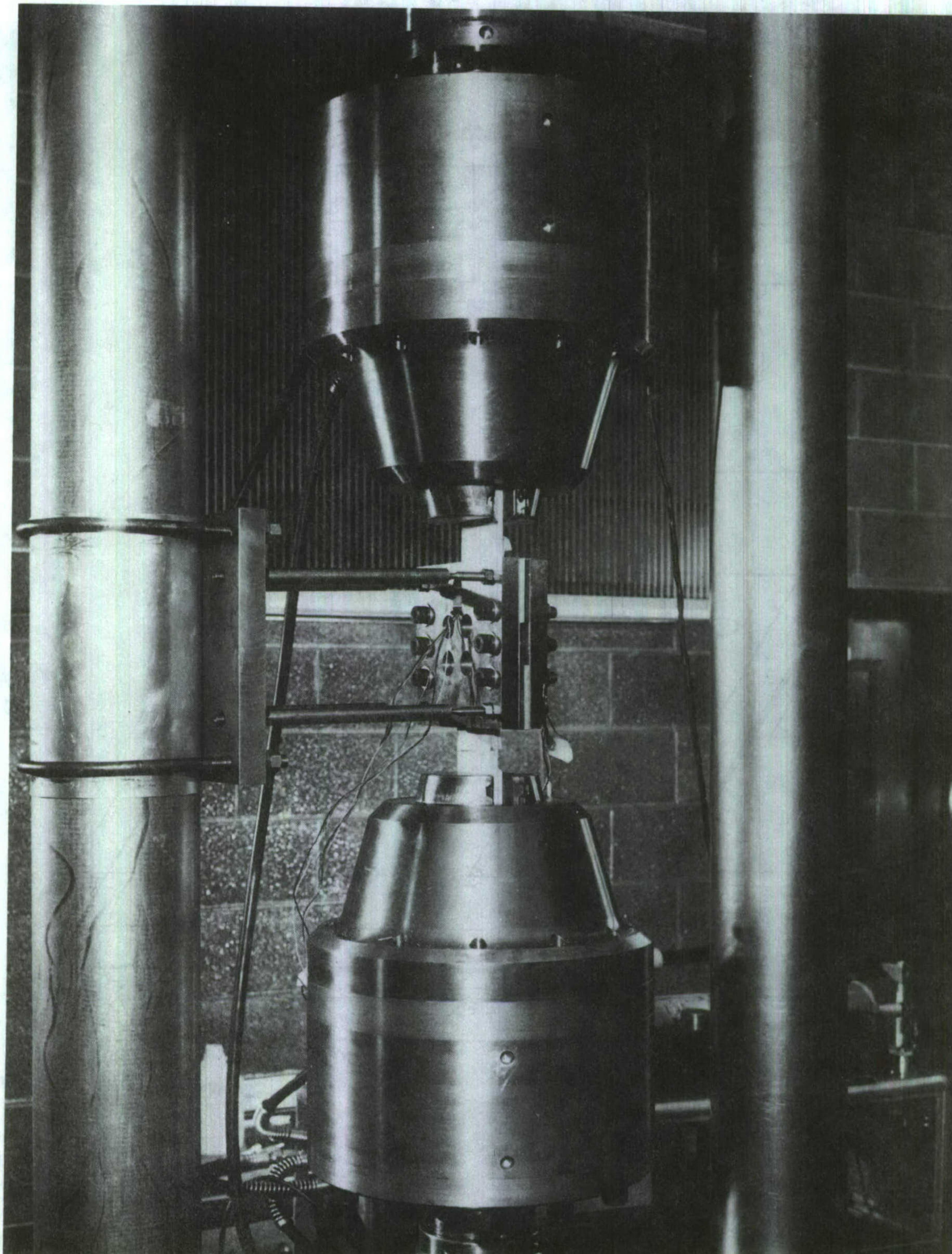


Figure 5. ARL Fatigue Machine And Loading Fixture

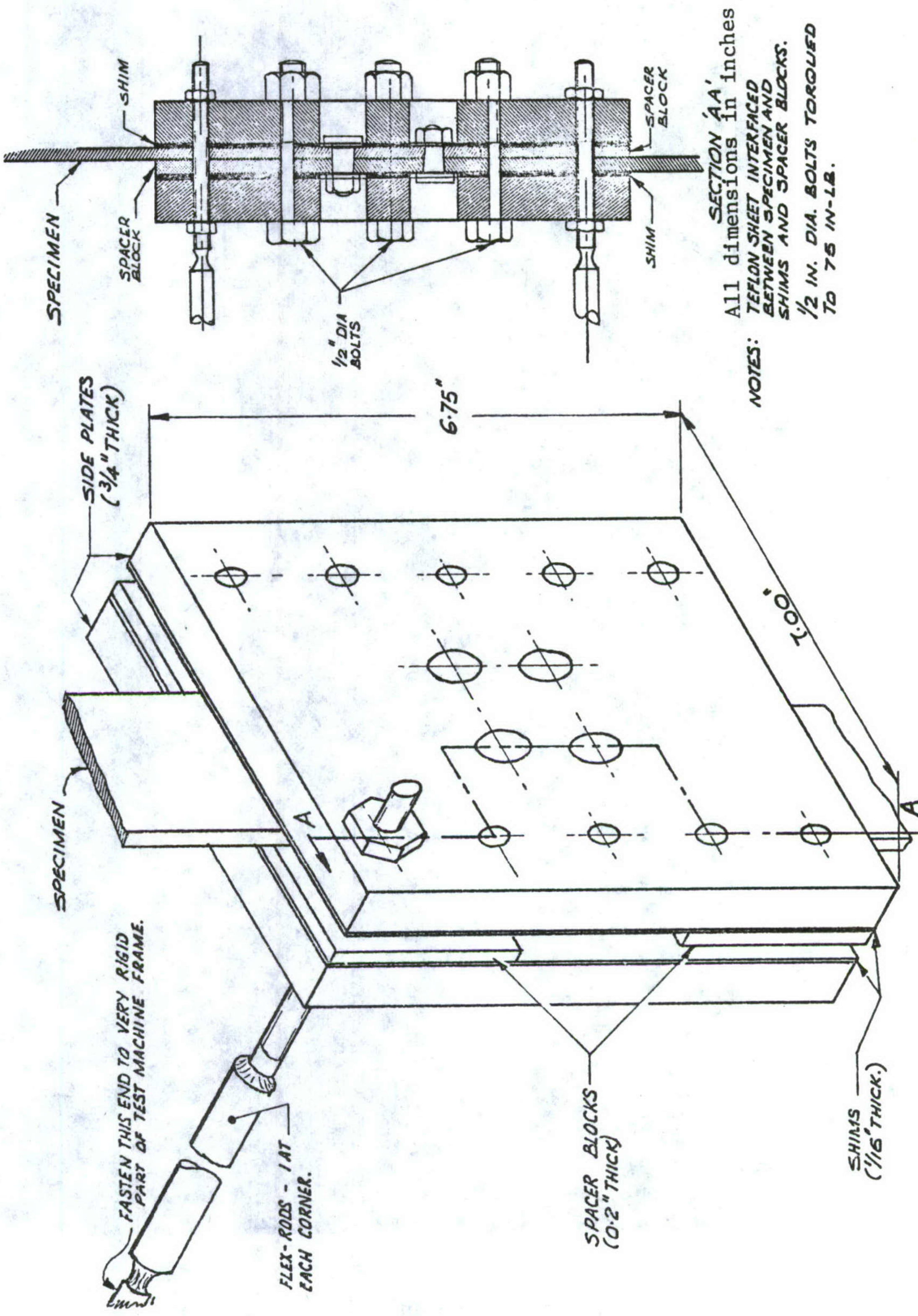


Figure 6. Bending Restraint Fixture

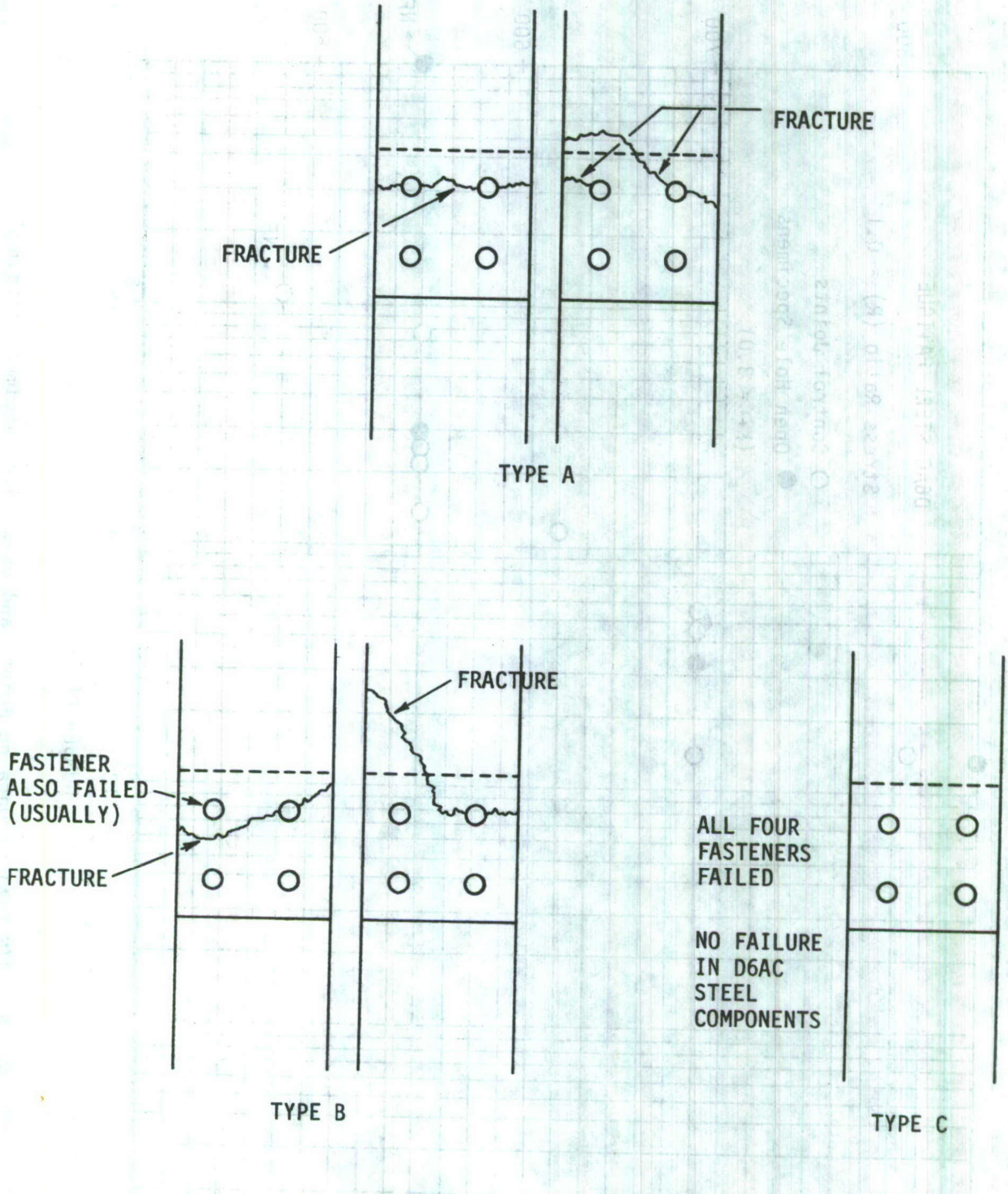


Figure 7. Fatigue Crack Paths and Typed of Failure

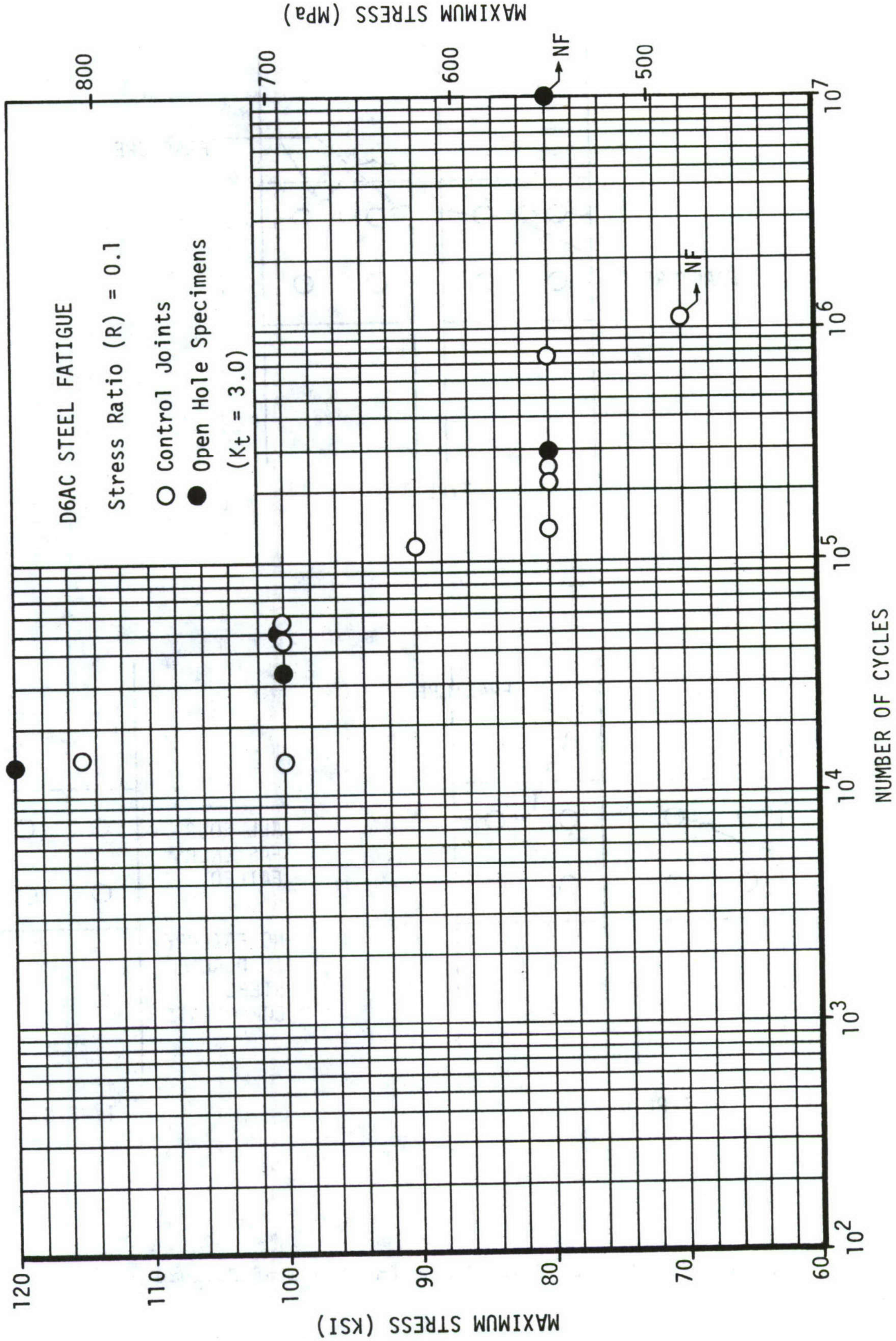


Figure 8. S/N Fatigue Data on Joints and Open Hole Specimens Obtained at AFML

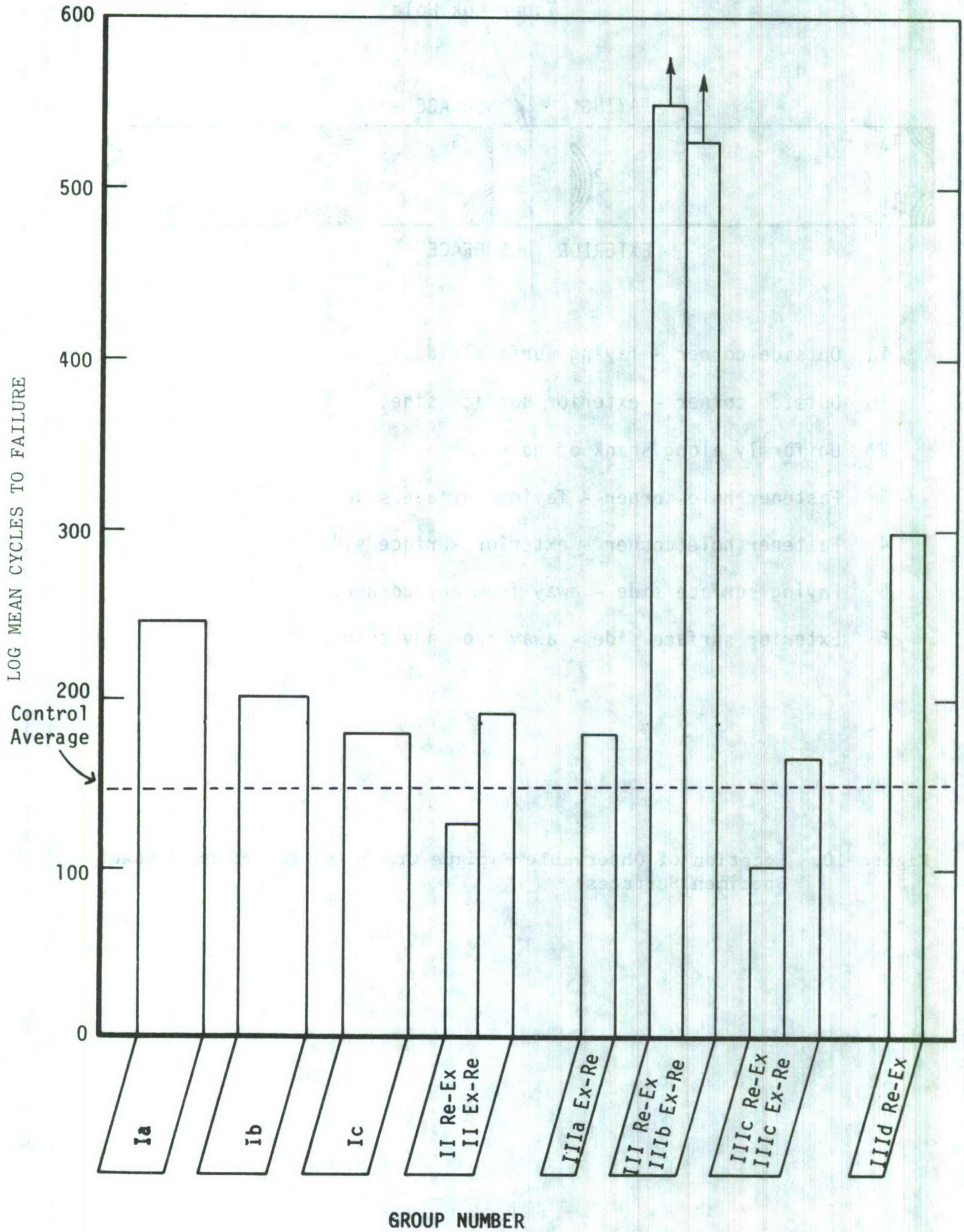
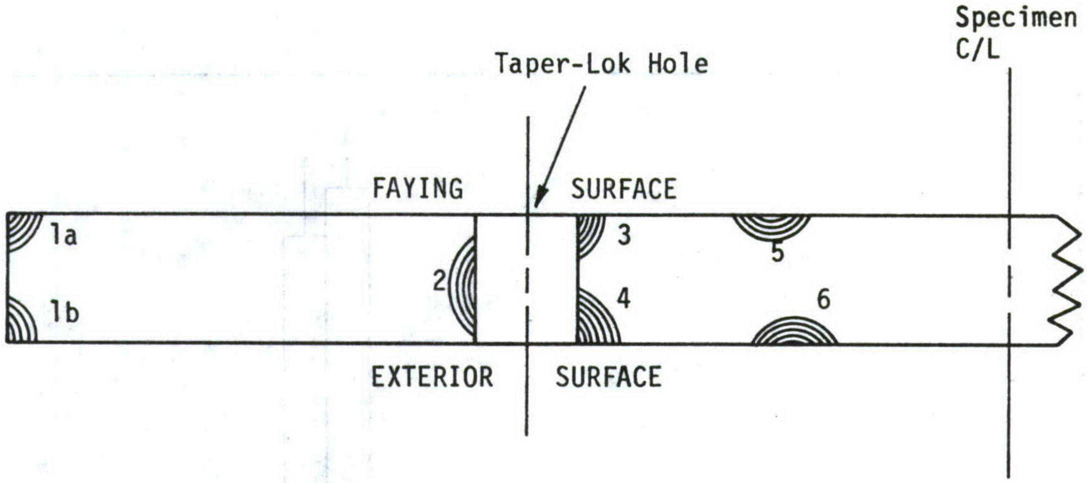


Figure 9. Average Fatigue Life of Exposure Groups at 80,000 psi Max Load Level (R = 0.1)



1a Outside corner - faying surface side.

1b Outside corner - exterior surface side.

2 Uniformly along shank of hole

3 Fastener hole corner - faying surface side.

4 Fastener hole corner - exterior surface side.

5 Faying surface side - away from any corner.

6 Exterior surface side - away from any corner.

Figure 10. Location of Observable Fatigue Cracks on Failed D6AC Steel Specimen Surfaces

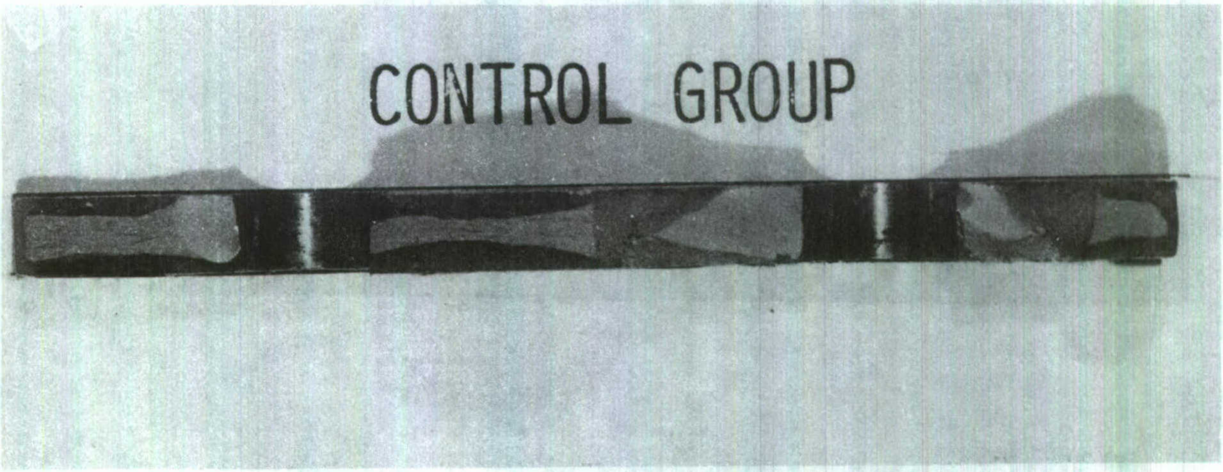


Figure 11. Specimen 113/J from the Control Group

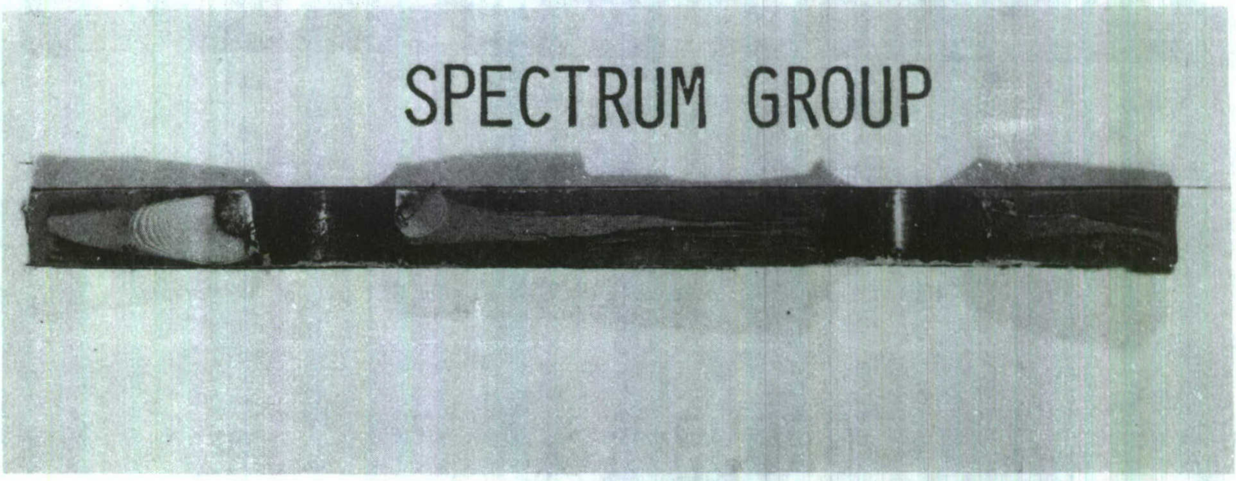


Figure 12. Specimen 150/87 from the Spectrum Group

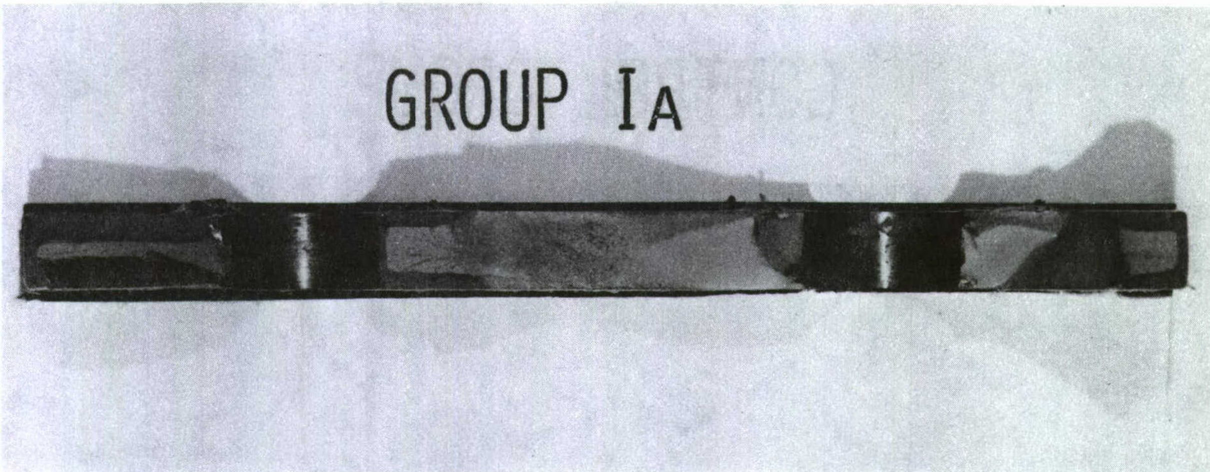


Figure 13. Specimen 170/124 from Group Ia

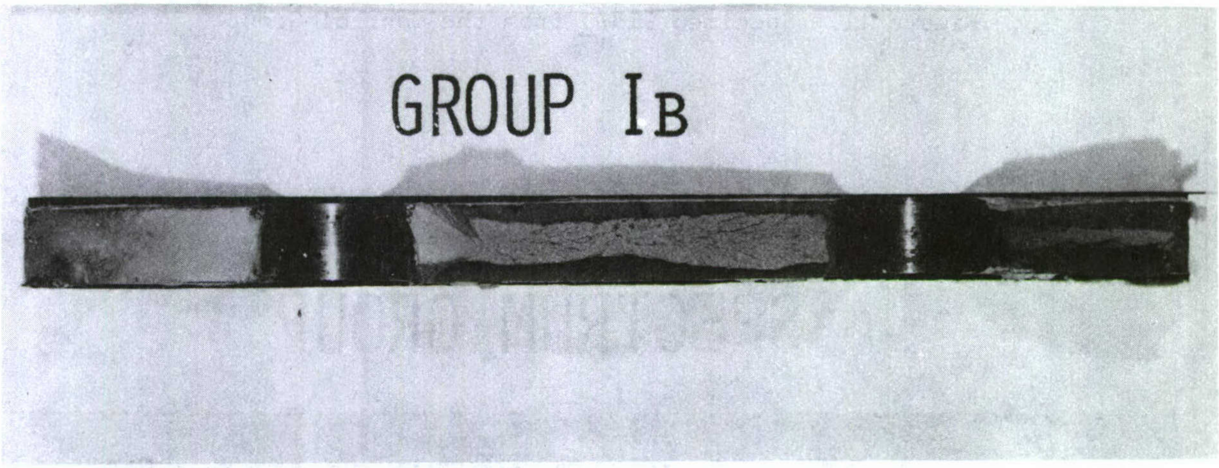


Figure 14. Specimen 149/151 from Group Ib

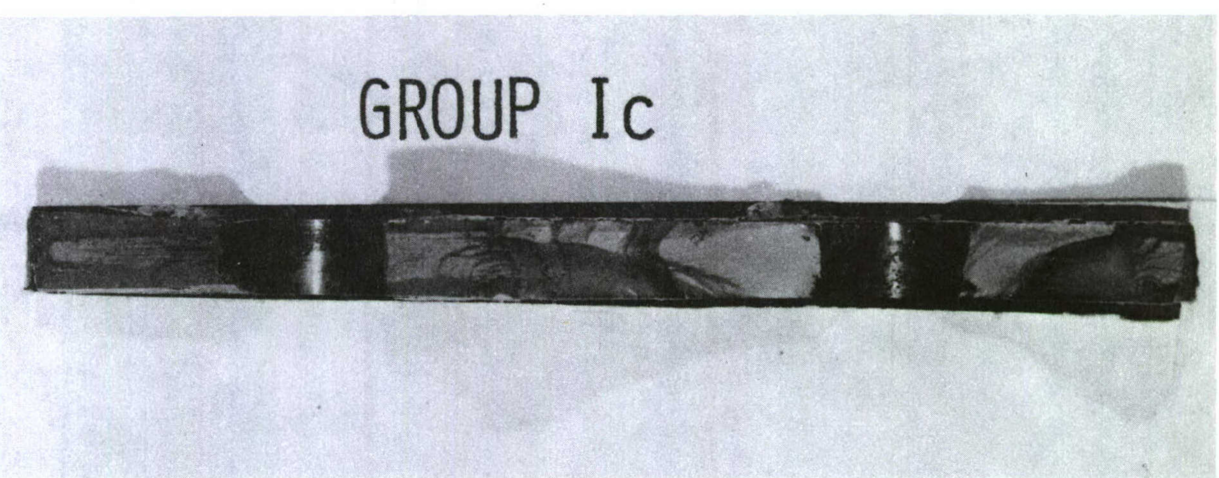


Figure 15. Specimen 35/M from Group Ic.

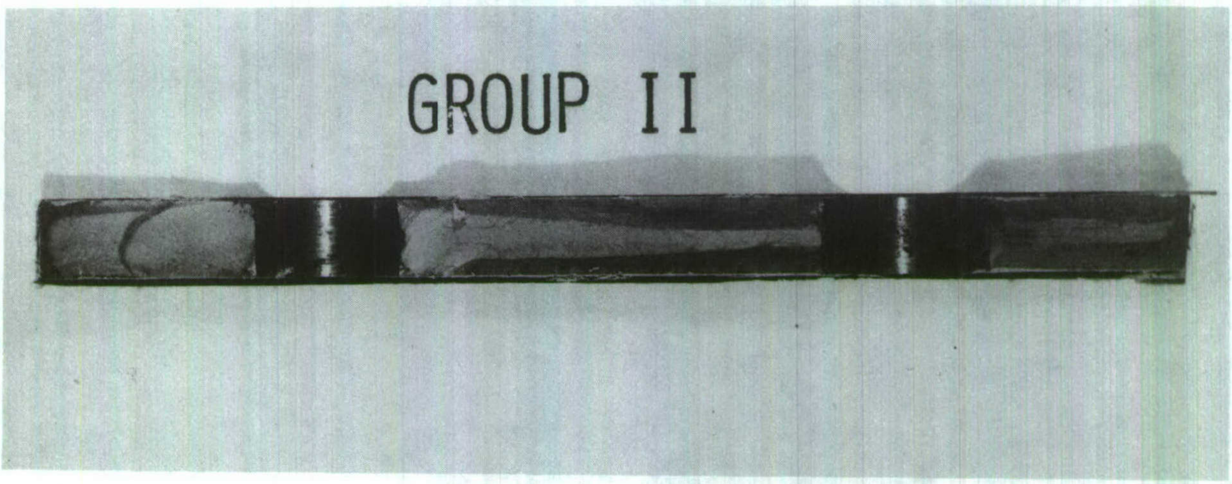


Figure 16. Specimen 112/G from Group II

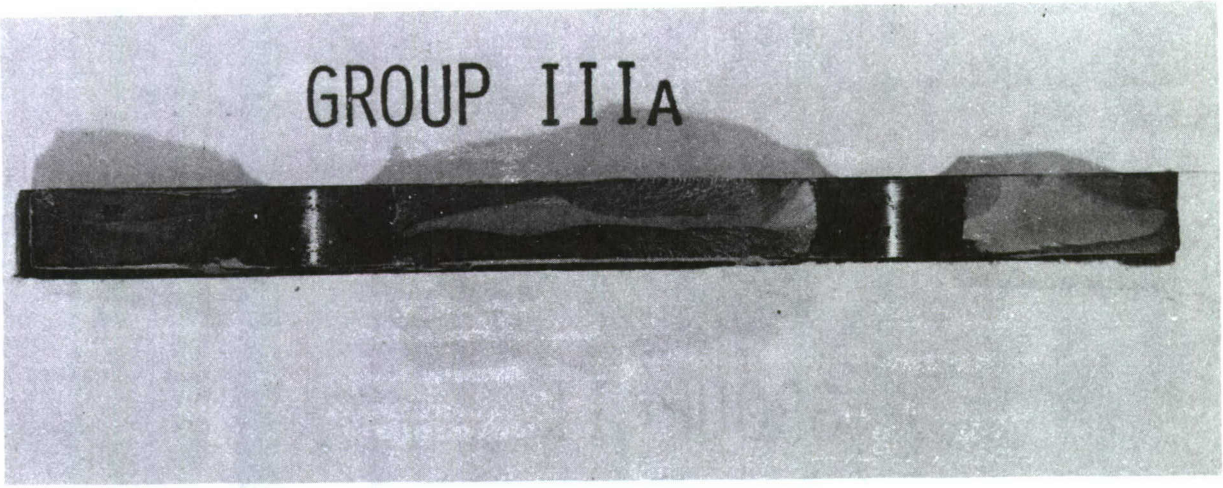


Figure 17. Specimen 239/281 from Group IIIa

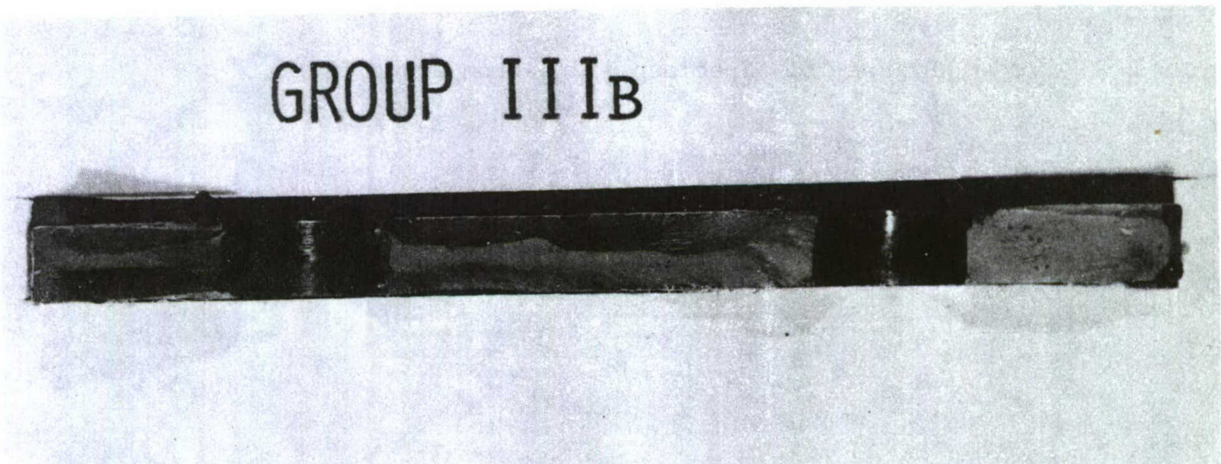


Figure 18. Specimen 31/154 from Group IIIb

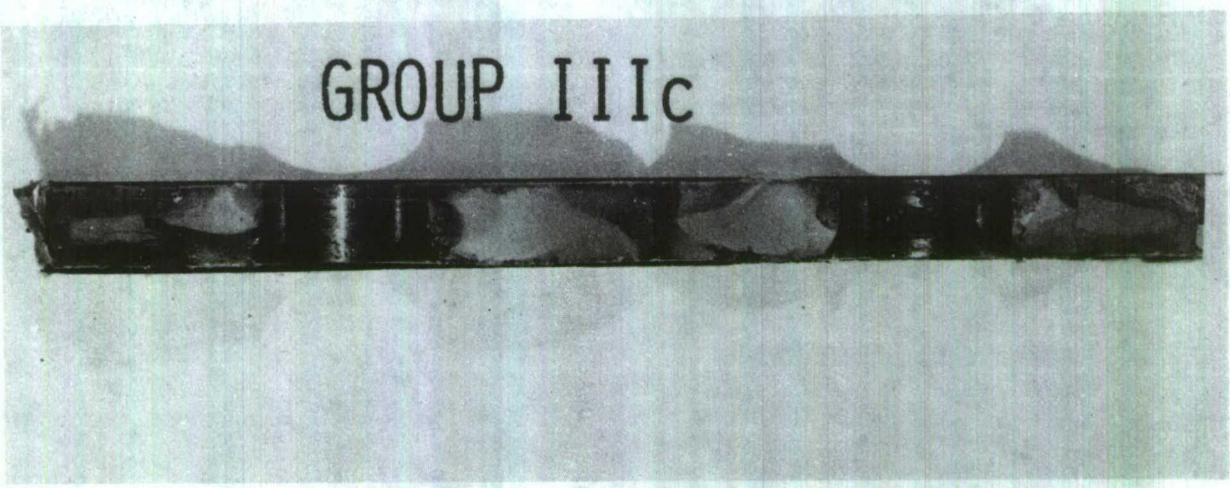


Figure 19. Specimen 127/172 from Group IIIc

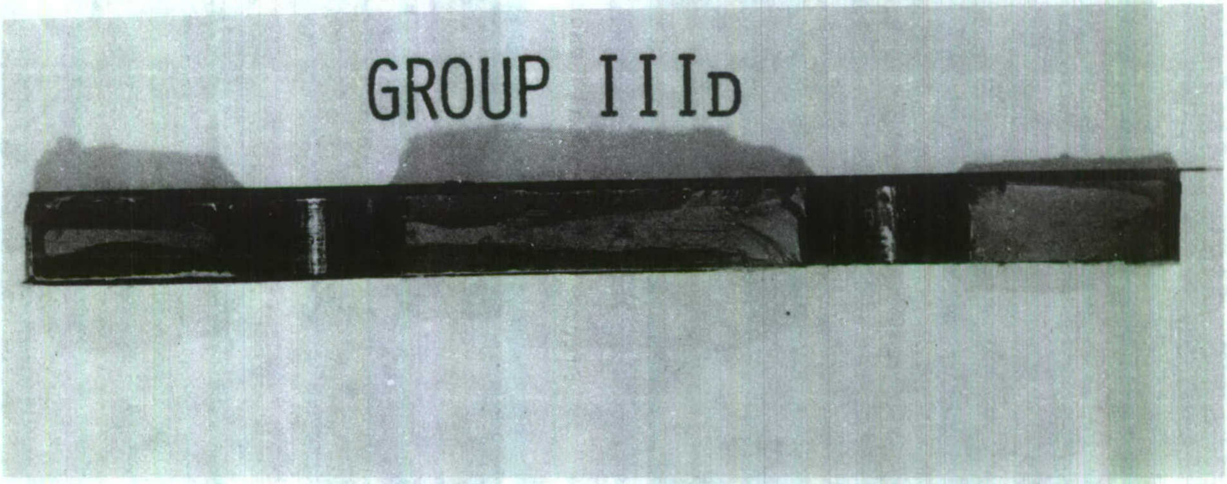


Figure 20. Specimen 303/H from Group IIId

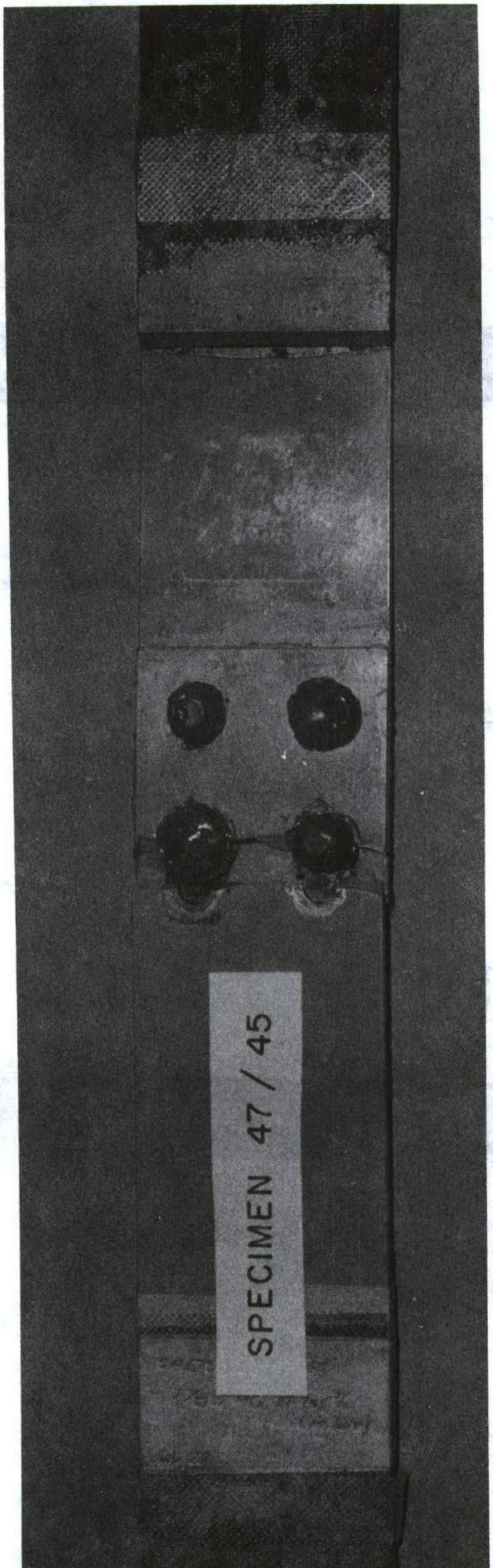


Figure 21. Typical Fracture Pattern, All Groups, D6AC Steel Specimens

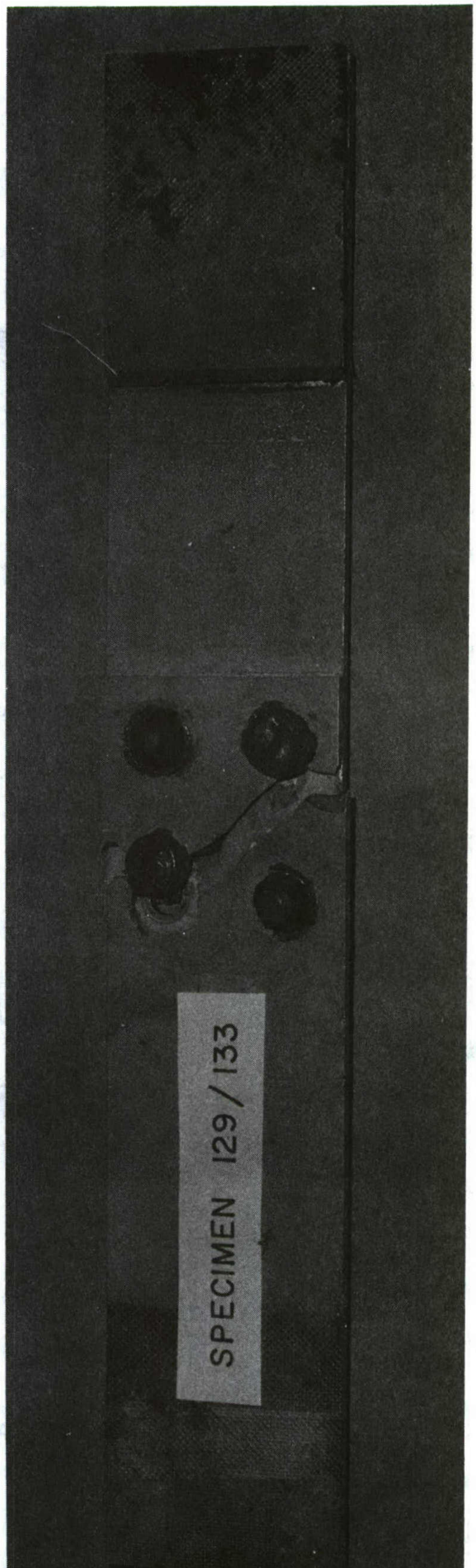


Figure 22. Non-typical Fracture Pattern, Specimen 129/133

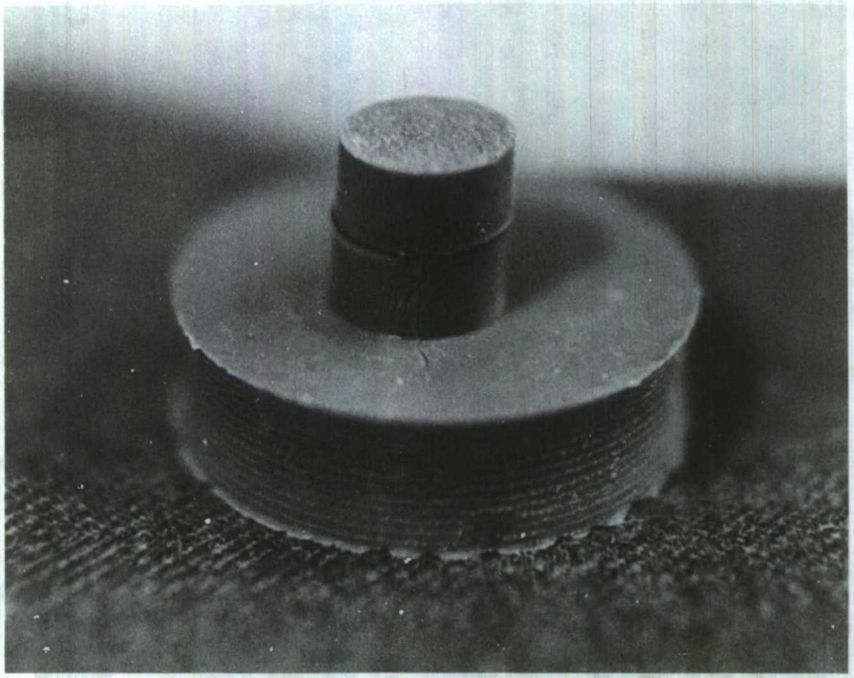


Figure 23. Magnetic Rubber Replica Showing Corner Crack Initiating from Faying Surface of Unfailed Hole

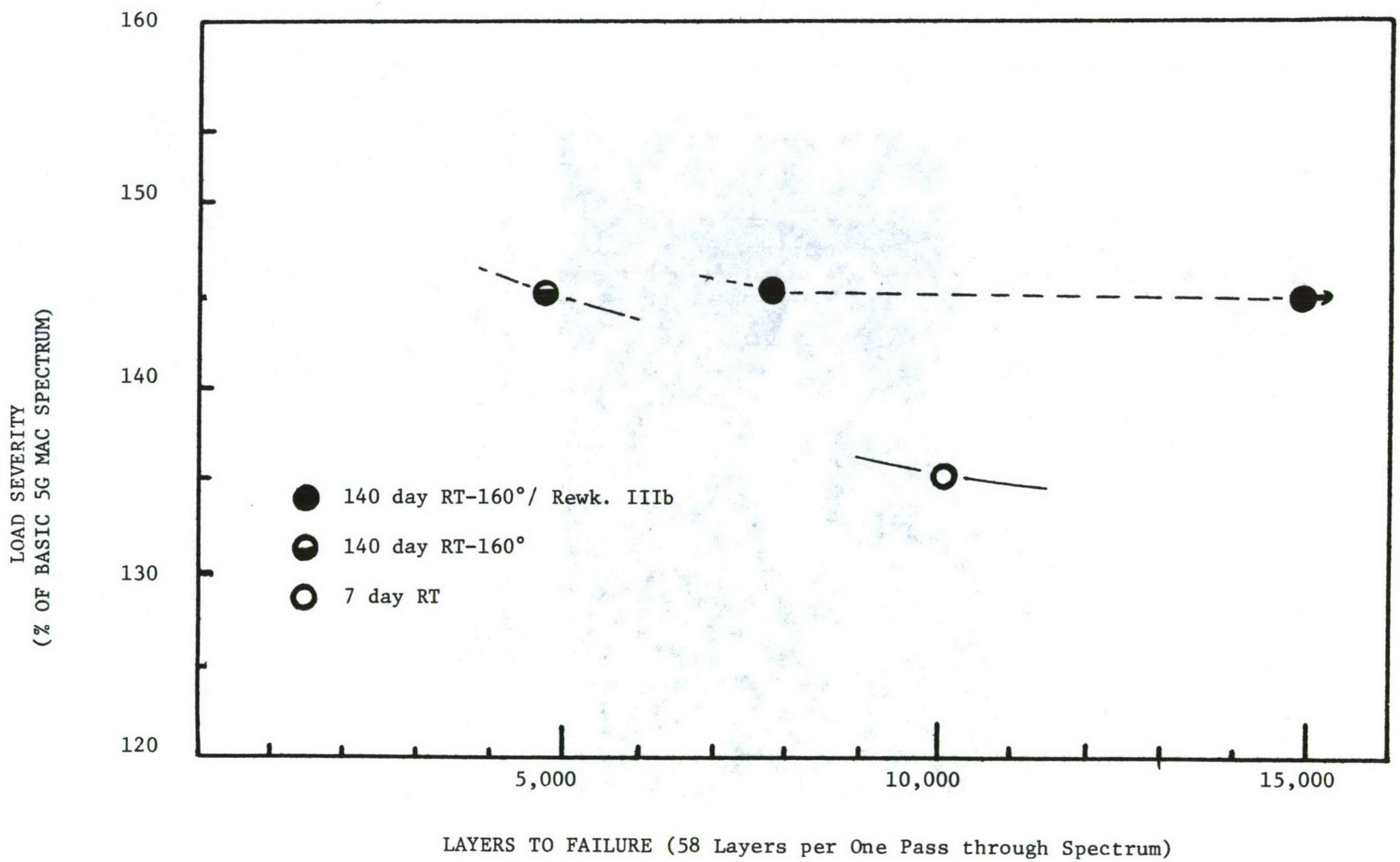


Figure 24. Results of Spectrum Tests on Steel-Steel Lap Joint Specimens

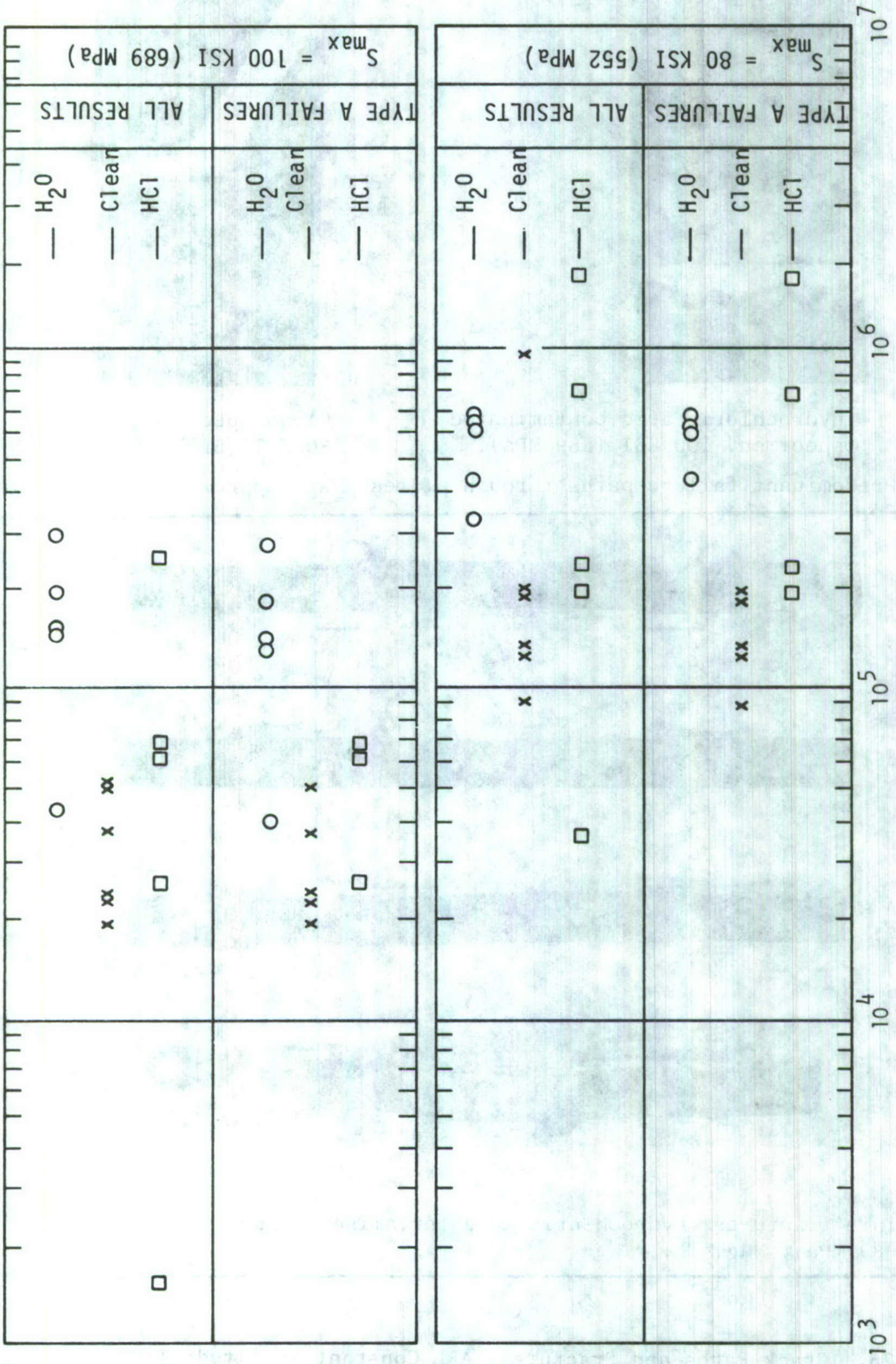
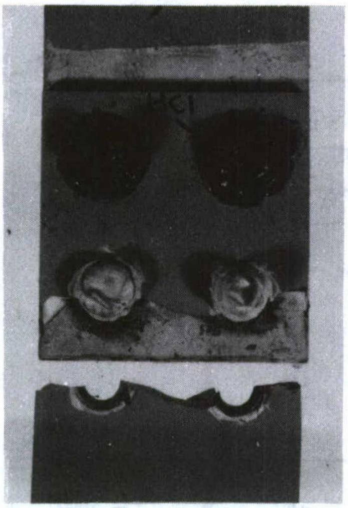
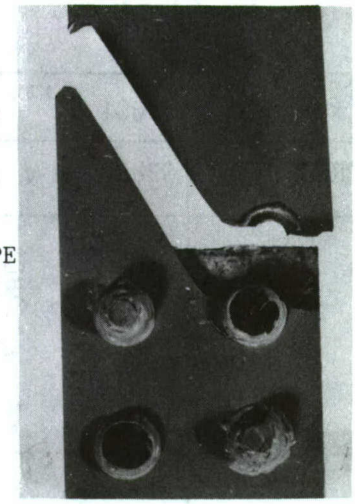


Figure 25. Comparison of Constant Amplitude Fatigue Lives Obtained at ARL

TYPE A



TYPE B



Hydrochloric acid contaminated specimen. 100 KSI (689 MPa).

Clean specimen. 80 KSI (552 MPa)

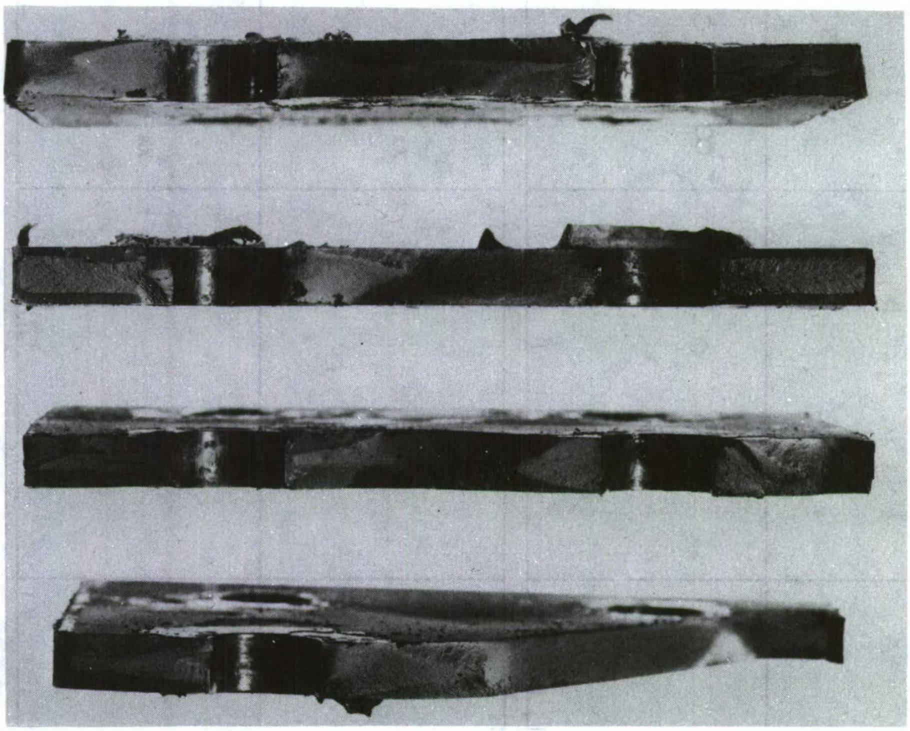
(a) Predominant failure paths through plates, Mag. Approx. ½.

TYPE A (61)

TYPE A (92)

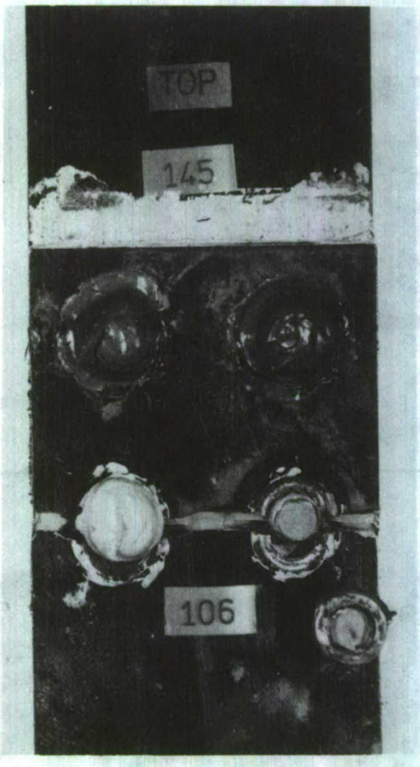
TYPE A (187)

TYPE B (242)

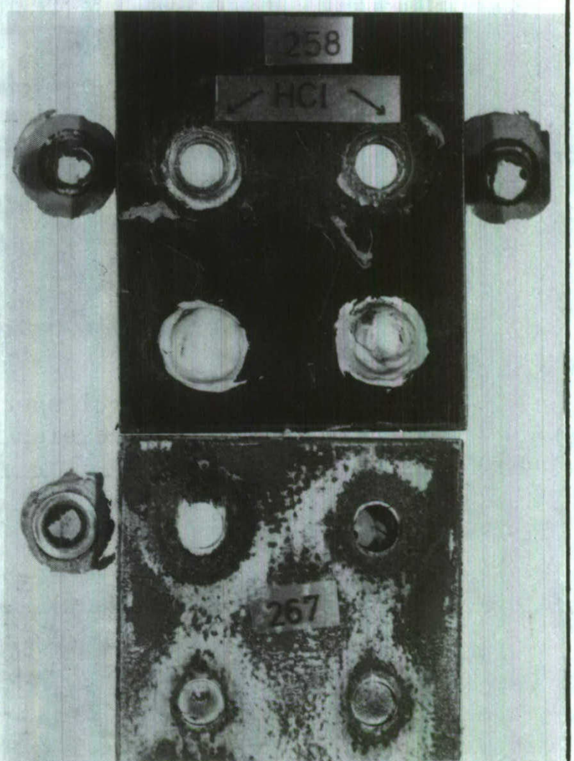


(b) Plate fractures, hydrochloric acid contaminated specimens, 100 KSI (689 MPa), Mag. 1½.

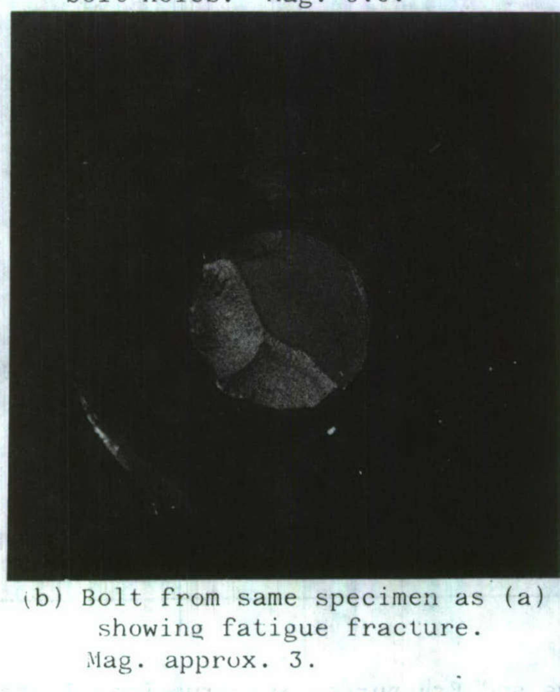
Figure 26. Crack Paths and Fractures, ARL Constant Amplitude Tests



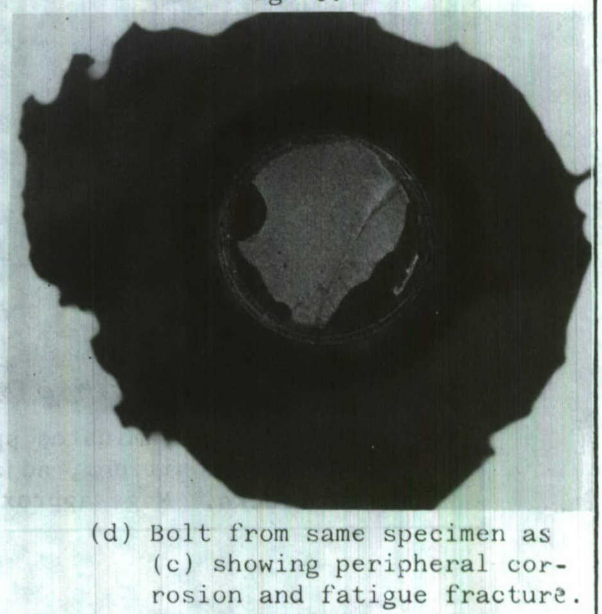
(a) Clean specimen, plate failure (Type A) through USA-assembled bolt holes. Mag. 0.6.



(c) Hydrochloric acid-contaminated specimen. Failure by fatigue of bolts in contaminated holes: bolts in clean holes failed by shear. Mag. 0.6.

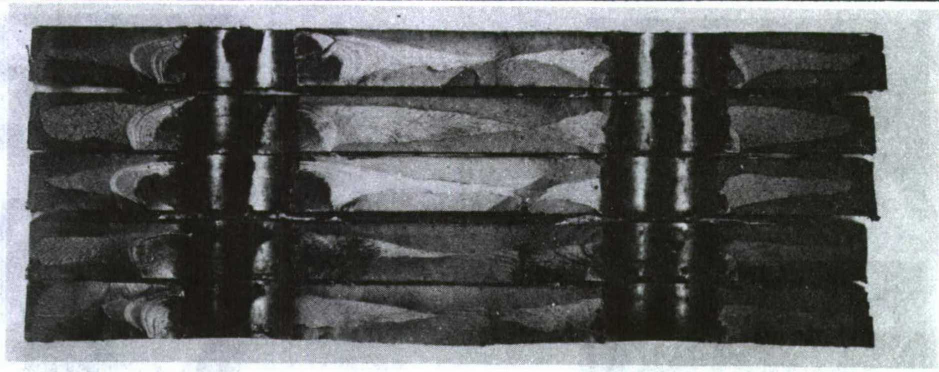


(b) Bolt from same specimen as (a) showing fatigue fracture. Mag. approx. 3.

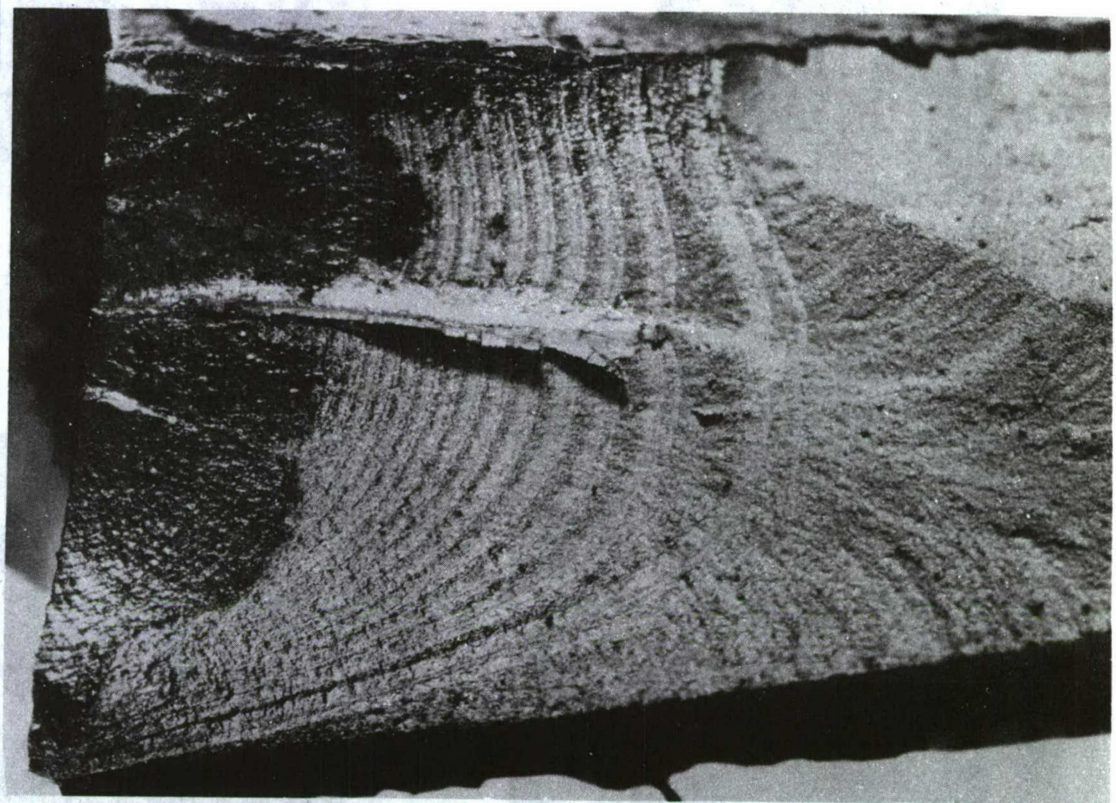


(d) Bolt from same specimen as (c) showing peripheral corrosion and fatigue fracture. Mag. Approx. 3.

Figure 27. Crack Paths and Fractures, Spectrum Load Tests at ARL



(e) Clean control specimens. All plate fractures show spectrum block progression markings. Mag. 1½.



(f) Water-contaminated specimen fracture (no. 100) showing crack front positions, adjacent to bolt hole, under progressive spectrum blocks. Mag. approx. 15.

Figure 27. Concluded. Crack Paths and Fractures, Spectrum Load Tests at ARL

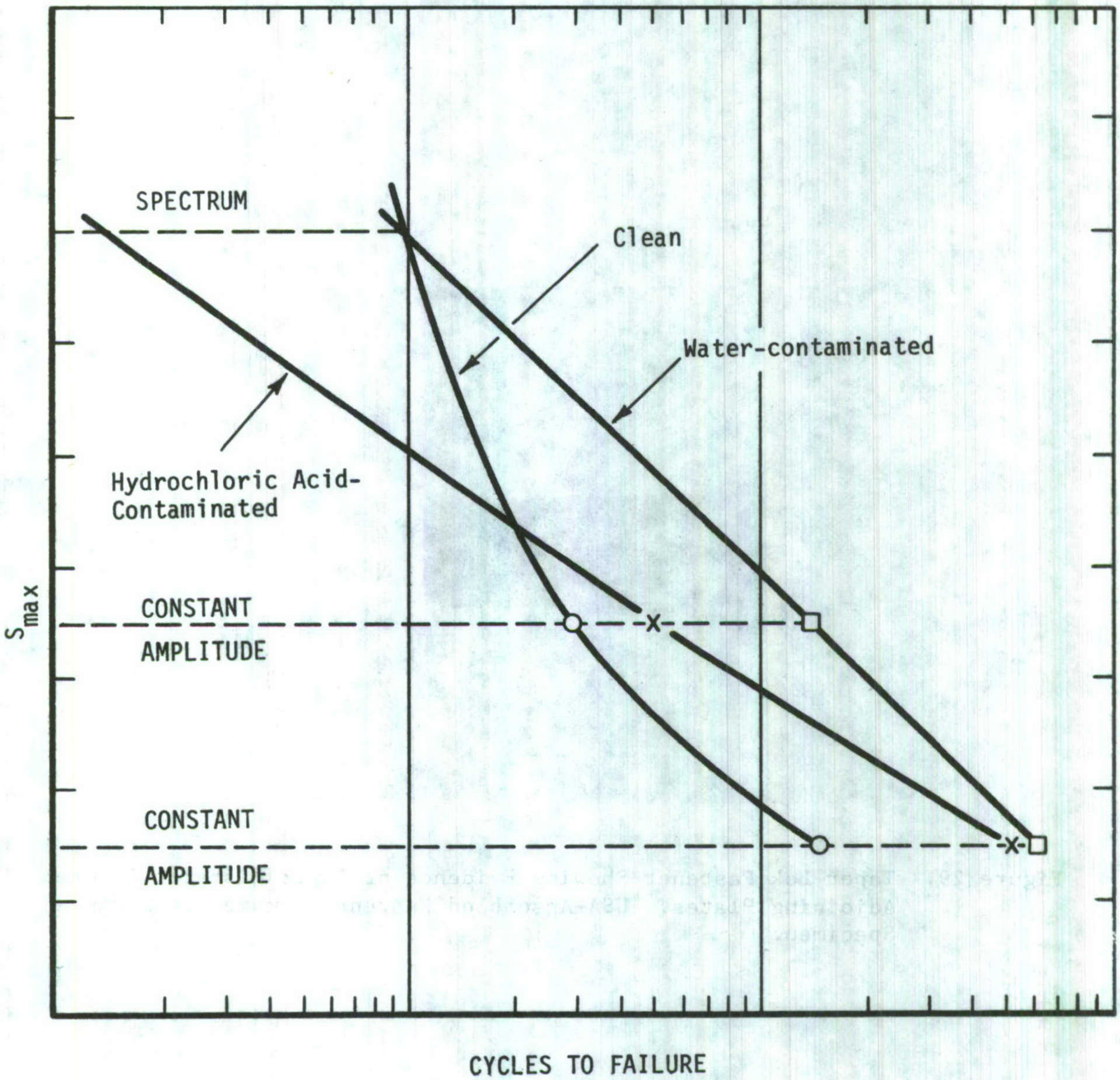


Figure 28. Schematic S/N Representation of Fatigue Test Results

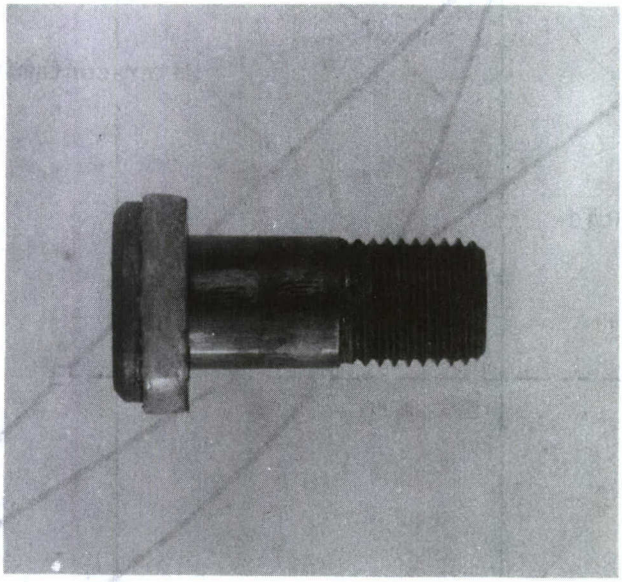


Figure 29. Taper-Lok Fastener Showing Evidence of Taper Mismatch Between Adjoining Plates. USA-Assembled Fastener Removed from Unused Specimen.

APPENDIX I

CHEMICAL ANALYSES AND HEAT TREATMENT OF D6AC STEEL

Metcut Associates Inc. (Cincinnati, Ohio, U.S.A.) Report No. 1184-19636-1, "Fabrication of Corrosion/Fatigue Specimens: Materials Documentation", June 1975, contains details of heat numbers, chemical analyses and the heat treatment schedule of D6AC steel joint components. These are summarized below.

CHEMICAL ANALYSES AND SPECIFICATION COMPOSITION RANGES OF D6AC STEEL

Heat No.	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu
8061365	0.48	0.76	0.007	0.002	0.20	0.56	1.07	1.03	0.10	0.12
8061936	0.46	0.78	0.009	0.001	0.23	0.58	1.08	1.00	0.10	0.22
8064194	0.47	0.77	0.008	0.004	0.24	0.58	1.08	1.02	0.10	0.12
AMS 6438A										
min.	0.45	0.60	--	--	0.15	0.40	0.90	0.90	0.08	--
max.	0.50	0.90	0.015	0.015	0.30	0.70	1.20	1.10	0.15	0.35

HEAT TREATMENT SCHEDULE FOR D6AC STEEL COMPONENTS

Austenitize at 1625°F ± 25°F (885°C ± 14°C) for 1 hour minimum.

Quench into salt at 400°F (204°C) with mild agitation, then air cool.

Rinse in hot water.

Temper at 1050°F ± 10°F (565°C ± 5°C) for 1 hour minimum, and air cool.

Re-temper at 1050°F ± 10°F (565°C ± 5°C) for 1 hour minimum, and air cool.

APPENDIX II

FABRICATION OF SPECIMENS

Metcut Research Associates, Inc., provided complete details of the manufacturing sequence, machining conditions and the fitting of the Taper-Lok fasteners.

The main steps in the fabrication of the steel-steel jap joint specimens were as follows:

1. Cut oversize steel components from D6AC steel plate.
2. Rough machine
3. Heat treat components as per General Dynamics Inc. Process Specification (G.D.P.S.) 26.01-3
4. Final grind to size
5. Shot peen to G.D.P.S. 74.03-1
6. Cadmium plate to G.D.P.S. 74.02-6 (QQ-P-416, Class 2, Type 2)
7. Paint (G. D. Master D. and A. Spec. 72255)
8. Bond on end tabs (Hysol Adhesive 9628)
9. Apply sealant (EC-5106) on faying surfaces, clamp in holding fixture, and allow to cure
10. Drill four holes (0.3594-inch diameter, J oil lubricant)
11. Machine taper ream four holes (J oil lubricant); deburr entrance and exist of holes, specimen ramaining clamped
12. Hand taper ream four holes (six-flute No. 7 tungsten carbide pin reamer) and clean
13. Apply sealant (EC 5106) under head of tapered fastener, and to aluminum alloy washer, threads and washer nut
14. Install Taper-Lok fasteners as per G.D. Standard M 063, with the washer under fastener head
15. Torque up to 570 in.-lb. (64.4 N.m) (G. D. Standard M 063)
16. Apply sealant (EC 5106) to completely cover fastener head and washer-nut
17. Remove specimen from holding fixture.

For partially-assembled specimens, the procedures were identical up to and including Step 12. The remaining steps were taken only with the two Taper-Lok fasteners at one end of the joint. The other pair of tapered holes was fitted for shipment with parallel-shank high tensile bolts and washers under both fastner heads and nuts, and torqued up to the same value as were the tapered fasteners. No sealant was applied to these fasteners.

The fabrication of the double dogbone specimens was similar except for the number of fastener holes. The steel-aluminum specimen fabrication was similar except for the machining and surface preparation of the aluminum component.

APPENDIX III

REWORK PROCEDURE TO REPLACE TAPER-LOK FASTENERS WITH STRAIGHT SHANK FASTENERS IN MANDRELIZED HOLES

All of the mandrelized steel-steel and steel-aluminum specimens were reworked to the same conditions as follows:

Initial Hole		.375 inch
Reamed Hole		.4175
Cold-Work Tool	.4160	
Sleeve (2t)	.0200	
Max Cold-Work-Tool Diam.		.4360
Cold-Work Interference		.0185
As-Cold-Worked Hole		.4266
Post-Ream Hole		.4370
Fastener Dia.		.4365
Torque		600 in. lb.

Several specimens were unbonded during fastener removal. Sealant was applied and they were reassembled after cold working. One specimen moved while being final reamed with the result that the aluminum hole was elongated. The cold work on this specimen is adequate. Two specimens were accidentally cold worked prior to measuring the intital hole size. Since the same starting hole reamers and tools were employed, the hole size would have been very close to those in the rest of the specimens. Specimen 11/274 was post-cold-work reamed with a slightly larger reamer (first specimen reamed), after which it was decided to switch to a slightly smaller reamer. The external edges of all holes were lightly deburred or chamfered using a hand tool.

APPENDIX IV

REWORK PROCEDURE TO REPLACE TAPER-LOK FASTENERS WITH K-LOBE FASTENERS IN STRAIGHT SHANK HOLES

The following procedure was used to rework test specimens from 3/8-inch Taper-Lok fasteners to 7/16-inch K-Lobe fasteners for full load transfer fatigue testing.

The installed Taper-Lok fastener and TLN Nuts were removed from the test specimens in pairs to maintain alignment.

Tapered holes were reamed to a straight hole utilizing a .4350-inch carbide 4-fluted reamer. Dowel pins were used for alignment in the 2 reamed holes while the remaining pair of fasteners were removed and tapered holes reamed. All holes maintained a tolerance of $\pm$ .0005 inch.

Specimens were assembled using PR1436-G sealant under both fastener head with washer and steel nut. K-Lobe fasteners used were 260 K.S.I. H-11 fasteners KLB62H7N9 with an aluminum washer similar to previous Taper-Lok installation. Nuts used were HW17-7 steel nuts torqued to 740 in-lb. seating torque.

K-Lobe fasteners were installed with 0.005/0.0055 inch interference. Push-in force was approximately 4000 lb. After installation, all fasteners were covered with sealant as with Taper-Lok specimens.

APPENDIX V

DERIVATION OF THE ARL 58-LAYER LOADING SPECTRUM FROM THE GENERAL DYNAMICS 5G MAC LOAD SPECTRUM

The General Dynamics 5G MAC load spectrum as employed in previous work on spectrum loading of D6AC steel specimens (7) is detailed in Table XIV. This spectrum was intended to represent the loads, sequences, numbers of cycles and cyclic frequencies of 200 flight hours of the F-111. It requires just over 24.5 hours of continuous testing time for one complete application of the spectrum (one spectrum block) of 17,241 cycles.

It was originally agreed that both AFML and ARL would use the 5G MAC spectrum for the spectrum loading tests on bolted joints, and that there should be a "four lifetime cut-off", that is, that specimens unbroken at the end of a testing time equivalent to four lifetimes of the aircraft should be considered to be "runouts". For the purposes of these tests, an aircraft lifetime is taken to be 4000 flight hours, and hence the "four lifetime cut-off" would represent 16000 flight hours, which equals 80 applications of the 200 flight hours loading sequence, corresponding to approximately 82 days of continuous testing per specimen.

A preliminary estimate of the fatigue life to be expected from "clean control" specimens under the 5G MAC spectrum was carried out at ARL to predict whether these specimens would fail within 80 spectrum blocks. (Indeed, it was desirable that the "contaminated" specimens should also fail within this period, in order to obtain a quantitative indication of the fatigue life ratios of clean to contaminated specimens under spectrum loading).

For this purpose, a family of theoretical 50% probability of failure S/N curves at various mean stresses for D6AC steel specimens with a single Taper-Lok bolt was used - this had been derived at ARL some years previously in connection with another project. Using Miner's hypothesis, the mean fatigue life was estimated initially to be not less than 576 spectrum blocks. Later when sufficient ARL and AFML constant amplitude "clean control" data were available, a similar calculation was made using a revised set of $S_a/S_m/N$ curves, and this gave an estimated mean life of not less than 506 spectrum blocks. The revised set of curves was obtained by redrawing the various S_m curves parallel to the originals, but through the $S_a/S_m/N$ co-ordinates obtained from the combined ARL/AFML test data on clean lap-joint specimens at 70,80,100 and 115 ksi (483,552,689 and 793 MPa). These seemed reasonable predictions since in the 5G MAC spectrum of 17241 cycles there are only 10 cycles whose maximum stress is in the range 80 to 100 ksi (552 to 689 MPa) and 3 whose maximum exceeds 100 ksi (689 MPa), for which maxima the corresponding constant amplitude lives at $R = +0.1$ were found to be of the order of 200,000 and 20,000 cycles respectively (see Table XVI).

The AFML roughly confirmed the estimate of 576 blocks. They observed that the original proposal to use the 5G MAC spectrum was made with the knowledge that, in previous tests on D6AC steel specimens, failure had occurred after 40 to 60 spectrum blocks. However, this result was obtained on open-hole specimens containing a 0.1 inch long precrack.

The AFML estimated, that for the lap-joint specimens, well over 50% of the total life would be required to initiate a detectable crack. This, combined with an estimate of 30 to 40 blocks to propagate a detectable crack to 0.1 inch, led them to suggest 200 to 400 blocks as a reasonable estimate for the life of a sound joint specimen. (Later AFML NDI results indicated that

99% of the life is consumed in initiating a crack and growing it to a depth of 0.075 inch to 0.1 inch (1.9mm to 2.5mm) in the lap-joint specimens).

The AFML thus concluded that the ARL estimate of 576 blocks was not unrealistic particularly when the retarding effect on crack growth of the tapered fasteners was added to their estimates above.

The AFML then commenced spectrum tests on lap-joint specimens which had been subjected to a variety of their external exposure/rework conditions. These tests comprised the total AFML effort on spectrum loading but were of an exploratory nature in relation to the ARL objectives. The AFML tested specimens, sequentially, for which the spectrum stresses, both maximum and minimum, were increased by 120%, 130%, 135%, 145% and 155%. On the basis of the results of some of these tests available at the time, combined with the AFML constant amplitude results, and in conjunction with ARL life estimates under these more-severe spectra, ARL considered increasing the maximum stresses by 155% and decreasing the minimum stresses to 55% of the original 5G MAC spectrum. The life predicted under this modified spectrum was 11.8 blocks.

A lap-joint Taper-Lok bolted specimen was then made from pieces of steel specimens fractured previously, and tested under this 155%/55% 5G MAC spectrum. The experimental life was 35 blocks, three times the predicted life. Finally, a 165% maximum stress/45% minimum stress 5G MAC spectrum, with all cycles applied at a frequency of 2.5Hz, was selected for the ARL spectrum load tests and is listed in Table XVIII. At this frequency, one spectrum block is applied in 115 minutes. The life calculated for these conditions was 8.5 blocks for clean control specimens, and on the basis of the previous test results, the expected experimental life was about 25 blocks.

☆U.S.Government Printing Office: 1979 — 657-002/97